



Poverty, Energy Use, Air Pollution and Health in Ghana: A Spatial Analysis

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**POVERTY, ENERGY USE, AIR POLLUTION AND HEALTH IN GHANA: A
SPATIAL ANALYSIS**

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A Dissertation Submitted to the Faculty of
The Harvard T.H. Chan School of Public Health
in Partial Fulfillment of the Requirements
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Poverty, energy use, air pollution and health in Ghana: a spatial analysis

Abstract

Under-five mortality is declining in most countries. Very few studies have measured under-five mortality, and its social and environmental determinants, at fine spatial resolutions, which is relevant for policy purposes. Our aim was to estimate under-five mortality and its social and environmental determinants at the district level in Ghana. We used 10% random samples of Ghana's 2000 and 2010 National Population and Housing Censuses. We applied indirect demographic methods and a Bayesian spatial model to the census data on total number of children ever born and children surviving to estimate under-five mortality (probability of dying by age five, 5q0) for each of Ghana's 110 districts. We used the census data to estimate the distributions of households or persons in each district for fuel used for cooking, sanitation facility, drinking water source, and parental educations. Median district 5q0 declined from 99 deaths per 1,000 live births in 2000 to 70 in 2010. The decline ranged between <5% in some northern districts, where 5q0 had been higher in 2000, to >40% in southern districts, where it had been lower in 2000, exacerbating existing inequalities. Primary education increased in men and women and more households had access to improved water and sanitation and cleaner cooking fuels. Higher use of liquefied petroleum gas for cooking was associated with lower 5q0 in multivariate analysis.

The second paper examines personal particulate matter exposures and locations of 56 students from eight schools in four neighborhoods in of varying socioeconomic status in Accra, Ghana, using gravimetric and continuous PM_{2.5} data, with time-matched global

positioning system coordinates. Personal PM_{2.5} exposures ranged from less than 10 µg/m³ to more than 150 µg/m³ (mean 56 µg/m³). Girls had higher exposure than boys (67 vs. 44 µg/m³; p-value = 0.001). Exposure was inversely associated with distance of home or school to main roads, but the associations were not statistically significant in the multivariate model. Use of biomass fuels in the area where the school was located was also associated with higher exposure, as was household's own biomass use. Paved schoolyard surface was associated with lower exposure.

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To Professor Majid Ezzati

To Comfort, Souzana, Liam, and Diamond

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Spatial inequalities and social and environmental determinants of under-five mortality in Ghana in 2000 and 2010: Bayesian spatial analysis of census data

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Abstract

Background: Under-five mortality is declining in most countries. Very few studies have measured under-five mortality, and its social and environmental determinants, at fine spatial resolutions, which is relevant for policy purposes.

Objectives: Our aim was to estimate under-five mortality and its social and environmental determinants at the district level in Ghana.

Methods: We used 10% random samples of Ghana's 2000 and 2010 National Population and Housing Censuses. We applied indirect demographic methods and a Bayesian spatial model to the census data on total number of children ever born and children surviving to estimate under-five mortality (probability of dying by age five, 5q0) for each of Ghana's 110 districts. We used the census data to estimate the distributions of households or persons in each district for fuel used for cooking, sanitation facility, drinking water source, and parental educations.

Results: Median district 5q0 declined from 99 deaths per 1,000 live births in 2000 to 70 in 2010. The decline ranged between <5% in some northern districts, where 5q0 had been higher in 2000, to >40% in southern districts, where it had been lower in 2000, exacerbating existing inequalities. Primary education increased in men and women and more households had access to improved water and sanitation and cleaner cooking fuels. Higher use of liquefied petroleum gas for cooking was associated with lower 5q0 in multivariate analysis.

Conclusions: Under-five mortality has declined in all of Ghana's districts but the cross-district inequality in mortality has increased. There is a need for additional data, including on

healthcare and additional environmental measurements, to understand the reasons for variations in mortality levels and trends.

Introduction

Mortality in children under five years of age has declined in most countries, with the decline accelerating since 2000 (UN IGME 2013). The pace of under-five mortality decline has been slower in sub-Saharan Africa (SSA) than in other regions, and SSA accounts for nearly one half of the global under-five deaths (Requejo et al. 2014; UN IGME 2013). Poverty-related risk factors, including unimproved water and sanitation and household air pollution from solid fuels, account for a large proportion of under-five deaths (Lim et al. 2012); parental, and especially maternal, education is an important predictor of child survival (Gakidou et al. 2010). These factors may also be among the determinants of within-country disparities in under-five mortality (Gakidou et al. 2007; Stevens et al. 2008).

Above and beyond global inequalities, there are important subnational inequalities in under-five mortality in relation to socioeconomic status (SES) and geography (Amouzou et al. 2014; Dwyer-Lindgren et al. 2014; Gakidou et al. 2007; Hosseinpoor et al. 2005; Houweling and Kunst 2010; Kraft et al. 2013; Ram et al. 2013; Vapattanawong et al. 2007). Very few studies have examined under-five mortality at fine spatial resolutions, which is relevant for assessing community determinants and interventions (Bauze et al. 2012; Dwyer-Lindgren et al. 2014; Ram et al. 2013; Sousa et al. 2010). Further, little has been done on how subnational variations and trends in under-five mortality are associated by social and environmental factors that have been found to affect child survival in individual-level studies (Gakidou et al. 2007; Stevens et al. 2008).

Ghana has had one of the largest declines in under-five mortality in SSA (Requejo et al. 2014; UN IGME 2013). Under-five mortality in Ghana dropped from 128 deaths per 1,000 live births in 1990 to 72 in 2012, a 45% reduction (UN IGME 2013). Ghana has also had one

of SSA's best economic performances, with its per-capita GDP growing by nearly 600% between 2000 and 2013 (The World Bank). Economic inequality, as measured by the Gini coefficient, increased slightly between 1998 and 2006 (The World Bank). It is unclear whether this national improvement is benefiting all local communities, how it might be affecting within-country inequalities, and whether it is associated with broad economic and environmental improvements or if it is driven by other factors.

In the analyses presented in this paper, we used geocoded data from two national censuses to estimate under-five mortality in Ghana at the district level in 2000 and 2010, and assessed variations and inequalities in under-five mortality in these two years and changes over the decade. We also analysed the distributions of social and environmental determinants of under-five mortality, and their associations with under-five mortality and its change. To our knowledge, this report is among the few high-resolution "small-area" studies of under-five mortality and its social and environmental determinants, and the only one to assess change in small-area units over a period of a decade.

Methods

Data sources

We used 10% random samples of Ghana's 2000 and 2010 National Population and Housing Censuses. Both censuses gather information on a number of individual and household level variables related to socioeconomic factors, living environment, and vital statistics. Each record in the census data had information on the census enumeration area (EA), the smallest geographical unit with an average population of 750. Our analysis was conducted at the district level, the country's second level subnational administrative divisions, with EAs mapped to the district of residence. There were 110 and 170 districts in the 2000 and 2010

censuses, respectively. We merged the 2010 districts, linking them to their original districts that had split since 2000, to create 110 common districts for our analyses.

We calculated the distributions of households or persons in each district for the following variables:

- cooking fuel: wood, charcoal, other biomass, kerosene, liquefied petroleum gas (LPG), electricity;
- sanitation facility: improved, unimproved;
- drinking water source: improved, unimproved;
- maternal education: none, primary, secondary or higher;
- paternal education: none, primary, secondary or higher; and
- urban vs. rural place of residence.

Classifications of drinking water and sanitation as improved vs. unimproved were based on WHO/UNICEF joint monitoring program categories for water supply and sanitation (<http://www.wssinfo.org>).

Statistical methods

District level under-five mortality: Our measure of under-five mortality was the probability of dying by five years of age (5q0). The censuses asked all women of childbearing age to report on the total number of children ever born and children surviving. This information is the basis for the application of indirect demographic models to estimate under-five mortality, an approach commonly used by researchers and by national and international statistical and health agencies. The method converts the proportion of deaths among children ever born to women in each five-year age group of the reproductive period into estimates of the probability of dying by exact ages of childhood, and calculates the number of years before the

survey date to which the estimates are referred (Hill et al. 2012; United Nations 1983). Estimates derived from the two youngest age groups of women (15-19 and 20-24 years) tend to be overestimated compared to the population average because children of women in these age groups tend to have higher risk of dying than those of older women (Hill et al. 2012). Therefore, and following other analyses (including those by the UN Inter-agency Group for Child Mortality Estimation) (Hill et al. 2012), we excluded 5q0 estimates based on reports of women aged 15-24 years. The remaining five estimates (one for each 5-year age group between 25 and 49 years), each with a reference date in years prior to the survey date, were used in our analysis. The reference dates for 5q0 estimates for the 2000 census covered the period 1987-1996; for the 2010 census the period was 1997-2007.

To obtain a single 5q0 estimate for each district for index years 2000 and 2010, we fitted a Bayesian space-time model to the five estimates per district from each census. The model included a linear time trend for estimates from each census in each district. The district intercepts and slopes were modelled using the Besag, York, and Mollie (BYM) model (Besag et al. 1991). In the BYM model, information is shared both locally (amongst neighbouring districts) through spatially-structured random effects with a conditional autoregressive (CAR) prior, and globally through spatially-unstructured Gaussian random effects. This approach balances between (overly) unstable within-district estimates and (overly) simplified aggregate national estimates. Samples from the posterior distributions of the intercepts and slopes were used to estimate 5q0 for years 2000 and 2010.

Correcting 5q0 estimates from summary birth histories: The national 5q0 estimates based on the census alone were different from estimates by the UN, which use a larger number of data sources (UN IGME 2013), especially for 2000 (these additional sources are not

representative at the district level). We adjusted our estimates to match the UN estimates in 2000 and 2010, because the additional data sources likely help provide more valid estimates. As detailed above, the linear trends fitted to the census-based national estimates were used to obtain 5q0 in 2000 and 2010. We then applied a correction factor, calculated as the ratio of national estimates of 5q0 levels from the UN to those from the census alone, to 5q0 estimates for each district. The mean of the corrected district estimates for the 2000 and 2010 censuses were 104.7 and 77.5, respectively, compared to 102.1 and 75.1 deaths per 1,000 live births as estimated by the UN.

Statistical analysis: We estimated the associations of under-five mortality with its social and environmental determinants at the district level. We analysed the associations in 2000 and 2010 as well as that of change in under-five mortality with changes in these factors. The model for associations in each census year was specified as below:

$$\ln(5q0) = \alpha + \beta X + U + V,$$

- 5q0 = district-level under-five mortality (per 1,000 live births)
- X = a vector of district-level risk factors (each as % households or persons), including:
 - cooking fuel type (wood; charcoal; other biomass; kerosene; LPG; electricity)
 - sanitation facility (improved; unimproved)
 - drinking water source (improved; unimproved)
 - maternal education (none; primary; secondary or higher)
 - paternal education (none; primary; secondary or higher)
 - place of residence (urban; rural)
- U = spatially-structured random effects
- V = unstructured random effects

- α, β = regression coefficients

When analysing change in under-five mortality, $Ln(5q0)$ and X were replaced with their 2010-2000 differences.

All analyses were implemented using the open-source statistical package R version 3.1.0 (R Project for Statistical Computing, Vienna, Austria) and WinBUGS version 1.4 (Spiegelhalter et al. 2003).

Results

In 2000, under-five mortality varied substantially among districts in Ghana, ranging from about 75 to nearly 150 deaths per 1,000 live births (Figure 1). Under-five mortality was above 100 per 1,000 live births in over half of the districts in 2000. The majority of these districts were in the three Northern regions of the country. There was also high under-five mortality in areas along the coastline of the Western and Central regions. Under-five mortality declined in all districts between 2000 and 2010, and was above 100 per 1,000 live births in only 13% of districts in 2010 (Figure 2A). In 2010, under-five mortality was below 70 deaths per 1,000 live births for nearly half of the districts, whereas no district had been this low in 2000.

Between 2000 and 2010, under-five mortality declined by over 40% in some southern districts but the decline was slower in the north, with nearly a third of districts having a less than 20% reduction (Figure 2B). Districts with the highest mortality in 2000 generally had a smaller decline, exacerbating existing cross-district inequalities, especially for relative inequalities. For example, the difference and ratio of the highest and lowest percentile of

district under-five mortality increased from 76 and 2.0 in 2000 to 78 and 2.5 in 2010, respectively.

From 2000 to 2010, the proportion of households without improved sanitation and drinking water decreased in all districts. Over 80% of households had improved drinking water in 47 districts and improved sanitation in 64 districts in 2010, compared to virtually none in 2000 (Figure 3). Despite the improvements, the share of households with improved sanitation was less than 80% in all districts in the Northern, Upper East and Upper West regions in 2010. There were also some reductions in the use of wood for cooking, largely replaced by charcoal, which emits less health damaging particulate matter (Bailis et al. 2005; Dionisio et al. 2012; Ezzati et al. 2000). The proportion of households using LPG also increased from 6% in 2000 to 18% in 2010. In some districts in Greater Accra over a quarter of households used LPG as the primary cooking fuel in 2010.

More women completed primary education and fewer were illiterate in every district in 2010 than in 2000 (Figure 3). In over one half of districts, including in all 24 districts in Northern Ghana, at least one half of women had not attended school or had not completed primary education in 2000; by 2010, this was the case in 25% of districts. Despite improvements in basic literacy and primary education, the proportion of women who attained secondary or higher education did not change noticeably.

In multivariate analysis, higher use of LPG for household cooking was associated with lower under-five mortality after adjusting for other factors, with each 10% shift from wood to LPG associated with 11.1% (95% CI 3.0-18.8%) decline in 5q0 (Figure 4). Associations for the other social and environmental variables were not consistent or were weak in the different

analyses although there were indications of beneficial effects from replacing wood with charcoal or kerosene, from improved sanitation (but not water), and from higher share of mothers and fathers with primary education.

Discussion

Our small-area analysis found that under-five mortality declined in all of Ghana's districts between 2000 and 2010, but the size of this decline varied considerably across districts. The pace of decline was steeper in southern districts, where under-five mortality was lower in 2000, than in the north, exacerbating existing cross-district inequalities, especially for relative inequality. We also found improvements in education and household environment including access to improved water and sanitation and cooking fuels. Higher use of liquefied petroleum gas for cooking was associated with lower under-five mortality, but the associations of either the level or change in under-five mortality with other social and environmental variables were weak.

Like our study, under-five mortality declined in all districts in Zambia and Papua New Guinea, and in some districts in India over time, with large subnational variation in the magnitude of decline (Bauze et al. 2012; Dwyer-Lindgren et al. 2014; Ram et al. 2013). Unlike our study, cross-district inequality decreased in Zambia over time, but the Indian study found a rise as we did in Ghana. The association between parental, especially maternal, education with child survival was weaker in our data than in some other population-based studies (Fink et al. 2014; Gakidou et al. 2010; Kraft et al. 2013; Pradhan and Arokiasamy 2010; Wang et al. 2014).

The main strength of our study is its novel and policy-relevant scope of analysing under-five mortality, and its socioeconomic and environmental determinants, at the small-area level. We used geocoded data from two national censuses, which included every household in the country. We also used Bayesian spatial analysis which balanced between unstable district level estimates and simplified aggregate national estimates to obtain consistent and comparable under-five mortality estimates for all districts.

Our study also has a number of limitations. Due to the absence of vital registration system in Ghana, we relied on demographic models to estimate under-five mortality at the district level. While this approach is well-tested and used by national and international agencies, it introduces uncertainty in our estimates. In particular, the estimates using the 2000 census were substantially different from the national estimates using others sources. We dealt with this issue by adjusting our estimates to be consistent with pooled estimates from all sources. This adjustment could introduce additional uncertainty in the district level estimates. We could not separate child deaths into those during the neonatal vs. subsequent periods, which are affected by different social, environmental, and healthcare factors. The social and environmental determinants of child health and survival were each measured using one or two questions in the census. This simplification of measurement may have affected their associations with under-five mortality. We had no information on healthcare access and interventions such as immunisation, insecticide-treated nets, and nutritional supplementation, which are important determinants of child survival (Adams et al. 2013; Amouzou et al. 2012; Monteiro et al. 2010). Similarly, we had no information on within-country migration, which might be partially responsible for changes in specific districts over time.

Conclusions

The Millennium Development Goals, and the policy emphasis and resources that have followed them, have led to acceleration of under-five mortality decline in Ghana and other countries in SSA. These efforts seem to be benefiting all of Ghana's districts, but the rate of progress has been slow and unequal across districts. There is therefore a need to both accelerate the decline, and to put special emphasis on districts that have progressed more slowly. Experiences of more equitable decline in countries such as Niger, Brazil, and Bangladesh show that achieving this requires multi-sectoral approaches while maintaining a major role for the health system (Adams et al. 2013; Amouzou et al. 2012; Monteiro et al. 2010). In particular, although we found weak associations between under-five mortality and some of the social and environmental factors, the role of these factors may have been partially masked by others including changes in the health services and health systems interventions, and hence there should be investments in education and household environment as a way to continue and accelerate improvements in child survival. At the same time, the weak association with these factors, and the large body of evidence on the efficacy of healthcare and health systems interventions for child health, should motivate increasing the coverage of healthcare interventions such as antenatal care, immunisation, insecticide-treated nets, and treatment of acute conditions such as pneumonia, malaria, and diarrhoea throughout Ghana with emphasis on equity in access and utilisation (Amouzou et al. 2012; Victora et al. 2012). Finally, improving measurement and monitoring of under-five mortality and its risk factors and interventions at sub-national level are particularly important for all SSA countries to better inform policies and programmes that facilitate equitable progress.

References

- Adams AM, Rabhani A, Ahmed S, Mahmood SS, Al-Sabir A, Rashid SF, et al. 2013. Explaining equity gains in child survival in bangladesh: Scale, speed, and selectivity in health and development. *Lancet* 382:2027-2037.
- Amouzou A, Habi O, Bensaid K, Niger Countdown Case Study Working G. 2012. Reduction in child mortality in niger: A countdown to 2015 country case study. *Lancet* 380:1169-1178.
- Amouzou A, Kozuki N, Gwatkin DR. 2014. Where is the gap?: The contribution of disparities within developing countries to global inequalities in under-five mortality. *BMC public health* 14:216.
- Bailis R, Ezzati M, Kammen DM. 2005. Mortality and greenhouse gas impacts of biomass and petroleum energy futures in africa. *Science* 308:98-103.
- Bauze AE, Tran LN, Nguyen KH, Firth S, Jimenez-Soto E, Dwyer-Lindgren L, et al. 2012. Equity and geography: The case of child mortality in papua new guinea. *PloS one* 7:e37861.
- Besag J, York J, Molli A. 1991. Bayesian image restoration, with two applications in spatial statistics. *Annals of the Institute of Statistical Mathematics* 1:20.
- Dionisio KL, Howie SR, Dominici F, Fornace KM, Spengler JD, Adegbola RA, et al. 2012. Household concentrations and exposure of children to particulate matter from biomass fuels in the gambia. *Environmental science & technology* 46:3519-3527.
- Dwyer-Lindgren L, Kakungu F, Hangoma P, Ng M, Wang H, Flaxman AD, et al. 2014. Estimation of district-level under-5 mortality in zambia using birth history data, 1980–2010. *Spatial and Spatio-temporal Epidemiology* 11:89-107.
- Ezzati M, Mbinda BM, Kammen DM. 2000. Comparison of emissions and residential exposure from traditional and improved cookstoves in kenya. *Environmental science & technology* 34:578-583.
- Fink G, Gunther I, Hill K. 2014. Slum residence and child health in developing countries. *Demography* 51:1175-1197.
- Gakidou E, Oza S, Vidal Fuertes C, Li AY, Lee DK, Sousa A, et al. 2007. Improving child survival through environmental and nutritional interventions: The importance of targeting interventions toward the poor. *JAMA : the journal of the American Medical Association* 298:1876-1887.
- Gakidou E, Cowling K, Lozano R, Murray CJ. 2010. Increased educational attainment and its effect on child mortality in 175 countries between 1970 and 2009: A systematic analysis. *Lancet* 376:959-974.
- Hill K, You D, Inoue M, Oestergaard MZ, Technical Advisory Group of United Nations Inter-agency Group for Child Mortality E. 2012. Child mortality estimation: Accelerated progress in reducing global child mortality, 1990-2010. *PLoS medicine* 9:e1001303.
- Hosseinpoor AR, Mohammad K, Majdzadeh R, Naghavi M, Abolhassani F, Sousa A, et al. 2005. Socioeconomic inequality in infant mortality in iran and across its provinces. *Bulletin of the World Health Organization* 83:837-844.
- Houweling TA, Kunst AE. 2010. Socio-economic inequalities in childhood mortality in low- and middle-income countries: A review of the international evidence. *British medical bulletin* 93:7-26.
- Kraft AD, Nguyen KH, Jimenez-Soto E, Hodge A. 2013. Stagnant neonatal mortality and persistent health inequality in middle-income countries: A case study of the philippines. *PloS one* 8:e53696.
- Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors

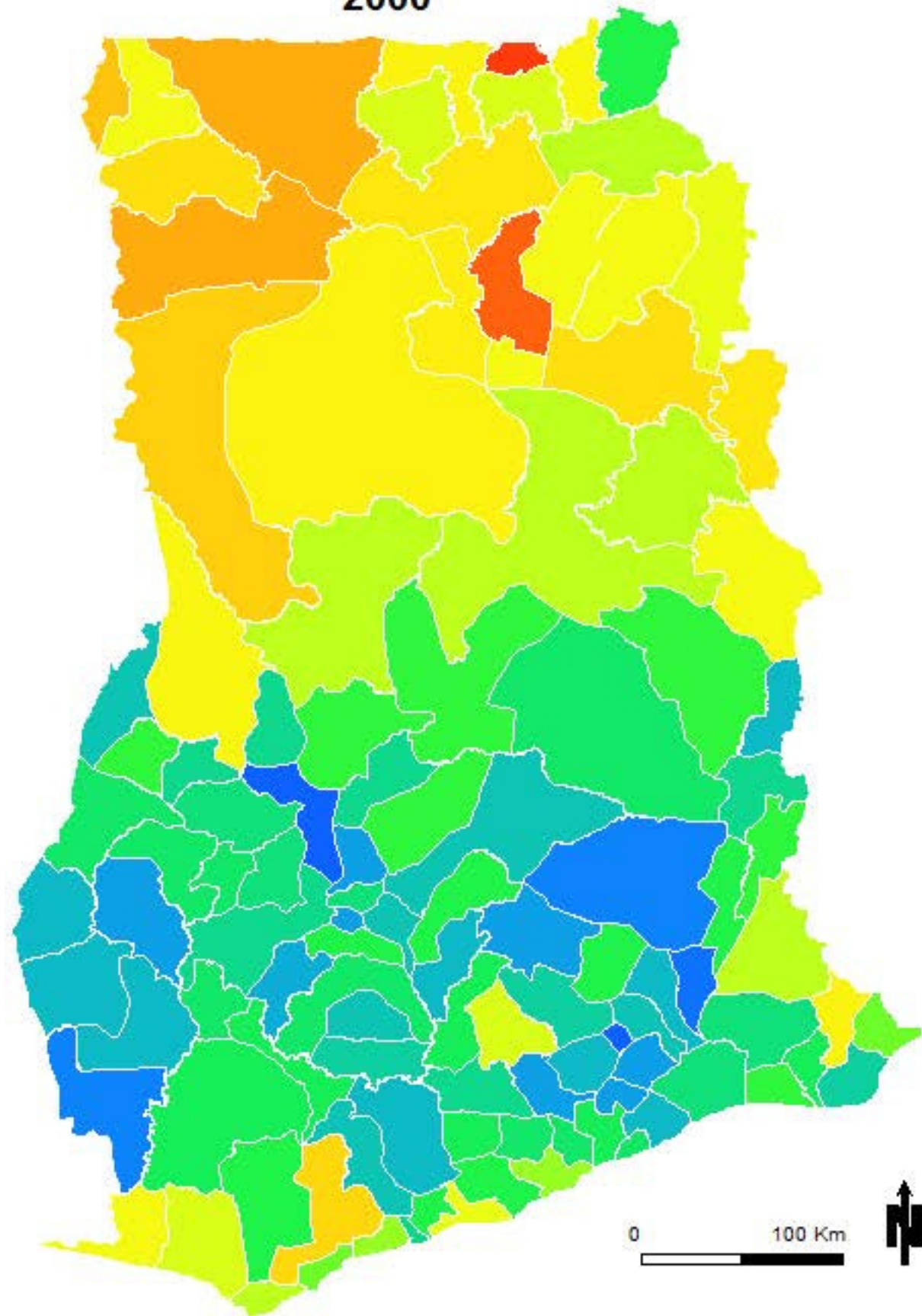
- and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the global burden of disease study 2010. *Lancet* 380:2224-2260.
- Monteiro CA, Benicio MH, Conde WL, Konno S, Lovadino AL, Barros AJ, et al. 2010. Narrowing socioeconomic inequality in child stunting: The Brazilian experience, 1974-2007. *Bulletin of the World Health Organization* 88:305-311.
- Pradhan J, Arokiasamy P. 2010. Socio-economic inequalities in child survival in India: A decomposition analysis. *Health Policy* 98:114-120.
- Ram U, Jha P, Ram F, Kumar K, Awasthi S, Shet A, et al. 2013. Neonatal, 1-59 month, and under-5 mortality in 597 Indian districts, 2001 to 2012: Estimates from national demographic and mortality surveys. *The Lancet Global Health* 1:e219-226.
- Requejo J, Bryce J, Victora C, team Ct. 2014. Fulfilling the health agenda for women and children: The 2014 report. (Countdown to 2015). Washington, DC USA:UNICEF and World Health Organization.
- Sousa A, Hill K, Dal Poz MR. 2010. Sub-national assessment of inequality trends in neonatal and child mortality in Brazil. *International Journal for Equity in Health* 9:21.
- Spiegelhalter D, Thomas A, Best N, Lunn D. 2003. Winbugs user manual v1.4. In: MRC Biostatistics Unit and Imperial College London, Part 1.4. Cambridge and London.
- Stevens GA, Dias RH, Ezzati M. 2008. The effects of 3 environmental risks on mortality disparities across Mexican communities. *Proceedings of the National Academy of Sciences of the United States of America* 105:16860-16865.
- The World Bank. 2013. World development indicators. In Washington, D.C.:The World Bank.
- UN IGME. 2013. United Nations inter-agency group for child mortality estimation. Levels & trends in child mortality (igme): Report 2013. In New York:UNICEF, WHO, The World Bank, United Nations.
- United Nations. 1983. Manual x: Indirect techniques for demographic estimation. New York:United Nations Department of International Economic and Social Affairs.
- Vapattanawong P, Hogan MC, Hanvoravongchai P, Gakidou E, Vos T, Lopez AD, et al. 2007. Reductions in child mortality levels and inequalities in Thailand: Analysis of two censuses. *Lancet* 369:850-855.
- Victora CG, Barros AJ, Axelson H, Bhutta ZA, Chopra M, Franca GV, et al. 2012. How changes in coverage affect equity in maternal and child health interventions in 35 Countdown to 2015 countries: An analysis of national surveys. *Lancet* 380:1149-1156.
- Wang H, Liddell CA, Coates MM, Mooney MD, Levitz CE, Schumacher AE, et al. 2014. Global, regional, and national levels of neonatal, infant, and under-5 mortality during 1990-2013: A systematic analysis for the global burden of disease study 2013. *Lancet* 384:957-979.

Table 1: Summary statistics of under-five mortality and its social and environmental determinants.

Variable	Census 2000	Census 2010	Change
	Median (IQR)	Median (IQR)	Median (IQR)
Under-five mortality (per 1,000 live births)	99.2 (90.6, 111.9)	70.2 (60.8, 84.5)	-26.9 (-34.4, -17.9)
Cooking fuel (percent of households)			
<i>Wood</i>	77.3 (63.3, 88.0)	61.7 (44.8, 73.4)	-13.8 (-18.8, -8.8)
<i>Charcoal</i>	15.6 (7.3, 26.0)	25.4 (15.6, 38.1)	7.6 (4.5, 12.0)
<i>Other biomass</i>	3.3 (1.6, 4.9)	5.2 (3.4, 6.6)	1.7 (1.0, 2.6)
<i>Kerosene</i>	1.4 (1.1, 1.7)	0.3 (0.2, 0.5)	-1.1 (-1.3, -1.0)
<i>LPG</i>	1.2 (0.5, 2.3)	6.7 (3.4, 11.6)	5.5 (2.9, 8.7)
<i>Electricity</i>	0.4 (0.2, 0.6)	0.3 (0.2, 0.3)	-0.2 (-0.4, 0.0)
Sanitation: toilet facility (percent of households)			
<i>Improved</i>	42.2 (23.2, 56.4)	83.0 (52.2, 90.7)	30.4 (17.0, 42.8)
<i>Unimproved</i>	57.8 (43.6, 76.8)	17.0 (9.3, 47.8)	-30.4 (-42.8, -17.0)
Drinking water source (percent of households)			
<i>Improved</i>	53.2 (40.4, 66.3)	76.3 (66.4, 86.8)	22.6 (13.0, 30.5)
<i>Unimproved</i>	46.8 (33.7, 59.7)	23.7 (13.2, 33.6)	-22.6 (-30.5, -13.0)
Maternal education (percent of women of child-bearing age)			
<i>None</i>	51.7 (42.4, 68.9)	31.2 (22.8, 48.6)	-18.6 (-21.7, -15.5)
<i>Primary</i>	37.1 (19.9, 43.4)	54.4 (36.1, 60.6)	16.9 (13.5, 20.1)
<i>Secondary or higher</i>	11.6 (8.4, 14.0)	12.4 (9.6, 16.6)	1.6 (-0.1, 3.2)
Paternal education (percent of men of child-bearing age)			
<i>None</i>	31.9 (25.3, 55.6)	16.6 (10.9, 37.2)	-14.4 (-17.7, -11.8)
<i>Primary</i>	44.6 (27.9, 51.4)	57.1 (42.9, 63.3)	13.0 (9.8, 16.0)
<i>Secondary or higher</i>	20.2 (16.0, 23.8)	21.7 (17.5, 25.8)	1.9 (-0.3, 3.8)
Place of residence (percent of households)			
<i>Rural</i>	74.1 (61.3, 82.6)	66.4 (56.5, 76.8)	-5.2 (-8.9, -0.9)
<i>Urban</i>	25.9 (17.4, 38.7)	33.6 (23.2, 43.5)	5.2 (0.9, 8.9)

Figure 1: Under-five mortality (deaths per 1,000 live births) by district in 2000 and 2010.

2000



18

2010

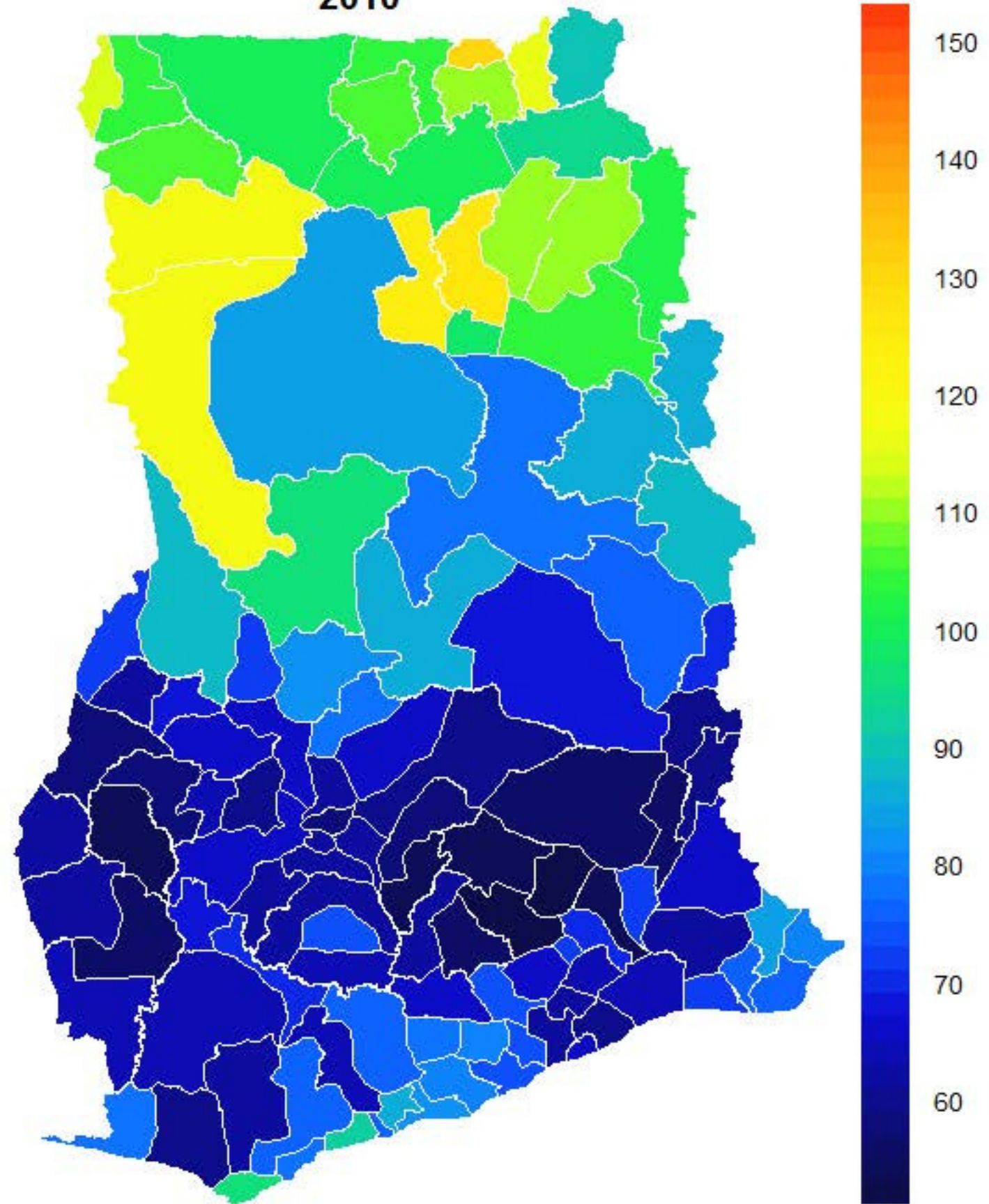
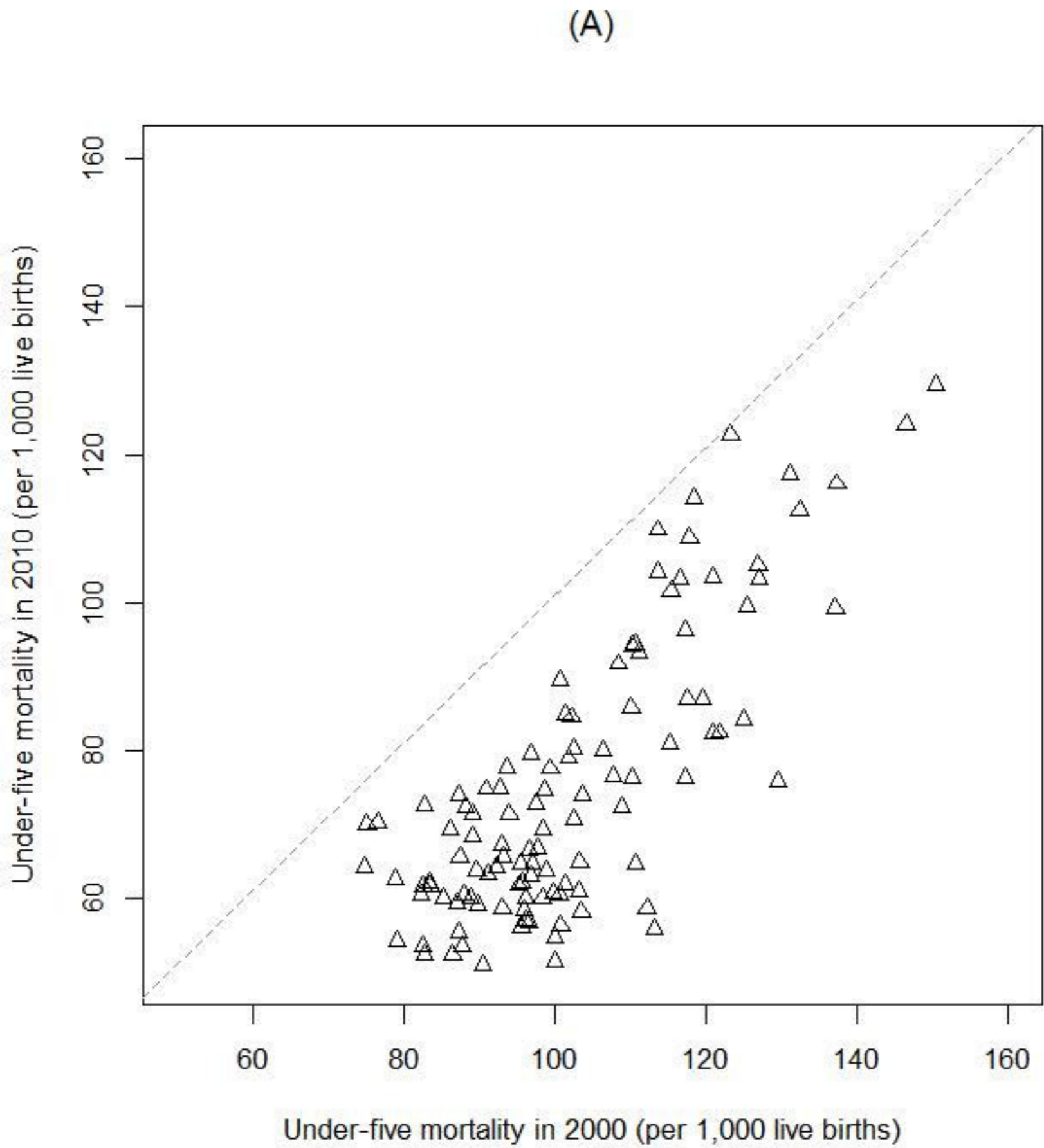


Figure 2: (A) Under-five mortality (deaths per 1,000 live births) in 2000 vs 2010. (B) Percent change from 2000 to 2010.



20

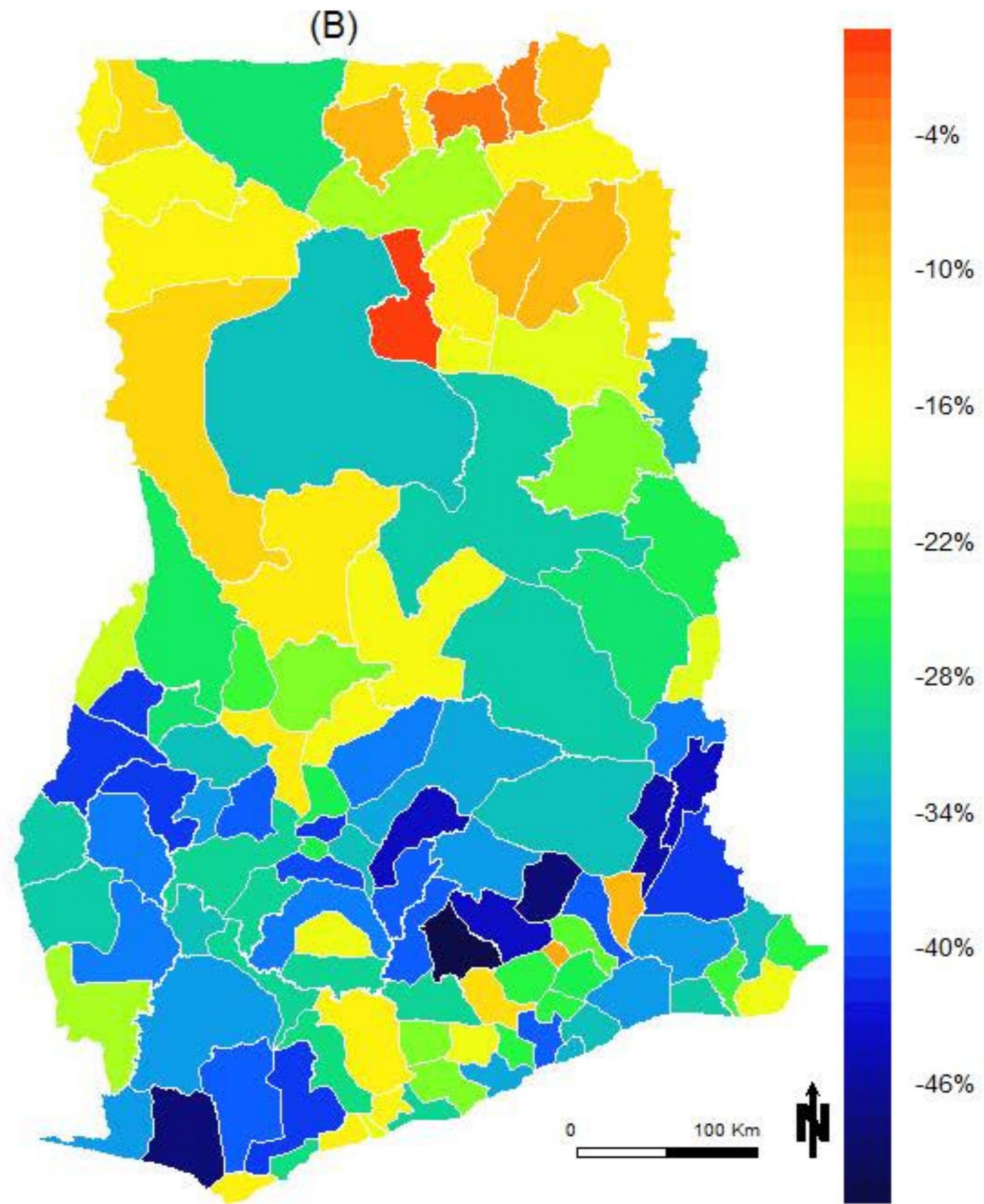
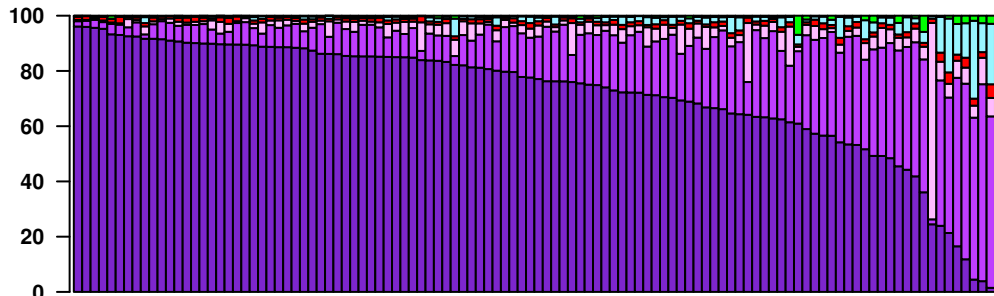


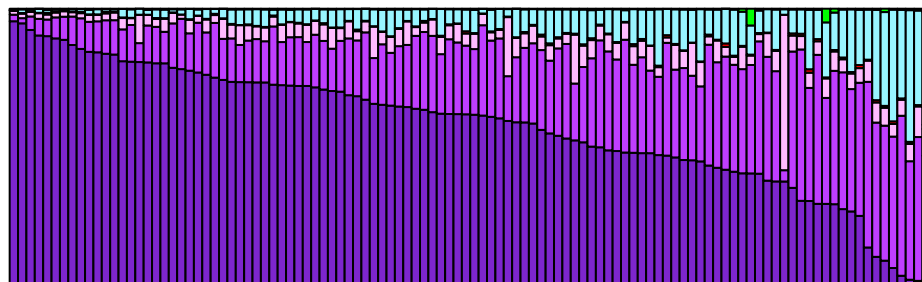
Figure 3: Distributions of household cooking fuel, sanitation facility, drinking water source, and maternal education by district in 2000 and 2010 (percent households/persons). Each bar represents one district with districts ordered by decreasing prevalence of the worst category for each census.

2000



22

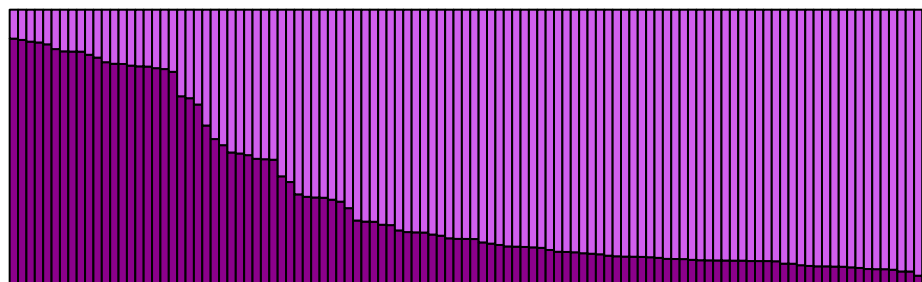
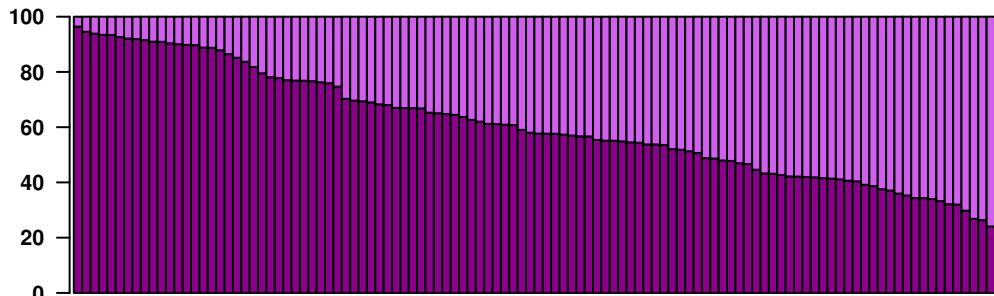
2010



Cooking fuel

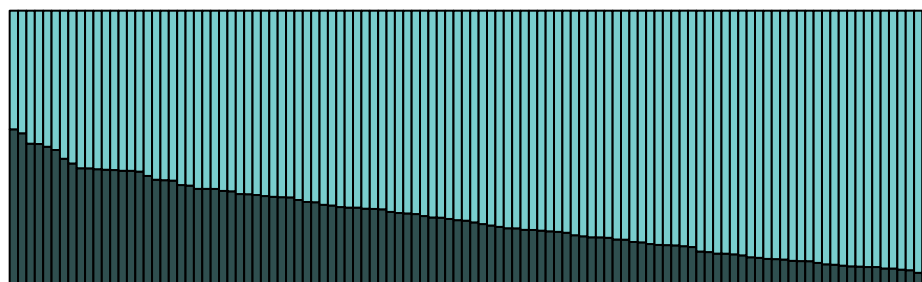
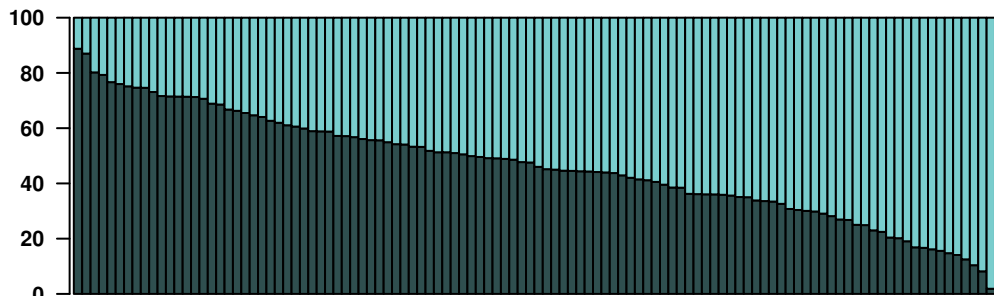
- Electricity
- LPG
- Kerosene
- Other biomass
- Charcoal
- Wood

Percent households



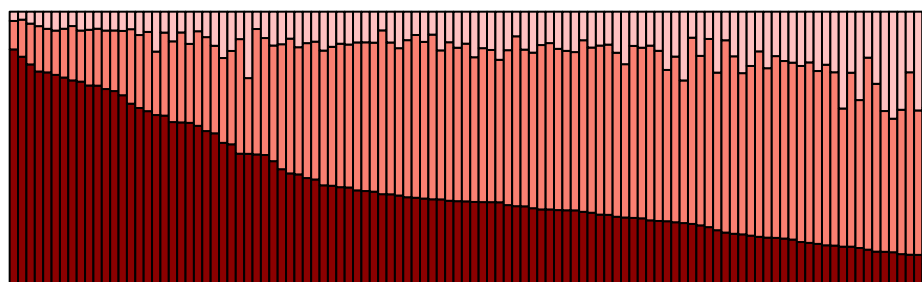
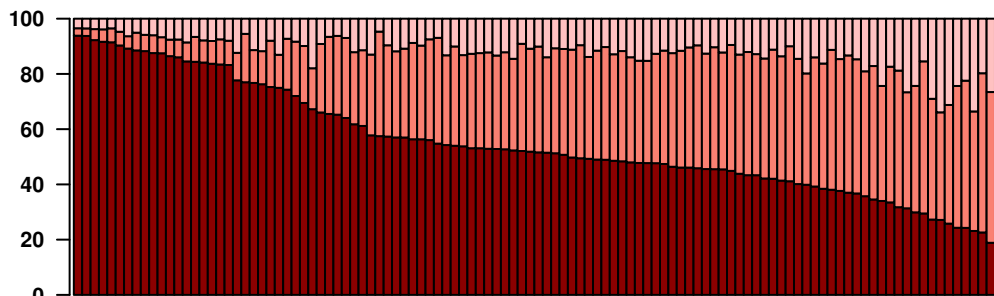
Sanitation

- Improved
- Unimproved



Drinking water

- Improved
- Unimproved

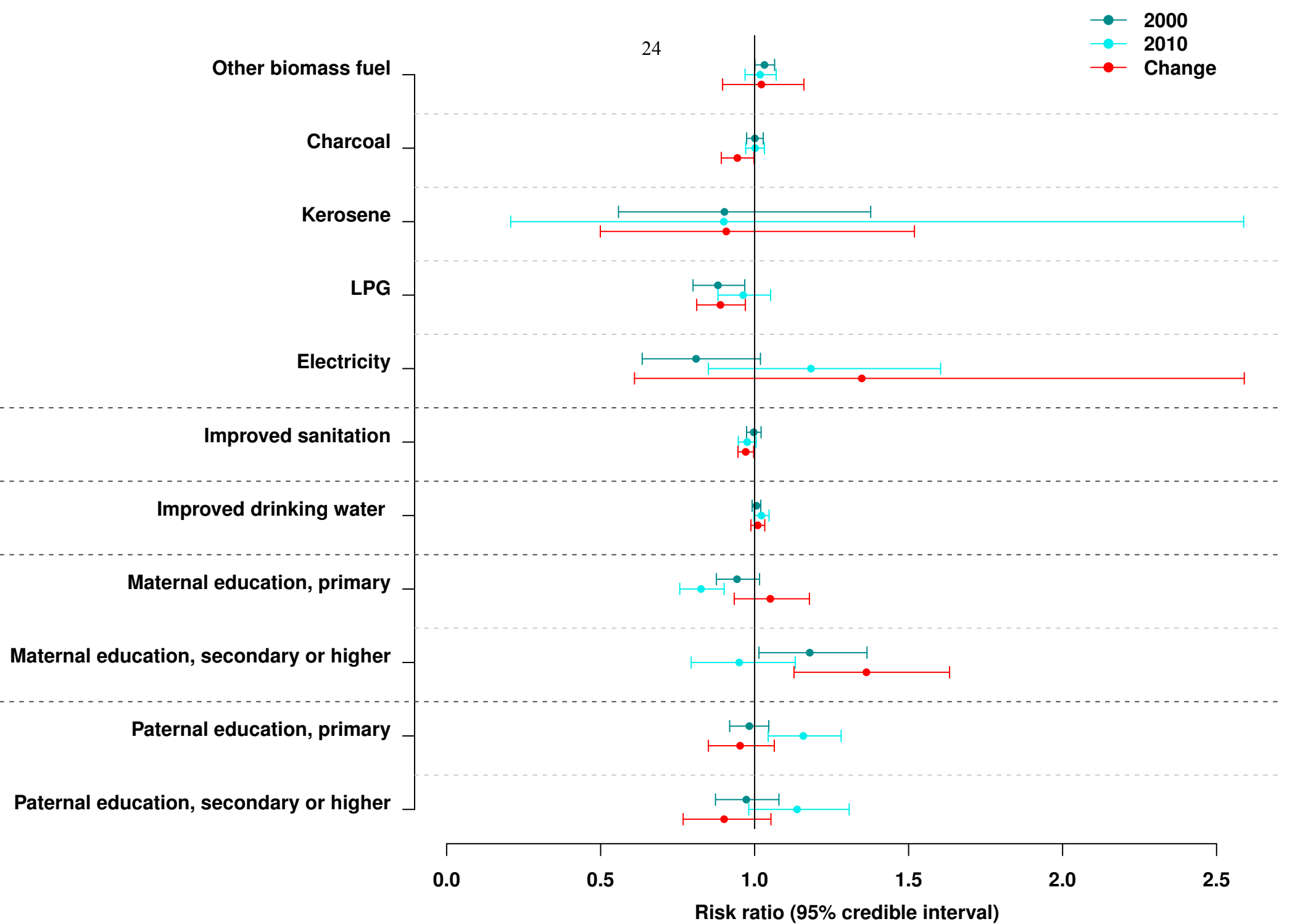


Maternal education

- Higher
- Primary
- None

Figure 4: Risk ratios and 95% credible intervals (2.5th and 97.5th percentiles of the posterior distributions of effect size parameters from the Bayesian model) from multivariate analysis of the association of under-five mortality with its social and environmental determinants in 2000, 2010, and their change.

Effect size for each variable represents the proportional change (decrease or increase) in 5q0 for a 10% higher prevalence of that variable (over space in a single census year or change over time between censuses), with the 10% shift coming from the reference variable. The reference variables were wood (for cooking fuel), unimproved sanitation, unimproved drinking water, no education (for maternal and paternal education).



ORIGINAL ARTICLE

Personal particulate matter exposures and locations of students in four neighborhoods in Accra, Ghana

Raphael E. Arku¹, Kathie L. Dionisio^{1,2}, Allison F. Hughes³, Jose Vallarino¹, John D. Spengler¹, Marcia C. Castro², Samuel Agyei-Mensah⁴ and Majid Ezzati^{5,6}

Air pollution exposure and places where the exposures occur may differ in cities in the developing world compared with high-income countries. Our aim was to measure personal fine particulate matter (PM_{2.5}) exposure of students in neighborhoods of varying socioeconomic status in Accra, Ghana, and to quantify the main predictors of exposure. We measured 24-hour PM_{2.5} exposure of 56 students from eight schools in four neighborhoods. PM_{2.5} was measured both gravimetrically and continuously, with time-matched global positioning system coordinates. We collected data on determinants of exposure, such as distances of homes and schools from main roads and fuel used for cooking at their home or in the area of residence/school. The association of PM_{2.5} exposure with sources was estimated using linear mixed-effects models. Personal PM_{2.5} exposures ranged from less than 10 $\mu\text{g}/\text{m}^3$ to more than 150 $\mu\text{g}/\text{m}^3$ (mean 56 $\mu\text{g}/\text{m}^3$). Girls had higher exposure than boys (67 vs 44 $\mu\text{g}/\text{m}^3$; P -value = 0.001). Exposure was inversely associated with distance of home or school to main roads, but the associations were not statistically significant in the multivariate model. Use of biomass fuels in the area where the school was located was also associated with higher exposure, as was household's own biomass use. Paved schoolyard surface was associated with lower exposure. School locations in relation to major roads, materials of school ground surfaces, and biomass use in the area around schools may be important determinants of air pollution exposure.

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Keywords: Africa; air pollution; adolescent health; exposure; traffic pollution

INTRODUCTION

Ambient air pollution is responsible for an estimated 3.2 million annual deaths worldwide.¹ The highest levels of air pollution in the world now occur in cities in Asia, the Middle East, and Africa.² Although there are some similarities in the sources and spatial patterns of air pollution in cities in developing countries compared with those in high-income countries (e.g., traffic-related pollution), there are also significant differences (e.g., biomass use for cooking).^{3–10} For example, biomass use, which is common in both rural and urban areas,^{11,12} accounts for between one third and one half of fine particulate matter (PM_{2.5}; particles below 2.5 micrometers in aerodynamic diameter) pollution in different neighborhoods of Accra, Ghana, with another 10–30% due to traffic and road dust.¹⁰ These factors are also important determinants of the spatial patterns of air pollution between and within neighborhoods, and of its concentrations in the household environment.^{5,8,13} Time–location–activity patterns in the developing world are also different from high-income countries due to differences in the built environment, transportation, and sociocultural factors. As a result, both the levels of air pollution exposure and places where the highest exposures occur may differ in cities in the developing world compared with high-income countries.

A number of studies have examined personal exposure to air pollutants for school children in high-income countries, with an emphasis on the role of traffic-related pollution.^{14–18} Although a few personal PM exposure studies exist in cities of developing countries,^{19,20} the great majority of exposure studies are from rural areas, and assessed the role of household cooking and heating as a source of exposure. To the best of our knowledge, only rural exposure studies exist in sub-Saharan Africa^{21,22} or studies that have measured school pollution but not personal exposure,^{23,24} despite the fact that the urban population in this region is growing faster than any other in the world.²⁵

In this paper, we report personal PM_{2.5} exposures of students in four neighborhoods in Accra, Ghana. In addition to being among the few studies of personal exposure to air pollution in cities of developing countries, the paper makes a number of contributions. First, by simultaneously collecting time-stamped continuous data on location and exposure, we are able to identify time and places where exposure tends to be high. Second, the study covers poor, middle-income, and wealthy neighborhoods, allowing for an assessment of social inequalities in exposure. Third, we collected data on household and community determinants of exposure and assessed their associations with measured exposures. Fourth, we examined the correlation between personal exposure and neighborhood ambient concentrations, which provides information on the measurement error when ambient

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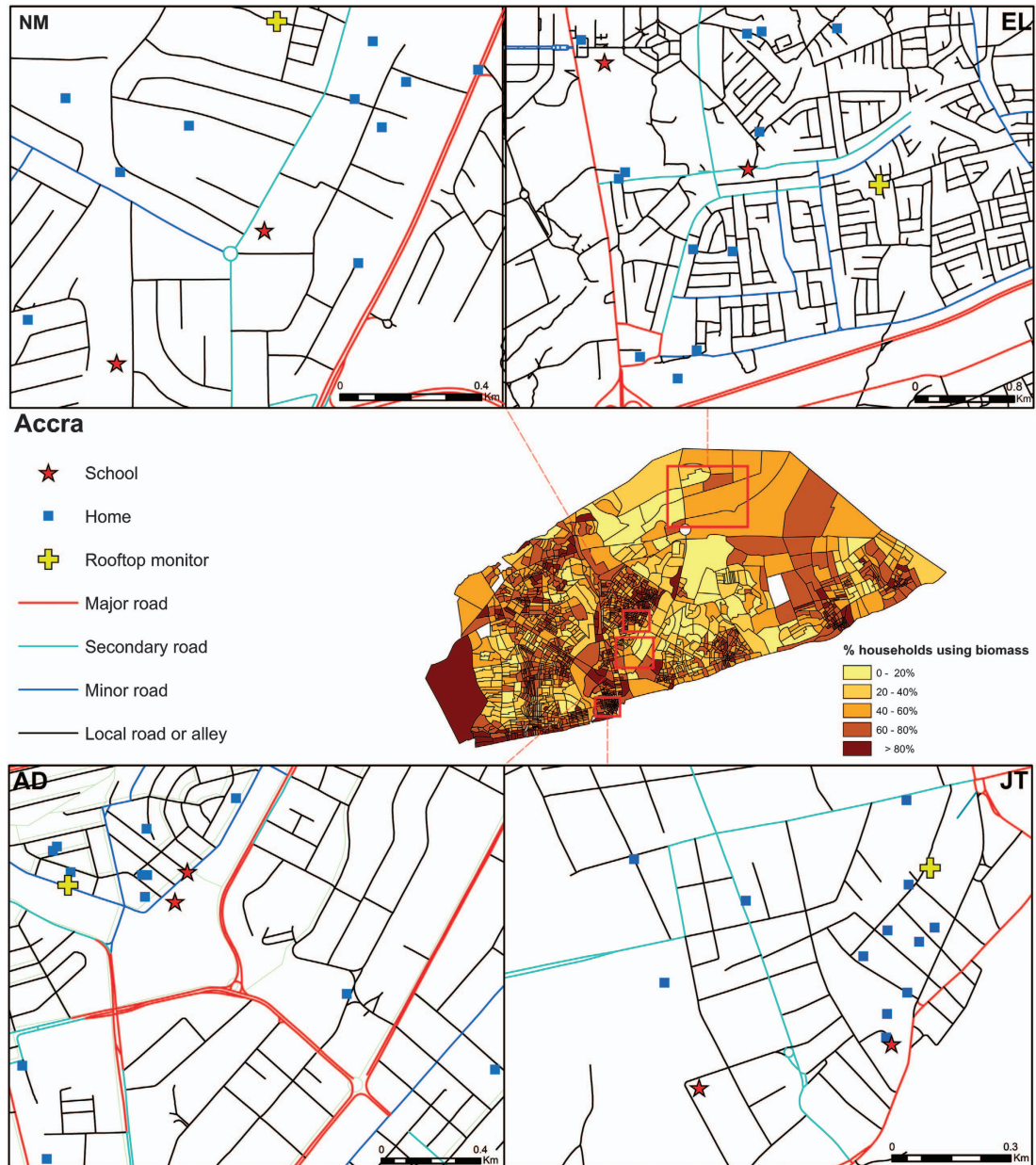


Figure 1. Study neighborhoods, schools, and homes. The colored biomass use map is delimited by enumeration areas (EA); each EA has approximately the same population size; hence, the area of an EA is inversely related to population density.

monitoring data are used instead of personal exposure in epidemiological studies in these settings.

MATERIALS AND METHODS

This study was approved by the Institutional Review Boards of the Harvard School of Public Health and the Noguchi Memorial Institute for Medical Research at the University of Ghana.

Study Location

Our study was conducted in four neighborhoods in Accra, Ghana: James Town/Usher Town (JT), Asylum Down (AD), Nima (NM) and East Legon (EL) (Figure 1). The study neighborhoods were selected such that they lay on a nearly straight line from the coast to the northern boundaries of the Accra Metropolitan Area, and had varying socioeconomic status (SES) based on data from the 2000 Population and Housing Census. JT and NM are densely

populated low-income communities where most residents use biomass for cooking at home and for cooking food to sell on the street.¹³ AD is a middle-class neighborhood, and EL is an upper-class, sparsely populated residential neighborhood where most families live on large plots of land in modern low-rise homes. Fewer people use biomass fuels in AD and EL than in JT and NM. Accra's Central Ring Road borders AD. Smoking is very uncommon in Ghana, with prevalence below 10% nationally and in our sample.^{10,26} Those who smoke commonly smoke outside the house.

Study Design

Between January and August 2008, we measured personal PM_{2.5} exposure and locations of 56 students who were between the ages of 10 and 17 years. The students were from two public junior high schools in each study neighborhood. The schools were visited prior to the start of measurement to explain the aims of the study and request participation; at least 90% of students in all schools agreed to participate. The study subjects were

selected by the school teachers, with approximately the same number of male and female students. Subjects were then enrolled following written consent from their parents. A minimum of six students from each school participated in the study. The locations of the schools and the students' residences are shown in Figure 1. Exposures were measured using portable PM monitors, and locations were recorded using global positioning system (GPS) devices. Both instruments were placed in backpacks worn by the subjects. The subjects were asked to keep the backpack as close to them as possible at all times.

We conducted measurements for each student over a 24-h period. The measurements were performed only on weekdays when the students attended school. A random one third (20 out of 56) of our subjects had repeated measurements, with an average of 2.5 measurements per subject. The repeated samples were collected the day after the first measurement, except when the first measurement was done on a Friday or before a holiday. We used structured questionnaires to collect information about the students' activities throughout the day, time spent near household cooking fire, the fuel used by the family for cooking and kitchen characteristics.

PM Measurement Methods

We used a combination of integrated gravimetric and continuous real-time monitors to measure PM_{2.5} exposure.

Integrated gravimetric PM_{2.5}. We used external elutriators connected to Personal Exposure Monitors (PEMs) (Harvard School of Public Health, HSPH, Boston, MA)²⁷ with a D₅₀ of 2.5 μm (aerodynamic diameter) at 1.8 liters per minute (1 pm) (±10%) and an internal level greased impaction surface. Inside the PEMs, PTFE filters with ring (Pall Life Sciences, Teflo, 0.2 μm pore size, 37 mm diameter) were back-supported by Whatman drain discs. PEMs were connected by Tygon PVC tubing to a Casella Apex Lite personal sampling pump (Casella USA, Amherst, NH) drawing air at 1.8 lpm. To conserve battery life, pumps were programmed to draw air for 1 out of every 6 min for a total of 290 min over the 24-h sampling period. Air flow rates were checked at the beginning and end of each sampling period using a calibrated rotameter. The PEM and pump were placed inside the backpack with the elutriator nozzle protruding through an opening in the backpack.

All filters were weighed pre- and post sampling on a Mettler Toledo MT5 microbalance maintained at HSPH Laboratory, after being conditioned in a temperature- and relative humidity (RH)-controlled environment (20.5 ± 0.2 °C, 39 ± 2% RH) for at least 24-h, and statically discharged via a polonium source. In both pre- and post weighing, samples were weighed twice; if these two masses were more than 5 μg apart, a third weighing was carried out. After the third weighing, the average of the two measured masses within 5 μg of each other was used for calculating concentrations. After every batch of 10 samples, the zero, span, and linearity of the balance were checked via a set of class 'S' weights.

Continuous PM_{2.5}. We used DustTrak (DT) model 8520 monitors (TSI, Shoreview, MN) for continuous measurement of PM_{2.5} exposure. PM_{2.5} exposure was measured every second, averaged, and recorded at 1-min intervals. The DTs were operated at a flow rate of 0.8 lpm, with an upstream external mini-PEM²⁷ used as the size selective inlet for PM_{2.5}. In the mini-PEM, a level greased well served as the impaction surface. The DTs were calibrated to a zero filter prior to each 24-h sampling period to avoid drifts.

Following earlier studies,^{4,5,8,13} we standardized the minute-by-minute PM records for RH using the relationship from a previous study.²⁸ The RH-standardized PM_{2.5} data were then adjusted using a correction factor (CF), calculated as the ratio of the co-located integrated (gravimetric) PM_{2.5} measurement to the average of the minute-by-minute continuous measurements over the same time period.^{4,5,8,13} We calculated the CF separately for each subject, using her/his own gravimetric and continuous measurements. Twenty five percent of the minute-by-minute continuous data were missing because the instrument malfunctioned, for example, due to laser or battery failure; another 1% was excluded due to concerns about data validity, for example, when the connecting tubing was bent in a way that limited airflow.

Ambient PM_{2.5}. We operated four simultaneous rooftop ambient gravimetric and continuous monitors, one in each study neighborhood (Figure 1). Measurements were done for 48 h every 6 days. The fixed sites were located in the residential areas in each neighborhood with relatively modest influence from direct traffic. Details on ambient measurements are

provided elsewhere.⁴ Personal PM_{2.5} exposures were measured on the same days as the ambient 48-h monitoring as much as possible.

Location Data

We used a Garmin eTrex Vista GPS device to record coordinates for each subject's residence and school, which were used to calculate average distances from the nearest main road in Arc-Map 10.1 (ESRI); road classification was based on geo-coded road map of Accra to reflect similar traffic density across our study neighborhoods. We also measured each subject's location at 1-min intervals using a GPS device placed in the outer pocket of the backpack that he/she wore.

Forty five percent of time–location data were missing because satellite signal was weak, most of which occurred indoors; another 1% was outliers due to measurement error. We addressed these issues in two steps. First, we repositioned outlier coordinates on the subject's walking path, using the median location of five ordered coordinates containing the outlier, retaining the temporal ordering of the data. Second, we imputed missing coordinates between 2200 and 0500 hours, when the subjects were likely to be at home based on the information from the time–location–activity questionnaires, using the home location. This reduced the proportion of missing coordinates to 14% of total minute-by-minute data.

Meteorological Variables

Data on meteorological variables (RH, number of hours with rain in each 24-h measurement period, and wind speed) were obtained from measurements at the Kotoka International Airport in Accra, as detailed in previous publications.^{4,5,8,13}

Household Fuel Use and Community Socioeconomic Status

We used a 10% sample of the Ghana 2000 Population and Housing Census to calculate the following variables for census enumeration areas (EA) that contained subjects' residences and schools:

- proportion of households that use charcoal or wood for cooking; and
- average SES, calculated as described previously based on housing characteristics, water and waste systems, and ownership of durable assets.^{8,13}

Data Management and Statistical Analysis

We synchronized date and time on the DT and GPS units. Continuous PM_{2.5} concentrations and location data were compiled into a single data set by matching on date and time, with each record representing a unique date, time, location, and PM concentration. Weather variables were incorporated into the data set using date and time.

We used the location data for all subjects to analyze and visualize where subjects spent the most time in each study neighborhood. Specifically, we calculated the density of time spent at any point in the neighborhood using the number of minutes that was spent at that point by all students, smoothed using a two-dimensional normal density kernel. We also graphically present the students' PM_{2.5} exposures by location. In these graphs, we averaged all continuous PM_{2.5} values within 20 m × 20 m grids to indicate places that on average are associated with higher/lower exposure.

We used regression analysis to examine the association of average daily personal PM_{2.5} exposure with its potential individual, household, and neighborhood determinants. We repeated the regressions both with and without adjustment for the neighborhood 48-h average ambient PM_{2.5} concentration. The former implies that neighborhood ambient PM_{2.5} may be (partially) independent of the local sources included in the model, for example, due to regional influence; the latter implies that neighborhood ambient PM_{2.5} itself is due to the local sources. To accommodate repeated measurements from subjects in the same school, we estimated the following linear mixed-effects model.

$$\ln(\text{PM}_{\text{personal exposure}}) = \beta_0 + \beta X + \gamma \text{Weather} [+ \delta \ln(\text{PM}_{\text{ambient}})] + b + \lambda + \epsilon$$

- PM_{personal exposure} = 24-h integrated personal PM_{2.5} exposure (μg/m³)
- X = a vector of covariates, including:
 - gender (male; female)
 - subject's household fuel (biomass; non-biomass)

Table 1. Demographic and exposure characteristics of the study subjects and school locations

	Neighborhood			
	JT	NM	AD	EL
No. of subjects	15	14	14	13
No. of subjects with distance from residence to the closest main road < 100 m	6	5	3	6
<i>Distance from closest main road (m)</i>				
School 1	< 50	< 50	170	< 10
School 2	230	280	185	230
<i>Schoolyard surface</i>				
School 1	Loose dirt	Paved broken	Paved	Loose dirt
School 2	Packed dirt	Paved	Packed dirt	Loose dirt
Sex (male/female)	7/8	7/7	6/8	7/6
Mean age (male/female)	14/13	13/13	13/13	14/14
<i>Kitchen type (no. of subjects)</i>				
Indoor kitchen	1	3	7	6
Open air kitchen	14	10	5	6
Separate cooking structure outside	0	1	2	1
<i>Cooking fuel used by subject's household during the 24-h personal measurement period (no. of subjects)</i>				
Wood	0	0	0	3
Charcoal	9	11	5	7
LPG	0	3	9	3
None	6	0	0	0
<i>Time spent near household cooking fire during the 24-h personal measurement period (no. of subjects)</i>				
Usually	9	6	8	4
Sometimes	6	5	5	8
None	0	3	1	1

- percent of households using biomass in the EA corresponding to the residence and school of the subject
- day of the week on which measurement was conducted
- weighted average of distances from the residence or school to main roads
- average household SES in the EA corresponding to the subjects' residence or school
- schoolyard surface (paved and paved broken; packed and loose dirt)
- time spent by subjects near household cooking fire during the 24-h personal measurement period (always or sometimes; none)
- Weather = a vector of the following weather variables:
 - number of hours since last precipitation before the start of the 24-h personal exposure measurement period
 - average wind speed (m/s) during the 24-h exposure measurement period
- PM_{ambient} = integrated ambient $PM_{2.5}$ concentration ($\mu\text{g}/\text{m}^3$) at a non-traffic rooftop site in the subject's neighborhood. We used linear interpolation to estimate ambient $PM_{2.5}$ on exposure measurement days when we had no ambient data.
- b = school-level random intercept²⁹
- λ = subject-level random intercept²⁹
- ε = vector of within-school and within-subject errors
- β , γ , and δ = regression coefficients

Table 2. Geometric mean personal $PM_{2.5}$ exposure and ambient $PM_{2.5}$ levels, by neighborhood and other characteristics

	Personal $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$)	No. of samples	Geometric mean
<i>Neighborhood</i>			
JT		26	50.6
NM		20	57.5
AD		21	36.9
EL		18	47.1
<i>Distance of subjects' residence from closest main road</i>			
Less than 100 m		34	51.4
Greater than 100 m		51	45.1
<i>Distance of schools from closest main road</i>			
Less than 100 m		37	61.9
Greater than 100 m		48	38.8
<i>Schoolyard surface</i>			
Paved and paved broken		32	47.9
Packed and loose dirt		53	47.3
<i>Gender</i>			
Male		40	37.5
Female		45	58.6
<i>SES of the EA of residence</i>			
Below median SES		42	55.3
Above median SES		43	41.5
<i>SES of the EA of school</i>			
Below median SES		48	58.4
Above median SES		37	36.3
<i>Ambient $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$)</i>			
<i>Neighborhood</i>			
JT		26	36.6
NM		20	79.9
AD		21	29.9
EL		18	24.9

The school-level random intercept helps remove the influence of unobserved factors that affect all measurements in each school. Both ambient and personal $PM_{2.5}$ concentrations were log-transformed to ensure that model residuals were normally distributed. Residual diagnostics suggested a better model fit when distance to main roads and weather variables were also log-transformed (as done in a previous study⁸).

All analyses were done using the open-source statistical package R version 3.0.0 (R Project for Statistical Computing, Vienna, Austria).

RESULTS

We collected 85 24-h integrated and 82 continuous personal $PM_{2.5}$ samples from 56 students in eight schools in the four study neighborhoods. Demographic characteristics of the students and the factors that may affect their air pollution exposure are summarized in Table 1. There were 38 male and 18 female students in our study, with a mean age of 13.5 years. Sixty-two percent of subjects resided in households that cooked with biomass fuel outdoors in an open-air shared courtyard; the majority of these used charcoal with only 7% cooking with firewood. Six students lived in households that purchased their food and did not cook on the measurement day. All subjects were from households in which no one smoked.

Average personal $PM_{2.5}$ exposure across all four neighborhoods was $56.0 \pm 33.5 \mu\text{g}/\text{m}^3$, with individual exposures ranging from less than $10 \mu\text{g}/\text{m}^3$ (during the rainy season) to more than $150 \mu\text{g}/\text{m}^3$ (just after dry and dusty season). Exposure was above $25 \mu\text{g}/\text{m}^3$,

Table 3. Coefficients for multivariate analysis of the association of personal PM_{2.5} with individual, household, neighborhood, and meteorological variables

Variable	Model 1		Model 2	
	Coefficient (95% CI)	P-value	Coefficient (95% CI)	P-value
<i>Dependent variable: ln(PM_{2.5})</i>				
	n = 82; R ² = 0.55 ^a		n = 82; R ² = 0.62 ^a	
Constant	1.000 (-1.058, 3.058)	0.34	0.508 (-1.548, 2.564)	0.63
Ln (neighborhood average ambient PM _{2.5})			0.294 (0.030, 0.557)	0.029
Households using biomass in the EA containing residence (%)	0.407 (-0.381, 1.195)	0.31	0.370 (-0.416, 1.156)	0.36
Households using biomass in the EA containing school (%)	1.227 (0.341, 2.114)	0.007	0.928 (0.013, 1.842)	0.047
Average distance from residence to main roads (m)	-0.044 (-0.329, 0.241)	0.76	-0.055 (-0.336, 0.226)	0.70
Average distance from school to main roads (m)	-0.059 (-0.194, 0.076)	0.39	-0.032 (-0.167, 0.104)	0.65
SES of the EA of residence	-0.043 (-0.146, 0.059)	0.41	-0.037 (-0.138, 0.064)	0.47
SES of the EA of school	0.094 (-0.066, 0.255)	0.25	0.094 (-0.063, 0.251)	0.24
<i>Household cooking fuel used during the 24-h personal measurement period</i>				
Non-biomass	0.0	NA	0.0	NA
Biomass	0.323 (0.065, 0.582)	0.014	0.267 (0.006, 0.527)	0.045
<i>Gender</i>				
Boys	0.0	NA	0.0	NA
Girls	0.484 (0.225, 0.742)	< 0.001	0.450 (0.192, 0.708)	0.001
<i>Time spent by subject near household cooking fire during the 24-h personal measurement period</i>				
None	0.0	NA	0.0	NA
Usually and sometimes	-0.298 (-0.777, 0.182)	0.22	-0.314 (-0.784, 0.156)	0.19
<i>Schoolyard surface</i>				
Paved and paved broken	0.0	NA	0.0	NA
Packed and loose dirt	0.278 (-0.105, 0.661)	0.15	0.474 (0.058, 0.889)	0.025
<i>Day of the week measurement was conducted^b</i>				
Monday	0.0	0.33	0.0	0.69
Tuesday	0.168 (-0.166, 0.501)		0.151 (-0.170, 0.473)	
Wednesday	0.061 (-0.348, 0.470)		0.045 (-0.352, 0.442)	
Thursday	-0.059 (-0.445, 0.327)		0.025 (-0.357, 0.407)	
Friday	0.348 (-0.180, 0.875)		0.257 (-0.259, 0.773)	
<i>Meteorological factor</i>				
Ln (hours since last rain)	0.141 (0.015, 0.267)	0.028	0.086 (-0.047, 0.219)	0.20
Ln (wind speed (m/s))	0.150 (0.062, 0.237)	0.001	0.134 (0.048, 0.221)	0.002

Model 2 is adjusted for neighborhood average PM concentrations at non-traffic rooftop sites and Model 1 is not. ^aTraditional R² is not clearly defined for mixed-effect models. We have reported the conditional R² that describes the proportion of variance explained by both fixed and random factors.³⁴ ^bP-values are given for the complete categorical variable using an F-test. The P-value for the categorical variable tests whether the inclusion of the variable in the model is significant.

the WHO guideline for 24-h ambient PM_{2.5}, for nearly 90% of the students.³⁰ Students in AD had the lowest exposure (geometric mean 36.9 μg/m³) and those in NM the highest (57.5 μg/m³) (Table 2). Exposure was significantly higher among girls than boys (67 vs 44 μg/m³; P-value = 0.001); higher exposure among girls persisted in the multivariate model even after adjusting for time spent near the cooking fire (Table 3). For those students with repeated measurement, mean difference between the first measurement and subsequent measurements was 9.2 μg/m³; the mean absolute difference was 32.2 μg/m³.

Over one third of the students lived within 100 m of busy roads (Figure 1 and Table 1). These subjects had higher PM_{2.5} exposure (geometric mean 51.4 μg/m³) than those who lived farther away from busy roads (45.1 μg/m³). Similarly, personal exposures at three schools that were < 50 m from busy roads were significantly higher than at the five schools located farther away from busy roads (72 vs 44 μg/m³; P-value < 0.001). Association of exposure with distances of schools and home from main roads was not significant in multivariate analysis (Table 3).

On weekdays, the students typically only traveled between their home and school, with few detours. The majority (~90%) commuted to school on foot, with distances ranging from a few meters to > 3 km. During their commute, the students' walking

paths traversed different areas and road types, including busy highways/roads, local roads, residential alleys and foot paths, and markets. Across all four neighborhoods, students were most likely to be in motion (defined as change in position > 5 m, which was the average movement of GPS data during night hours) at about 0800 hours (i.e., immediately before school) and around 1600 hours (immediately after school).

Figure 2 shows that students primarily spent their weekdays at home, at school, or walking between the two, with schools having the highest density of student time. We observed differences in movement patterns between the low- and high-SES neighborhoods. In the high SES, sparsely populated, residential neighborhood of EL, children spent almost all of their out-of-school time at their home. In JT, a low-income and densely populated neighborhood, the children spent time in locations other than their home, but within their own neighborhood. When divided by the time of the day, 73% of the time spent at home by these students was between 2200 and 0600 hours; 1% between 0800 and 1500 hours, and the remaining 26% at other times of the day. In contrast, 85% of all the time spent at school was between 0800 and 1500 hours. Only about a third of total measurement minutes were spent at locations other than home and school.

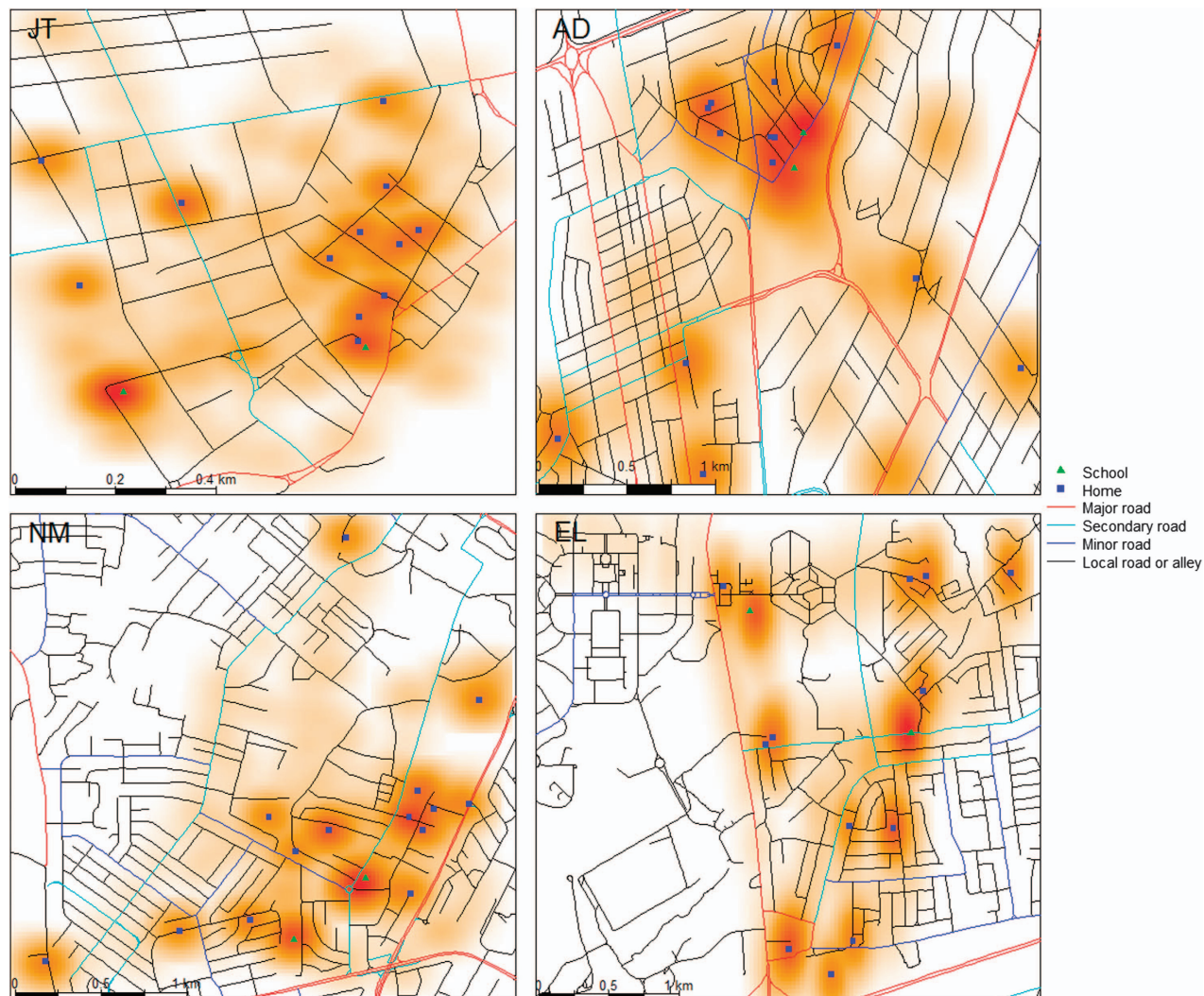


Figure 2. Density of time spent by the students at different locations. The graph shows the extent of time spent by all students, with the darker density demonstrating more time spent or a larger number of students spending time at a point.

The average of minute-to-minute $PM_{2.5}$ concentrations along the children's walking paths are shown in Figure 3. When taken over the course of the day, exposures were highest between around 0800 and 1200 hours, declining slowly to their lowest levels between 2000 hours and around midnight, when they rose again. This pattern is consistent with the temporal pattern of ambient pollution, reported elsewhere.⁴ Geometric mean of continuous exposure data decreased with increasing distance from main roads: $51.3 \mu\text{g}/\text{m}^3$ for distances < 50 m, $47.7 \mu\text{g}/\text{m}^3$ for distances between 50 m and 100 m, $37.7 \mu\text{g}/\text{m}^3$ for distances between 100 m and 200 m, and $32.7 \mu\text{g}/\text{m}^3$ for distances > 200 m. By location, average exposures were about the same at home (geometric mean $36.5 \mu\text{g}/\text{m}^3$) and school ($39.1 \mu\text{g}/\text{m}^3$), but were higher at other locations ($43.2 \mu\text{g}/\text{m}^3$), which mostly included walking to and from school. Taking into account the average levels of exposure and the time spent in each location, 41% of the total exposure occurred at home, 25% at school, and the remaining 34% at other locations. We tested the relative contributions of time and space to total exposure; neighborhood of residence and distance from closest main road together explained 10.4% of the variance of the continuous exposure data; only $\sim 3\%$ was explained by time.

When considered by neighborhood, the students' exposures at their schools were lowest in AD, but walking along major roads in this neighborhood was associated with high exposure levels. In JT, exposure was $> 100 \mu\text{g}/\text{m}^3$ at homes and along alleys, where a large number of biomass stoves are used for cooking street food.^{5,8} The places with highest exposures in NM were around the local market and central bus station, both located on a busy road (Figure 3).

To provide more detail on movement and exposure patterns, Figure 4 shows location by time and exposure for three example students. The 99th percentile of $PM_{2.5}$ exposure for these students was $> 350 \mu\text{g}/\text{m}^3$. A student in NM walking along a secondary road was exposed to slightly higher $PM_{2.5}$ during his morning commute to school than during his return commute through residential alleys (Figure 4a). A student in AD experienced higher exposure at or near school than at home or while commuting (Figure 4b). A third student from JT had high $PM_{2.5}$ exposure throughout the day irrespective of her location (Figure 4c).

Personal exposure to fine particles was on average 23% higher than ambient concentrations with geometric means of $47.5 \mu\text{g}/\text{m}^3$ and $38.5 \mu\text{g}/\text{m}^3$, respectively (Figure 5). We found moderate correlation between personal exposure and neighborhood



Figure 3. Spatial pattern of $PM_{2.5}$ exposures of the study subjects, by neighborhood. The graph shows average of all minute-by-minute exposures, with averaging done in $20\text{ m} \times 20\text{ m}$ grids. Annual geometric mean $PM_{2.5}$ concentrations at residential monitoring sites were $50.5\ \mu\text{g}/\text{m}^3$ in JT, $31.1\ \mu\text{g}/\text{m}^3$ in AD, $28.4\ \mu\text{g}/\text{m}^3$ in NM, and $23.2\ \mu\text{g}/\text{m}^3$ in EL. Annual geometric mean $PM_{2.5}$ concentration at a roadside monitoring site was $35.2\ \mu\text{g}/\text{m}^3$ in NM.⁴

ambient concentrations ($r=0.42$; 95% CI 0.23–0.58). In NM, personal exposures were lower than ambient levels, with a geometric mean personal-to-ambient ratio of 0.60. Most personal $PM_{2.5}$ exposures in JT and EL were higher than the ambient levels, resulting in geometric mean personal-to-ambient ratios of 1.24 and 1.55, respectively. Personal exposures were similar to ambient $PM_{2.5}$ levels in AD.

In unadjusted analysis, personal $PM_{2.5}$ exposure was inversely related to the SES of the EA of residence and school, with geometric mean of exposure being $58.4\ \mu\text{g}/\text{m}^3$ for students from schools in below-median-SES EAs and $36.3\ \mu\text{g}/\text{m}^3$ for those in above-median-SES EAs (Table 2). Similarly, students living in low-SES EAs had geometric mean exposure of $55.3\ \mu\text{g}/\text{m}^3$ vs $41.5\ \mu\text{g}/\text{m}^3$ for those living in high-SES EAs (Table 2). There was no consistent or significant association with SES in the multivariate model (Table 3).

In multivariate analysis, personal $PM_{2.5}$ exposure was higher in schools with dirt schoolyard surface than those which were paved, but the finding was only significant in the model that adjusted for ambient $PM_{2.5}$ (Table 3). Household biomass use in the EA where the school is located was significantly associated with higher personal $PM_{2.5}$ exposure. A student attending a school located in an EA where all households use biomass fuel would have 241%

(95% CI 41–728%) and 153% (95% CI 1–531%) higher personal $PM_{2.5}$ exposure than his/her counterpart attending school in an EA where biomass was not used, respectively, in the model with and without adjustment for neighborhood ambient $PM_{2.5}$. There was no statistically significant association between personal $PM_{2.5}$ exposure and biomass fuel use in the EA of residence. Using biomass at home was associated with higher $PM_{2.5}$ exposure, by 31–38% in the different models. There was also little association between $PM_{2.5}$ exposure and day of week.

DISCUSSION

While cities in the developing world have the highest PM concentrations, there has been limited data on human exposure, especially for children and adolescents. Our study provides a detailed analysis of the movements and exposures of school children in a growing metropolitan area. We found higher exposure in lower-SES neighborhoods, an influence from biomass use at home and around the school, and from the construction of the schoolyard surface. We also found that boys had lower exposure than girls, even after adjustment for time spent near the cooking fire.

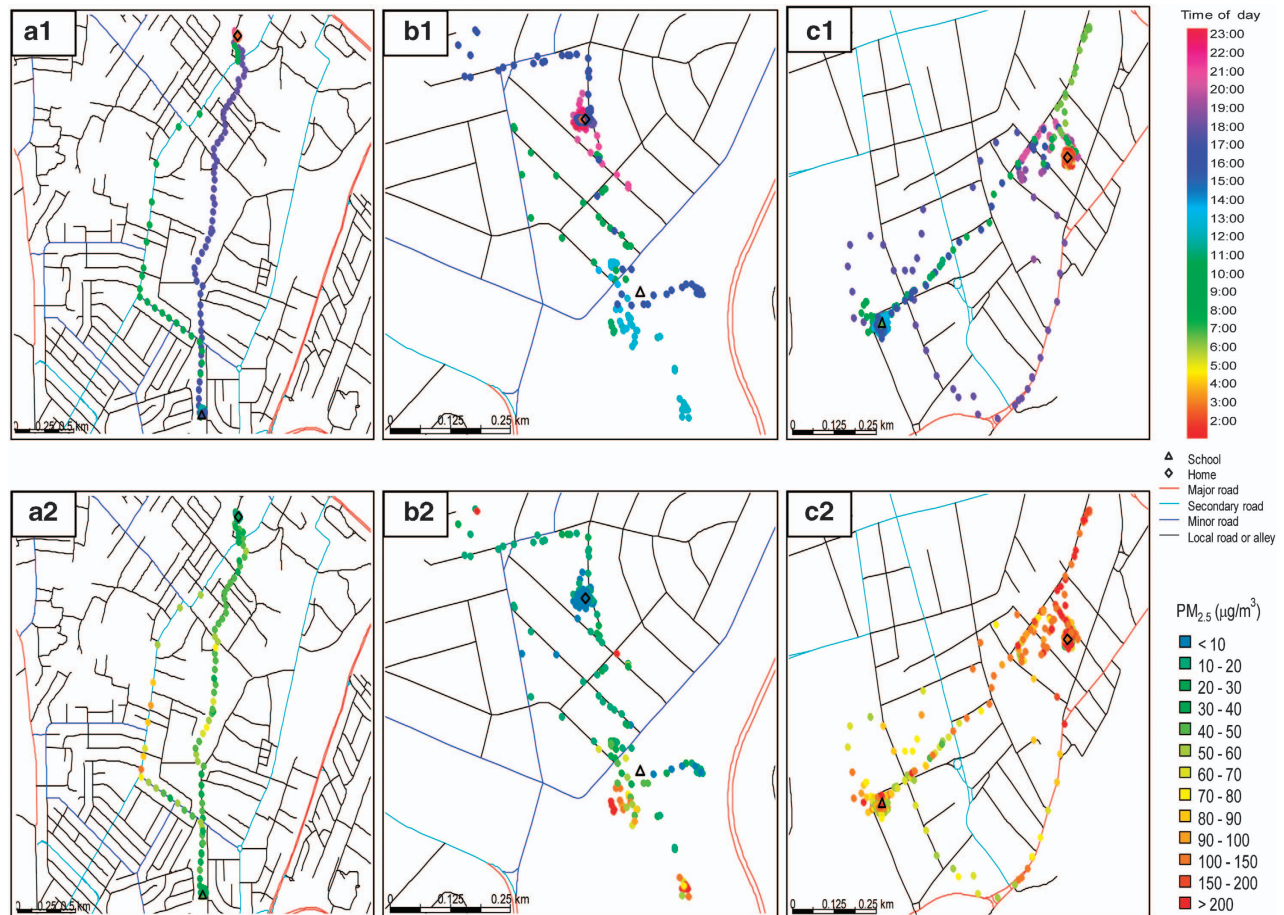


Figure 4. Minute-by-minute location and $\text{PM}_{2.5}$ exposure for three example subjects in (a1, a2) NM, (b1, b2) AD, and (c1, c2) JT.

Due to the absence of similar data, especially from the developing world, our results could only be broadly compared with other exposure studies. Personal $\text{PM}_{2.5}$ exposure for school children in Accra neighborhoods were more than double those in USA^{17,18,31} and in Europe.^{14,32} In USA and the Netherlands, higher personal $\text{PM}_{2.5}$ exposure was associated with proximity of homes and schools to major roads.^{14,17,32}

There are a number of innovations and strengths to our study. We combined geo-referenced data about the neighborhood (from the census and road map), the students' homes and schools, and their movements and exposures to have rich data on exposure to air pollution and its individual, household, and community determinants in a city of a developing country. This in turn permitted mapping locations throughout the day, and identifying times and places where high exposures occurred. The data were from students in eight schools across four neighborhoods with varying SES (Figure 1), allowing for analysis in relation to community SES. Simultaneous ambient and personal exposure enabled us to examine the relationship between the two.

The data used in this study also have a number of limitations that are common to many field research studies. Equipment malfunction led to the loss of some of the continuous location and exposure data. We could impute missing GPS data for the night period using the subject's home location, to reduce the missing data to only 14%. DT monitors use light scattering technique, which is subject to error. Although we systematically corrected the continuous PM data, the steps involved introduced additional uncertainty. Further, it would have been ideal to have data on time spent near specific pollution sources, which may have been

additional predictors of personal exposure. Logistical difficulties, including distance between study neighborhoods, restricted our ability to conduct personal measurements simultaneously in all four study neighborhoods. Further, our data covered only 8 months of the year and therefore, could not be used to assess seasonality of exposure. For the same reason, we did not have 24-h PM data from the students' homes and schools, as we did for neighborhood ambient pollution. Finally, carrying the backpacks fitted with the monitors may have modified the students' behavior despite their statements that this was not the case. GPS data confirm self-reported activities that school attendance occurred as usual.

Our findings indicate that household fuel use and school location may be determinants of children's air pollution exposure in Accra. The role of biomass fuel is further supported by findings that it may contribute between 38% and 48% of total PM mass in Accra¹⁰ and be a determinant of the spatial pattern of air pollution within neighborhoods.^{5,8} If the role of biomass burning as an important determinant of school children's exposure is established in further studies, it should motivate focus on policies that specifically address urban biomass use and create incentives and conditions for transition to cleaner fuels such as LPG.¹³ Similarly, the role of schoolyard surface can be further investigated through intervention studies that involve exposure measurement before and after paving schoolyards. If these studies show a significant reduction in students' exposure, existing schools can be modified to reduce exposure by paving and regular cleaning of schoolyards and roads around them. More broadly, as Ghana makes strides toward universal primary education (Millennium Development

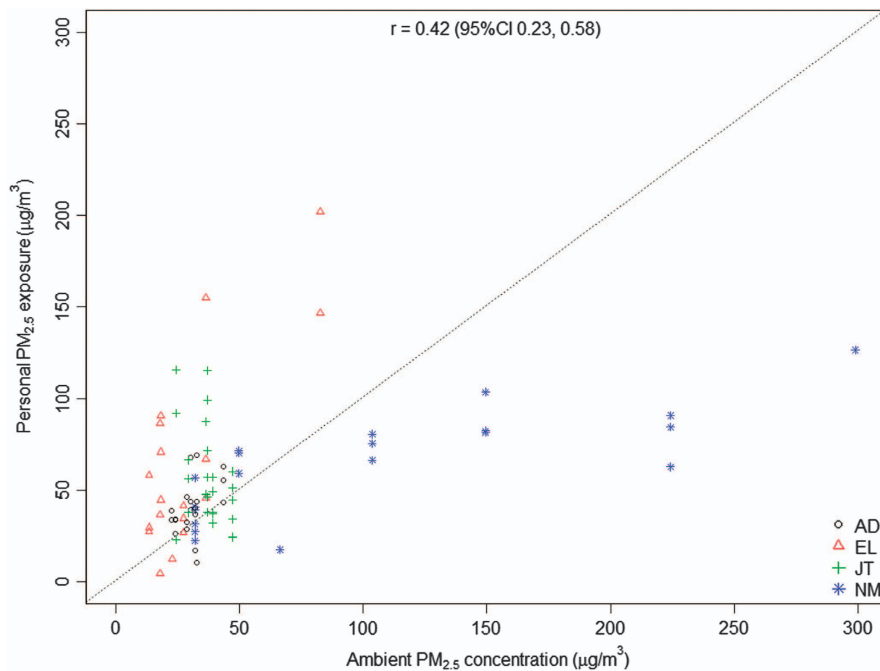


Figure 5. The relationship between personal $PM_{2.5}$ exposure and ambient $PM_{2.5}$.

Goal 2), new schools will also inevitably be built. There is a need for evidence base that inform locations of new schools and for their structure and materials, that for example, ensure sufficient distance between main roads and schools³³ to curb students' air pollution exposure.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

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REFERENCES

- Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H *et al*. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 2012; **380**: 2224–2260.
- Brauer M, Amann M, Burnett RT, Cohen A, Dentener F, Ezzati M *et al*. Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. *Environ Sci Technol* 2012; **46**: 652–660.
- Arku RE, Vallarino J, Dionisio KL, Willis R, Choi H, Wilson JG *et al*. Characterizing air pollution in two low-income neighborhoods in Accra, Ghana. *Sci Total Environ* 2008; **402**: 217–231.
- Dionisio KL, Arku RE, Hughes AF, Vallarino J, Carmichael H, Spengler JD *et al*. Air pollution in Accra neighborhoods: spatial, socioeconomic, and temporal patterns. *Environ Sci Technol* 2010; **44**: 2270–2276.
- Dionisio KL, Rooney MS, Arku RE, Friedman AB, Hughes AF, Vallarino J *et al*. Within-neighborhood patterns and sources of particle pollution: mobile monitoring and geographic information system analysis in four communities in Accra, Ghana. *Environ Health Perspect* 2010; **118**: 607–613.
- Padhi BK, Padhy PK Assessment of intra-urban variability in outdoor air quality and its health risks. *Inhal Toxicol*. 2008; **20**: 973–979.
- van Vliet E, Kinney P Impacts of roadway emissions on urban particulate matter concentrations in sub-Saharan Africa: new evidence from Nairobi, Kenya. *Environ Res Lett* 2007; **2**: 045028.
- Rooney MS, Arku RE, Dionisio KL, Paciorek C, Friedman AB, Carmichael H *et al*. Spatial and temporal patterns of particulate matter sources and pollution in four communities in Accra, Ghana. *Sci Total Environ* 2012; **435-436**: 107–114.
- Etyemezian V, Tesfaye M, Yimer A, Chow JC, Mesfin D, Nega T *et al*. Results from a pilot-scale air quality study in Addis Ababa, Ethiopia. *Atmos Environ* 2005; **39**: 7849–7860.
- Zhou Z, Dionisio KL, Verissimo TG, Kerr AS, Coull B, Arku RE *et al*. Chemical composition and sources of particle pollution in affluent and poor neighborhoods of Accra, Ghana. *Environ Res Lett* 2013; **8**: 044025.
- Bailis R, Ezzati M, Kammen DM Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa. *Science* 2005; **308**: 98–103.
- Bonjour S, Adair-Rohani H, Wolf J, Bruce NG, Mehta S, Pruss-Ustun A *et al*. Solid fuel use for household cooking: country and regional estimates for 1980–2010. *Environ Health Perspect* 2013; **121**: 784–790.
- Zhou Z, Dionisio KL, Arku RE, Quaye A, Hughes AF, Vallarino J *et al*. Household and community poverty, biomass use, and air pollution in Accra, Ghana. *Proc Natl Acad Sci USA* 2011; **108**: 11028–11033.
- van Roosbroeck S, Wichmann J, Janssen NA, Hoek G, van Wijnen JH, Lebrecht E *et al*. Long-term personal exposure to traffic-related air pollution among school children, a validation study. *Sci Total Environ* 2006; **368**: 565–573.
- Borgini A, Tittarelli A, Ricci C, Bertoldi M, De Saeger E, Crosignani P Personal exposure to $PM_{2.5}$ among high-school students in Milan and background measurements: the EuroLifeNet study. *Atmos Environ* 2011 8// **45**: 4147–4151.
- Spira-Cohen A, Chen LC, Kendall M, Lall R, Thurston GD Personal exposures to traffic-related air pollution and acute respiratory health among Bronx school-children with asthma. *Environ Health Perspect* 2011; **119**: 559–565.
- Spira-Cohen A, Chen LC, Kendall M, Sheesley R, Thurston GD Personal exposures to traffic-related particle pollution among children with asthma in the South Bronx, NY. *J Expo Sci Environ Epidemiol* 2010; **20**: 446–456.
- Crist KC, Liu B, Kim M, Deshpande SR, John K Characterization of fine particulate matter in Ohio: indoor, outdoor, and personal exposures. *Environ Res* 2008; **106**: 62–71.
- Du X, Kong Q, Ge W, Zhang S, Fu L. Characterization of personal exposure concentration of fine particles for adults and children exposed to high ambient concentrations in Beijing, China. *J Environ Sci* 2010; **22**: 1757–1764.
- Jiang R, Bell ML A comparison of particulate matter from biomass-burning rural and non-biomass-burning urban households in northeastern China. *Environ Health Perspect* 2008; **116**: 907–914.
- Ezzati M, Saleh H, Kammen DM The contributions of emissions and spatial microenvironments to exposure to indoor air pollution from biomass combustion in Kenya. *Environ Health Perspect* 2000; **108**: 833–839.
- Dionisio KL, Howie SR, Dominici F, Fornace KM, Spengler JD, Adegbola RA *et al*. Household concentrations and exposure of children to particulate matter from biomass fuels in The Gambia. *Environ Sci Technol* 2012; **46**: 3519–3527.
- Kistnasamy EJ, Robins TG, Naidoo RN, Batterman S, Mentz GB, Jack Cet *et al*. The relationship between asthma and ambient air pollutants among primary school students in Durban, South Africa. *Int J Environ Health* 2008; **2**: 365–385.

- 24 Naidoo RN, Robins TG, Batterman S, Mentz G, Jack C Ambient pollution and respiratory outcomes among schoolchildren in Durban, South Africa. *S Afr J Child Health* 2013; **7**: 127–134.
- 25 United Nations Department of Economic and Social Affairs (Population Division) 2011.
- 26 World Health Organization. *Global Status Report on Noncommunicable Diseases 2010*. World Health Organization (WHO): Geneva, 2011).
- 27 Demokritou P, Kavouras IG, Ferguson ST, Koutrakis P Development and laboratory performance evaluation of a personal multipollutant sampler for simultaneous measurements of particulate and gaseous pollutants. *Aerosol Sci Technol* 2001/01/01 **35**: 741–752.
- 28 Chakrabarti B, Fine P, Delfino R, Sioutas C Performance evaluation of an active personal DataRAM PM2.5 Mass Monitor (Thermo Anderson pDR-1200) designed for continuous personal exposure measurements. *Atmos Environ* 2004; **38**: 3329–3340.
- 29 Laird NM, Ware JH Random-effects models for longitudinal data. *Biometrics* 1982; **38**: 963–974.
- 30 WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. 2005.
- 31 Wu C-F, Delfino RJ, Floro JN, Quintana PJE, Samimi BS, Kleinman MT et al. Exposure assessment and modeling of particulate matter for asthmatic children using personal nephelometers. *Atmos Environ* 2005; **39**: 3457–3469.
- 32 Van Roosbroeck S, Jacobs J, Janssen NAH, Oldenwening M, Hoek G, Brunekreef B. Long-term personal exposure to PM2.5, soot and NOx in children attending schools located near busy roads, a validation study. *Atmos Environ* 2007; **41**: 3381–3394.
- 33 Amram O, Abernethy R, Brauer M, Davies H, Allen RW Proximity of public elementary schools to major roads in Canadian urban areas. *Int J Health Geogr* 2011; **10**: 68.
- 34 Nakagawa S, Schielzeth H A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods Ecol Evol* 2013; **4**: 133–142.

Feasibility of using hospital administrative records to study the association of air pollution exposure and birth weight in Accra, Ghana

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Background and significance

In the past two decades, child survival has improved considerably in all high mortality countries (UN IGME 2014). Increasing international commitment, and the ongoing policies and programmes by national governments have been important factors in this achievement. Yet, an estimated 6.3 million children died before the age of five in 2013, with the majority of these deaths concentrated in sub-Saharan Africa (SSA) (UN IGME 2014). In 2013, the top ten countries with the highest child mortality were all in SSA (Wang et al. 2014).

Close to one half of the global mortality of children under age five occurs in the neonatal period – the first 28 days of life (Liu et al. 2015). The proportion of child deaths occurring in the neonatal period has increased over the last two decades, and this trend could continue if efforts are not focused on reducing neonatal deaths in high-mortality countries (Wang et al. 2014).

Child and neonatal health and mortality in Ghana

Trends in child mortality in Ghana parallel those in other SSA countries (Figure 1). Most recent estimates put Ghana's under-five mortality at 71.4 deaths per 1,000 live births, which is far from the Millennium Development Goal 4 target of 40 deaths by 2015 (UN IGME 2014; Wang et al. 2014). Ghana is among the 26 countries that accounted for 80% of the global child deaths in 2013 (Wang et al. 2014). Between 1990 and 2013, neonatal mortality declined by only a fourth. Although annual rates of change increased over that same period, neonatal deaths as a share of all child deaths in Ghana have increased from around 30% to 40% (UN IGME 2014). At the same time, Ghana is experiencing increasing population growth, with a slow decline in fertility (The World Bank 2014). Given the high fertility and

child mortality rates, it is critical to identify major risk factors for child survival and key interventions needed to address neonatal deaths in Ghana.

Risk factors for neonatal mortality

The primary risk factors for neonatal mortality are preterm birth, intrauterine growth restriction, or a combination of the two. Being born too early, too tiny or both, may result in low birth weight (LBW; birth weight < 2,500 g), a condition which increases the risk of neonatal mortality (McCormick 1985). Preterm birth complications were one of the top three leading causes of infant deaths in 2013 (Liu et al. 2015). In 2010, more than 35% of all births in SSA were estimated to be with term and preterm low birth weight (Lee et al. 2013). But unlike high-income countries, little is known about the risk of dying for infants in these categories of birth in SSA.

Air pollution as a risk factor for low birth weight

A number of studies have linked maternal exposure to air pollution during pregnancy with adverse birth outcomes, particularly restricted fetal growth, LBW, and reduced gestational duration (Dadvand et al. 2013; Fleischer et al. 2014; Pedersen et al. 2013; Sapkota et al. 2012; Slama et al. 2008; Stieb et al. 2012). In addition, maternal exposure to air pollution could increase the risk of other adverse health effects in childhood (Choi et al. 2012; Perera et al. 2009). However, the results have been inconsistent, regardless of the exposure windows or timings examined (Dadvand et al. 2013; Sapkota et al. 2012; Stieb et al. 2012). Many studies, including meta-analyses, have shown consistent indication of association of fine particulate matter (PM_{2.5}; particles below 2.5 micrometers in aerodynamic diameter) with LBW (Dadvand et al. 2013; Fleischer et al. 2014; Pedersen et al. 2013; Sapkota et al. 2012).

So far, studies that found adverse effects of air pollution on birth outcomes are mostly from Western cities, where exposure levels are relatively low compared with developing country cities. Applying policies and interventions to developing countries based on findings from high-income settings might not achieve the desired outcome as the nature of the association between birth outcomes and air pollution exposure at high exposure levels is poorly understood. Although a few studies have assessed indoor air pollution and pregnancy outcomes in rural areas of developing world countries (Boy et al. 2002; Thompson et al. 2011), little or nothing is known about the association of air pollution exposure with birth weight in high-pollution developing country cities. In addition, there are currently no known large birth cohorts or longitudinal studies in any of the high-pollution and high-child mortality SSA countries (Campbell and Rudan 2011). Given the drawbacks of the cost and time involved, as well as follow-up issues related to prospective cohort studies, it is critical to take advantage of hospital administrative data to retrospectively assess air pollution as a risk factor for LBW and infant mortality in the a data-poor setting of SSA, a place where the social and economic conditions are unstable.

Objective and hypothesis

This evaluation has been conducted in view of a potential future study that would investigate the associations of exposure to air pollutants with birth weight, term LBW, and other possible outcomes (e.g. preterm birth, and head circumference). The findings will provide knowledge based information for the planning of a large-scale study of air pollution and low birth weight in Accra. The primary objective of this preliminary study is to assess the feasibility of the use of hospital administrative records for understanding air pollution health effects on pregnancy outcomes in Accra. This assessment seeks to address whether: a) the available health administrative data can be used to assess PM pollution-related adverse pregnancy

outcomes, in particular birth weight; b) the data can be used in the design of follow-up studies in such settings; c) the number of births that occur in the city would provide a large enough sample size; and d) birth weight distribution in such complex source-pollution environments varies substantially across neighborhoods. Hypotheses for the future study include:

- Maternal exposure to high levels of ambient air pollution during pregnancy is inversely associated with restricted fetal growth.
 - Prevalence of biomass fuel use in maternal residential neighborhood is a major predictor of birth weight.
 - The distance of maternal residence to a main road is negatively associated with risk of LBW.
- Mothers who are exposed to seasonal Harmattan dusts (~ December-February) during critical gestational time windows (trimesters) will have increased risk of LBW.

To achieve the above objectives, we explored important environmental and social risk factors for child survival in Accra, conducted an appraisal of maternal and child health care system and infrastructure, and examined existing data sources as well as future data needs. We conclude by proposing recommendations for a future study on the association of PM and birth outcomes.

Air pollution in Accra

Although previous studies have explored the impacts of prenatal exposures to various air pollutants on birth outcomes, we focus on PM_{2.5}, which is consistently found to be associated with birth weight. Accra has a population of approximately 3 million residents. Fast paced population and economic growth is causing a steep rise in localized industrialization, and

motorization. But many roads are still unpaved or left unswept, the use of old imported vehicles is still widespread, and household and community air pollution, mostly from the burning of solid fuels, is still high. These sources are the major determinants of the patterns of PM pollution between and within Accra neighborhoods, and of its concentrations in the household environment (Arku et al. 2008; Dionisio et al. 2010a; Zhou et al. 2011). In previous work, we found annual mean PM_{2.5} from outdoor monitors in Accra ranged between 30 and 70 µg/m³ in different neighborhoods in seasons without Harmattan dusts (Dionisio et al. 2010a); levels could exceed 100 µg/m³ during the Harmattan. Also, the mean (SD; standard deviation) 24-hr personal PM_{2.5} for school children from the same neighborhoods was 56.0 (33.5) µg/m³ (Arku et al. 2014). The highest personal PM_{2.5} exposures could occur in relation to major roads, household's own biomass use as well as community biomass use around schools locations (Arku et al. 2014; Zhou et al. 2011). Overall, biomass burning is responsible for between 30-50% of the city's fine particulate pollution, with an additional 10-30% from traffic and road dust (Zhou et al. 2013). These sources and levels of air pollution exposure as well as the places where the highest exposures occur in Accra significantly differ compared with cities in high-income countries, where air pollution-birth effect studies have been conducted thus far. In addition, housing conditions and the built environment in Accra are different from high-income cities, and thus may influence PM exposures and its health effects. Hence, particulate pollution may be a major risk factor for fetal and child health in Accra.

Maternal and child health care in Accra

As with the rest of the country, health service delivery in Accra is provided by the Ghana Health Service (GHS). The health delivery structure in the metropolis is divided into six administrative districts, which include Ablekuma, Ashiedu-Keteke, Ayawaso, Kpeshie,

Okaikoi, and Osu-Clotney (Figure 3). Each district is managed by a government polyclinic (Figure 4). The city has about 20 government-owned health facilities and more than 300 private facilities, which are nearly equally distributed in the six districts, except for Ayawaso which has about 25% of the total.

Along the continuum of mother and child care services, antenatal care and birth could occur at any facility, but immunization for both child and mother are restricted to the government facilities and some designated private facilities (Figure 5). Thus, babies born outside of these facilities are required to report at any of the designated centres for their vaccines. GHS approves WHO recommendation of a minimum of four antenatal visits for pregnant women (World Health Organization 2007). Over 95% of pregnant women in the metropolis receive antenatal care from skilled providers. Immunization for pregnant women and children against preventable diseases, including tuberculosis, poliomyelitis, diphtheria, neonatal tetanus, whooping cough, hepatitis B, haemophilus influenza type b, measles and yellow fever, is conducted through the Expanded Program on Immunization (EPI). At each immunization centre, the vaccines are administered through the Reproductive and Child Health (RCH) Unit, which is responsible for coordinating the implementation of reproductive and child health activities. Vaccination for a child starts at birth with Bacillus Calmette–Guérin (BCG; against tuberculosis) and Polio, and concludes in the 18th month with measles. More than 95% of newborn babies in Accra receive BCG and Polio vaccines.

Despite the high antenatal coverage, and the high proportion of babies being delivered by skilled health personnel, child mortality remains relatively high in the metropolis (Figure 2). Under-five mortality declined from 87.1 deaths per 1,000 live births in 2000 to 59.5 in 2010, about a 32% reduction (Table 1). Almost half of these deaths occurred in the first month of

life (DHS 2003; Ghana Statistical Service (GSS) 2009) (Figure 2). Over the same period, there were some improvements in key social and environmental risk factors for child mortality; the number of men and women who attained primary education had increased and more households had access to improved water and sanitation and cleaner cooking fuels (GSS, 2010).

Mother and newborn health information

In general, acquisition of hospital administrative data that are of good quality and relevance for research is almost impossible in Accra. There are severe limitations with regard to standards for data capture, organization, and repository. The scant information that is kept by health facilities exists mainly in hand-written ledger books, which are difficult to trace after a calendar year. Specifically, records of prenatal, delivery, neonatal data are all paper based.

Crucial mother-child administrative records necessary for a study of the association of air pollution exposure and birth weight are kept by the individual women in Maternal and Child health Record books (see appendix 1). Pre-natal information about a mother as recorded in the Maternal Record book include:

- Neighbourhood of residence;
- Age;
- Level of education;
- Occupation;
- Date of first visit;
- Menstrual history;
- Ultrasound scan test report;
- Expected delivery date; and

- Active cell phone number;

Information recorded in the Child Health book about a newborn includes:

- Date and place of birth;
- Sex;
- Birth weight (Kg);
- Immunization records; and
- Weight at each subsequent vaccination visit (commences at sixth week after birth).

Additionally, more than 90% of pregnant women in Accra undertake routine ultrasound scans, which can be used alone or combined with menstrual history to estimate gestational age at birth. GHS encourages three ultrasound scans for every pregnancy; one at the first visit, and the final around the eighth month. Many women have only two scans, with a few having single scan, mostly for lack of money as the cost is paid out of pocket. The scan results are usually attached to the maternal health record book. According to the protocol used for ultrasound scan in Accra, gestational age of fetus/newborn based on the ultrasound scan is estimated using 40 weeks, with a normal pregnancy range between 37 and 42 weeks.

Identification of new mother and child

Conducting a study of the association of air pollution exposure with pregnancy outcomes in Accra will require identification and enrollment of would-be or current mothers. Newborn babies and their mothers could be easily identified through RCH staffs, who administer BCG and Polio vaccines at birth (in the maternity wards), or at first contact (at an immunization center). After enrollment, both maternal and child health record books could then be obtained from the mother. As mentioned above, because vaccines are administered daily at

the polyclinics, and twice weekly at selected public/private facilities, there will be a need for daily enrollment at each facility.

To ascertain household and community information for each mother-child, home visits will be required following enrolment. Cell phone numbers in the maternal health record books would be the key in contacting participants for directions to their residence. By the end of January, 2015, Ghana's mobile penetration was 115.15% (Ghana National Communication Authority 2014). Although many individuals own dual-sim phones or multiple cell phones with active lines, each household in Accra has been estimated to have at least one active cell phone.

Before mothers can be contacted through the RCH unit, four levels of consent (authorisation) are needed: (i) study approval letter from GHS ethics committee; (ii) general introduction letter from GHS' Greater Accra Regional Headquarters to the Accra Metropolitan Health Directorate; (iii) introduction letter from the Metropolitan Director to each district/health facility; and (iv) approval letter from the Medical Superintendent in-charge of a facility to the RCH and Maternity units. At each stage, the principal investigator (PI) is responsible for picking up and delivering the necessary document to the appropriate authority.

Feasibility of planned study

To determine the feasibility of the proposed study, we collected baseline data on number of births and birth weights to determine the power of the proposed study (Table 2). Due to the absence of vital registration system in Ghana, we estimated the total number of births using the number of BCGs administered per district. We collated BCG data from three districts (locations of health facilities in the three districts are shown in Figure 6). An estimated

60,000 live births occur annually in the metropolis, with more than two-thirds of these births occurring in government facilities. Less than 2% of all deliveries are attended by traditional birth attendants (TBA) or occur at home. Babies that are born at home (e.g. by TBAs) would have to report to a health facility within 24 hours of delivery for their birth weights and at-birth vaccines. Monthly BCG records from January-August 2014 seems to indicate seasonal variations in child births in Accra, with highest number of births occurring in April-June.

Birth weights, measured in kilograms, were assessed using records from RCH registers at three polyclinics and a private hospital. Between January and October, 2014, average birth weight across all four facilities was $3,167 \pm 458$ g ($n= 5,899$), with individual birth weights ranging from 1,200 g to 6,000 g. Mean birth weight was similar across polyclinics, differing by < 90 g (3,141-3,227 g). Prevalence of LWB was less than 6% at these facilities. We could not assess whether infants with LBW were term or preterm deliveries.

Given the high number of births in Accra per year, and the marked exposure contrasts, statistical power of such a study to detect associations of $PM_{2.5}$ exposures with birth weight will be very large if detailed information on potential confounding factors at the individual, household and community-level are collected and included in the analysis. With mean (SD) $PM_{2.5}$ exposures of 50 (35) $\mu\text{g}/\text{m}^3$, and a type I error of 5%, we have $> 95\%$ power to detect a 2 g reduction in birth weight for a unit increase in $PM_{2.5}$.

Exposure measurement

Measurement methods and assignment of numerical estimate of $PM_{2.5}$ exposures to participants are beyond the scope of this evaluation. As required of all field research studies, high quality and detailed $PM_{2.5}$ exposure assessment data is paramount to assess its

relationship with birth weight. Through previous studies in Accra, extensive information on detailed air pollution monitoring at the community, household and personal-level is available, along with other individual, household, and community-level indicators of exposure (Arku et al. 2008; Arku et al. 2014; Dionisio et al. 2010a; Dionisio et al. 2010b; Zhou et al. 2011; Zhou et al. 2013). In addition the specific studies in Accra, a number of exposure assessment methods currently exist to assess community level exposures at fine resolution, including novel satellite-based estimates and GIS and satellite data to characterize local air pollution sources (Brauer et al. 2012; Kloog et al. 2011; van Donkelaar et al. 2010). With these resources and techniques, air pollution-birth weight study in will be able to provide the full range of exposure seen across Accra neighborhoods in order to make inferences about air pollution and birth weight in the context of a large number of other individual, household, community, and country-level risk factors.

Conclusion and recommendations for the proposed research project

Being aware of the overall maternal and child health care infrastructure of Accra, as well as types and sources of hospital administrative data available helps provide an understanding of how to design and conduct an air pollution-birth effect study in such settings. We assessed the availability and sources of neonatal and maternal anthropometric and demographic information in Accra. Relevant outcomes and data needs and data available for a successful conduct a study of the association of air pollution exposure with birth weight in Accra are summarized in Table 3. Our assessments establish that it is feasible to use the available health administrative data to study the association of PM pollution with adverse pregnancy outcomes. There exists an established health care structure that would facilitate enrolment of study participants. The annual number of births in the city would provide enough sample size

to statistically power such study. The study design could leverage the high immunization coverage at birth and cell phone penetration to enrol and follow up on participants.

References

- Arku RE, Vallarino J, Dionisio KL, Willis R, Choi H, Wilson JG, et al. 2008. Characterizing air pollution in two low-income neighborhoods in accra, ghana. *Science of the total environment* 402:217-231.
- Arku RE, Dionisio KL, Hughes AF, Vallarino J, Spengler JD, Castro MC, et al. 2014. Personal particulate matter exposures and locations of students in four neighborhoods in accra, ghana. *Journal of Exposure Science and Environmental Epidemiology*.
- Boy E, Bruce N, Delgado H. 2002. Birth weight and exposure to kitchen wood smoke during pregnancy in rural guatemala. *Environmental Health Perspectives* 110:109.
- Brauer M, Amann M, Burnett RT, Cohen A, Dentener F, Ezzati M, et al. 2012. Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. *Environmental science & technology* 46:652-660.
- Campbell A, Rudan I. 2011. Systematic review of birth cohort studies in africa. *Journal of global health* 1:46.
- Choi H, Wang L, Lin X, Spengler JD, Perera FP. 2012. Fetal window of vulnerability to airborne polycyclic aromatic hydrocarbons on proportional intrauterine growth restriction. *PLoS One* 7:e35464.
- Dadvand P, Parker J, Bell ML, Bonzini M, Brauer M, Darrow LA, et al. 2013. Maternal exposure to particulate air pollution and term birth weight: A multi-country evaluation of effect and heterogeneity.
- DHS. 2003. Ghana statistical service (gss), ghana health service (ghs), icf macro. Ghana demographic and health survey 2003. Accra, ghana: Gss, ghs, and icf macro.
- Dionisio KL, Arku RE, Hughes AF, Vallarino J, Carmichael H, Spengler JD, et al. 2010a. Air pollution in accra neighborhoods: Spatial, socioeconomic, and temporal patterns. *Environmental science & technology* 44:2270-2276.
- Dionisio KL, Rooney MS, Arku RE, Friedman AB, Hughes AF, Vallarino J, et al. 2010b. Within-neighborhood patterns and sources of particle pollution: Mobile monitoring and geographic information system analysis in four communities in accra, ghana. *Environmental health perspectives (Online)* 118:607.
- Fleischer NL, Merialdi M, van Donkelaar A, Vadillo-Ortega F, Martin RV, Betran AP, et al. 2014. Outdoor air pollution, preterm birth, and low birth weight: Analysis of the world health organization global survey on maternal and perinatal health. *Environmental health perspectives* 122:425.
- Ghana National Communication Authority. 2014. Available: <http://www.nca.org.gh/>.
- Ghana Statistical Service (GSS) GHSG, and Macro International. 2009. Ghana maternal health survey 2007. Calverton, Maryland, USA: GSS, GHS, and Macro International.
- GSS. 2000 population and housing census: Summary report of final report. Accra, Ghana:Ghana Statistical Services.
- GSS. 2010. 2010 population and housing census: Summary report of final report. Accra, Ghana:Ghana Statistical Service.
- Kloog I, Koutrakis P, Coull BA, Lee HJ, Schwartz J. 2011. Assessing temporally and spatially resolved pm 2.5 exposures for epidemiological studies using satellite aerosol optical depth measurements. *Atmospheric Environment* 45:6267-6275.
- Lee AC, Katz J, Blencowe H, Cousens S, Kozuki N, Vogel JP, et al. 2013. National and regional estimates of term and preterm babies born small for gestational age in 138 low-income and middle-income countries in 2010. *The lancet global health* 1:e26-e36.
- Liu L, Oza S, Hogan D, Perin J, Rudan I, Lawn JE, et al. 2015. Global, regional, and national causes of child mortality in 2000-13, with projections to inform post-2015 priorities: An updated systematic analysis. *Lancet* 385:430-440.

- McCormick MC. 1985. The contribution of low birth weight to infant mortality and childhood morbidity. *The New England journal of medicine*.
- Pedersen M, Giorgis-Allemand L, Bernard C, Aguilera I, Andersen A-MN, Ballester F, et al. 2013. Ambient air pollution and low birthweight: A european cohort study (escape). *The Lancet Respiratory Medicine* 1:695-704.
- Perera FP, Li Z, Whyatt R, Hoepner L, Wang S, Camann D, et al. 2009. Prenatal airborne polycyclic aromatic hydrocarbon exposure and child iq at age 5 years. *Pediatrics* 124:e195-e202.
- Sapkota A, Chelikowsky AP, Nachman KE, Cohen AJ, Ritz B. 2012. Exposure to particulate matter and adverse birth outcomes: A comprehensive review and meta-analysis. *Air Quality, Atmosphere & Health* 5:369-381.
- Slama R, Darrow L, Parker J, Woodruff T, Strickland M, Nieuwenhuijsen M, et al. 2008. Meeting report: Atmospheric pollution and human reproduction. *Environmental Health Perspectives* 116:791-798.
- Stieb DM, Chen L, Eshoul M, Judek S. 2012. Ambient air pollution, birth weight and preterm birth: A systematic review and meta-analysis. *Environmental research* 117:100-111.
- The World Bank. 2014. World development indicators : Reproductive health.
- Thompson LM, Bruce N, Eskenazi B, Diaz A, Pope D, Smith KR. 2011. Impact of reduced maternal exposures to wood smoke from an introduced chimney stove on newborn birth weight in rural guatemala. *Environmental health perspectives* 119:1489.
- UN IGME. 2014. Levels and trends in child mortality: Estimates developed by the un inter-agency group for child mortality estimation (igme) - report 2014.UNICEF, the World Health Organization (WHO), the World Bank, the United Nations.
- van Donkelaar A, Martin RV, Brauer M, Kahn R, Levy R, Verduzco C, et al. 2010. Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: Development and application. *Environmental health perspectives* 118:847-855.
- Wang H, Liddell CA, Coates MM, Mooney MD, Levitz CE, Schumacher AE, et al. 2014. Global, regional, and national levels of neonatal, infant, and under-5 mortality during 1990-2013: A systematic analysis for the global burden of disease study 2013. *Lancet* 384:957-979.
- World Health Organization. 2007. Standards for maternal and neonatal care. Department of Making Pregnancy Safer and Department of Reproductive Health and Research.
- Zhou Z, Dionisio KL, Arku RE, Quaye A, Hughes AF, Vallarino J, et al. 2011. Household and community poverty, biomass use, and air pollution in accra, ghana. *Proceedings of the National Academy of Sciences* 108:11028-11033.
- Zhou Z, Dionisio KL, Verissimo TG, Kerr AS, Coull B, Arku RE, et al. 2013. Chemical composition and sources of particle pollution in affluent and poor neighborhoods of accra, ghana. *Environmental Research Letters* 8:044025.

Table 1: Summary statistics of under-five mortality and social and environmental factors related to child survival in the Accra metropolis. Source: Analysis of Ghana's 2000 and 2010 National Population and Housing Censuses.

Variable	Census 2000	Census 2010
Population size (millions)	1.2	3.0
No. of households (thousands)	200	600
Under-five mortality (per 1,000 live births)	87.1	59.5
Cooking fuel (percent of households)		
<i>Wood</i>	4.5	1.9
<i>Charcoal</i>	58.6	42.9
<i>Other biomass</i>	4.4	6.2
<i>Kerosene</i>	2.5	0.8
<i>LPG</i>	28.2	47.7
<i>Electricity</i>	1.8	0.5
Sanitation: toilet facility (percent of households)		
<i>Improved</i>	46.3	88.4
<i>Unimproved</i>	53.7	11.6
Drinking water source (percent of households)		
<i>Improved</i>	42.8	67.2
<i>Unimproved</i>	57.2	32.8
Maternal education (percent of women of child-bearing age)		
<i>None</i>	25.8	11.9
<i>Primary</i>	42.9	52.3
<i>Secondary or higher</i>	31.2	35.8

Table 2: Number of births and summary statistics of birthweight by district between Jan-Aug, 2014.

District	No. of births	Mean birthweight (g)* (95% CI)
Okaikoi	6,639	3,165 (3,141, 3,189)
Ayawaso	8,092	3,201 (3,174, 3,227)
Ablekuma	1,4168	3,172 (3,149, 3,196)
Asiedu	1,812	3,087 (3,039, 3,136)

* Birth weight records were from the polyclinics only

Table 3: Relevant outcomes and data needs.

Outcome	Variable needed	Variable available
Term birth weight (continuous variable)	<ul style="list-style-type: none"> - Gestational age - Date of birth - Birth weight in grams (g) 	<ul style="list-style-type: none"> - Menstrual history - Ultrasound scan - Date of birth - Birth weight in kilograms (Kg)
Term low birth weight (< 2,500 g at birth)	<ul style="list-style-type: none"> - Gestational age - Date of birth - Birth weight in grams (g) 	<ul style="list-style-type: none"> - Menstrual history - Ultrasound scan - Date of birth - Birth weight in kilograms (Kg)
Preterm birth (< 37 completed weeks of gestation)	<ul style="list-style-type: none"> - Gestational age - Date of birth 	<ul style="list-style-type: none"> - Menstrual history - Ultrasound scan - Expected delivery date
Head circumference	Head circumference (cm)	
Childhood development (stunting, wasting, and underweight)	<ul style="list-style-type: none"> - Weight - Height - Age in months (all taken at specific intervals) 	<ul style="list-style-type: none"> - Weight - Age in months (all taken at immunization visit between birth and 18 months)

Figure 1: Trends in under-five mortality (deaths per 1,000 live births; 5q0) and neonatal mortality (deaths per 1,000 live births) in Sub-Saharan Africa (SSA) and Ghana between 1990 and 2013. Source: <http://www.childmortality.org/>.

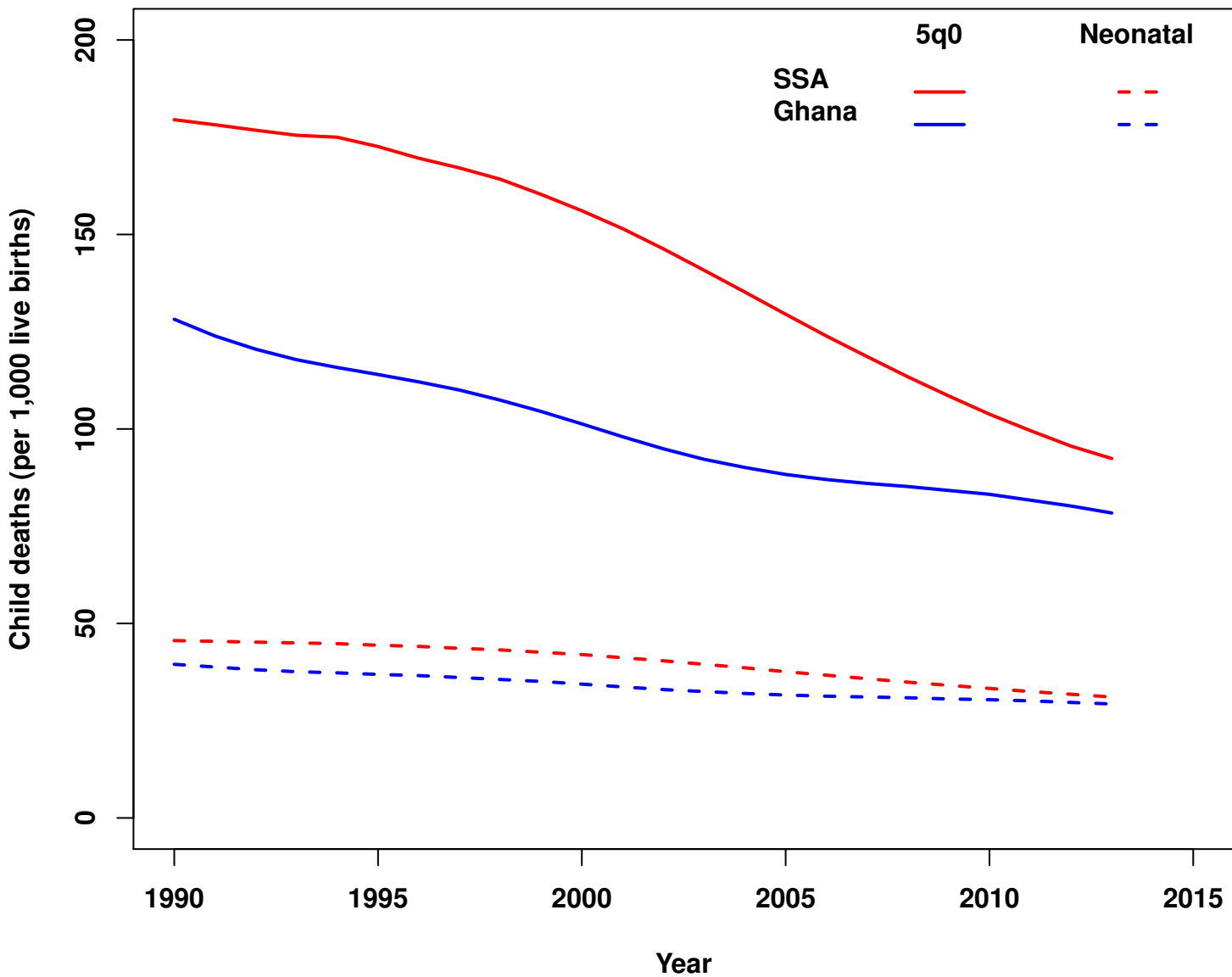


Figure 2: Trends in under-five mortality (deaths per 1,000 live births; 5q0) and neonatal mortality (deaths per 1,000 live births) in Accra, Ghana, between 1988 and 2008. Source: Ghana Demographic and Health Surveys 1988, 1993, 1998, 2003, 2008 (GSS/GHS/ICF Macro).

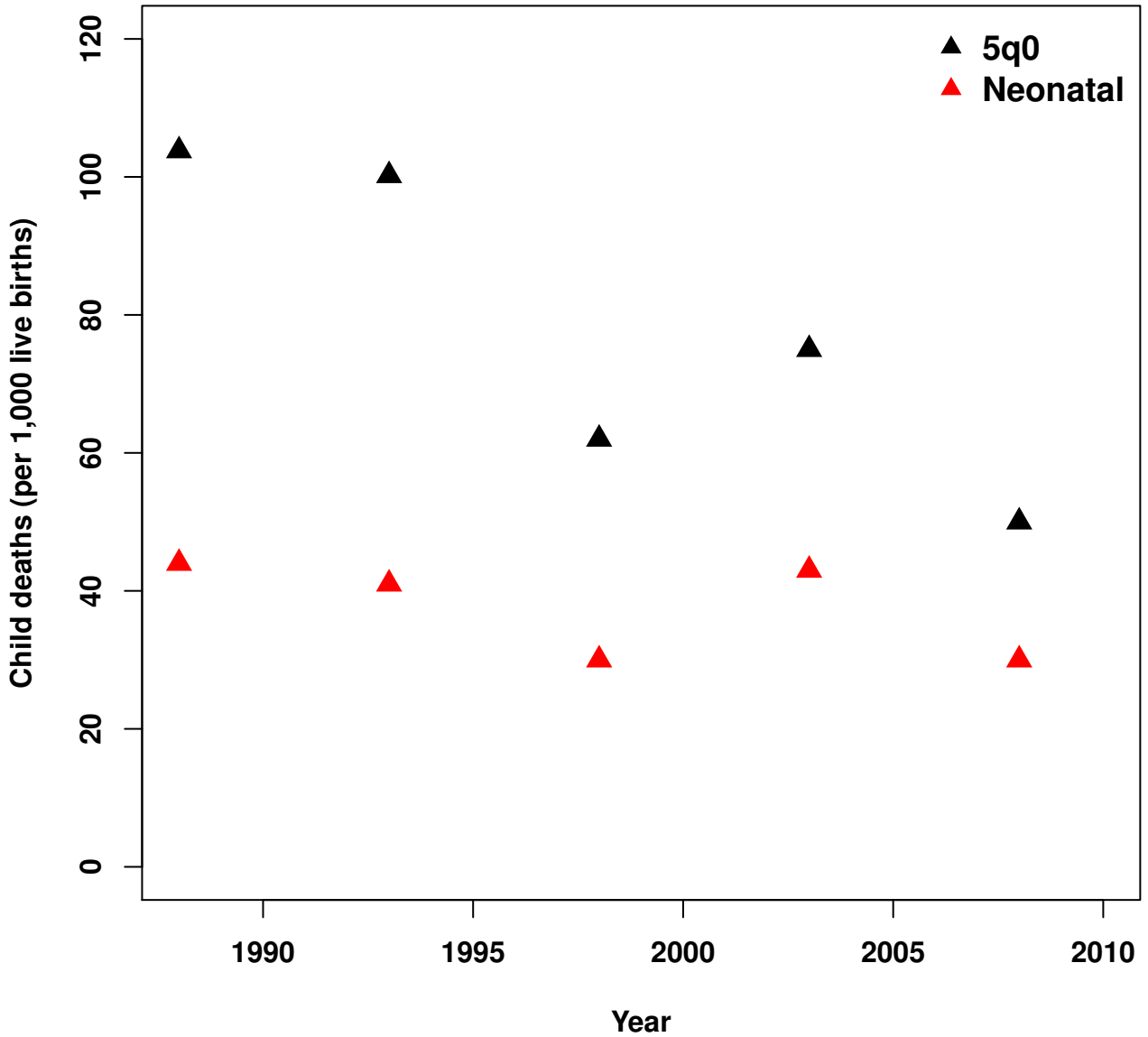


Figure 3: Ghana Health Service administrative districts in the Accra metropolis.

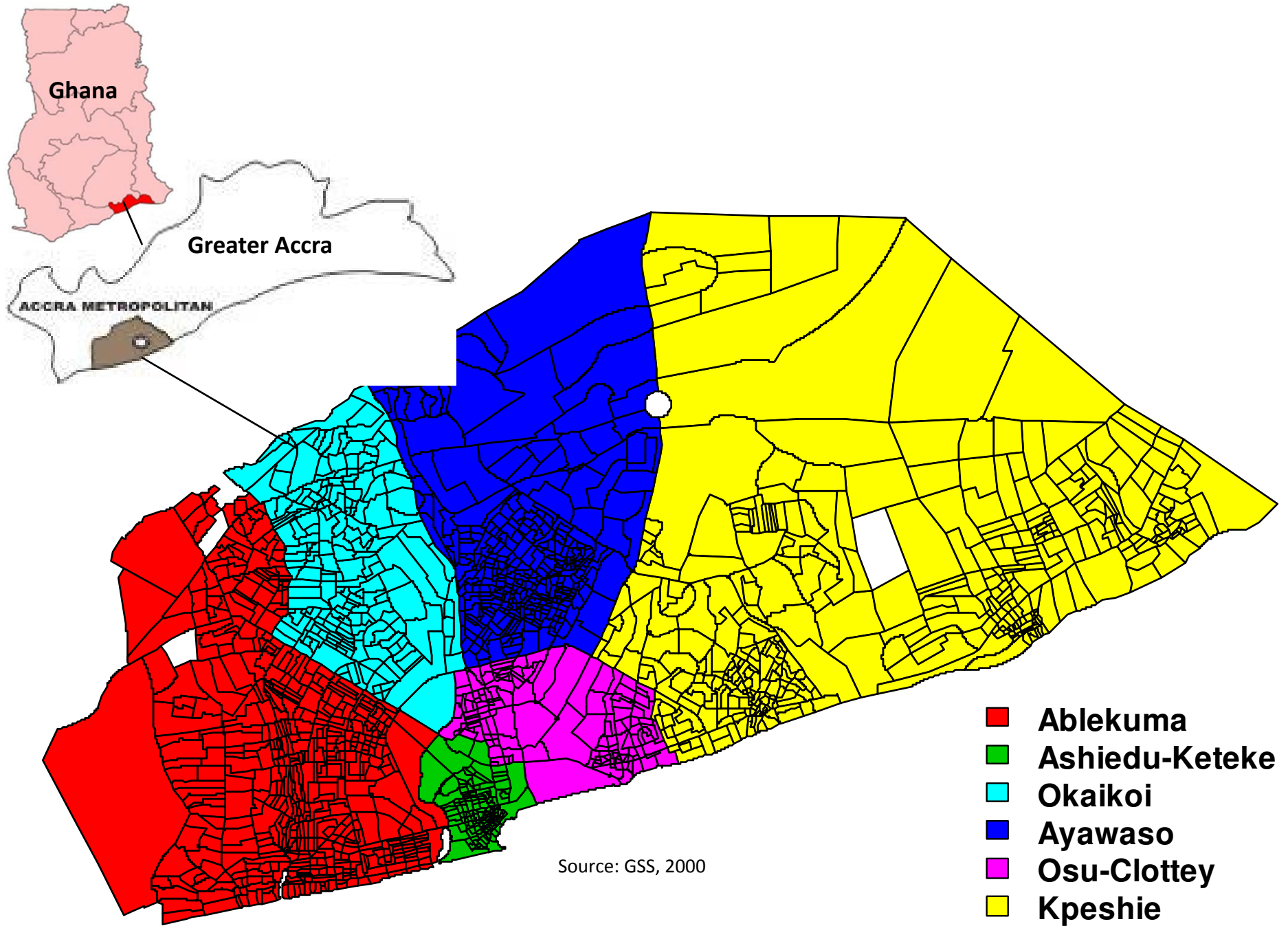
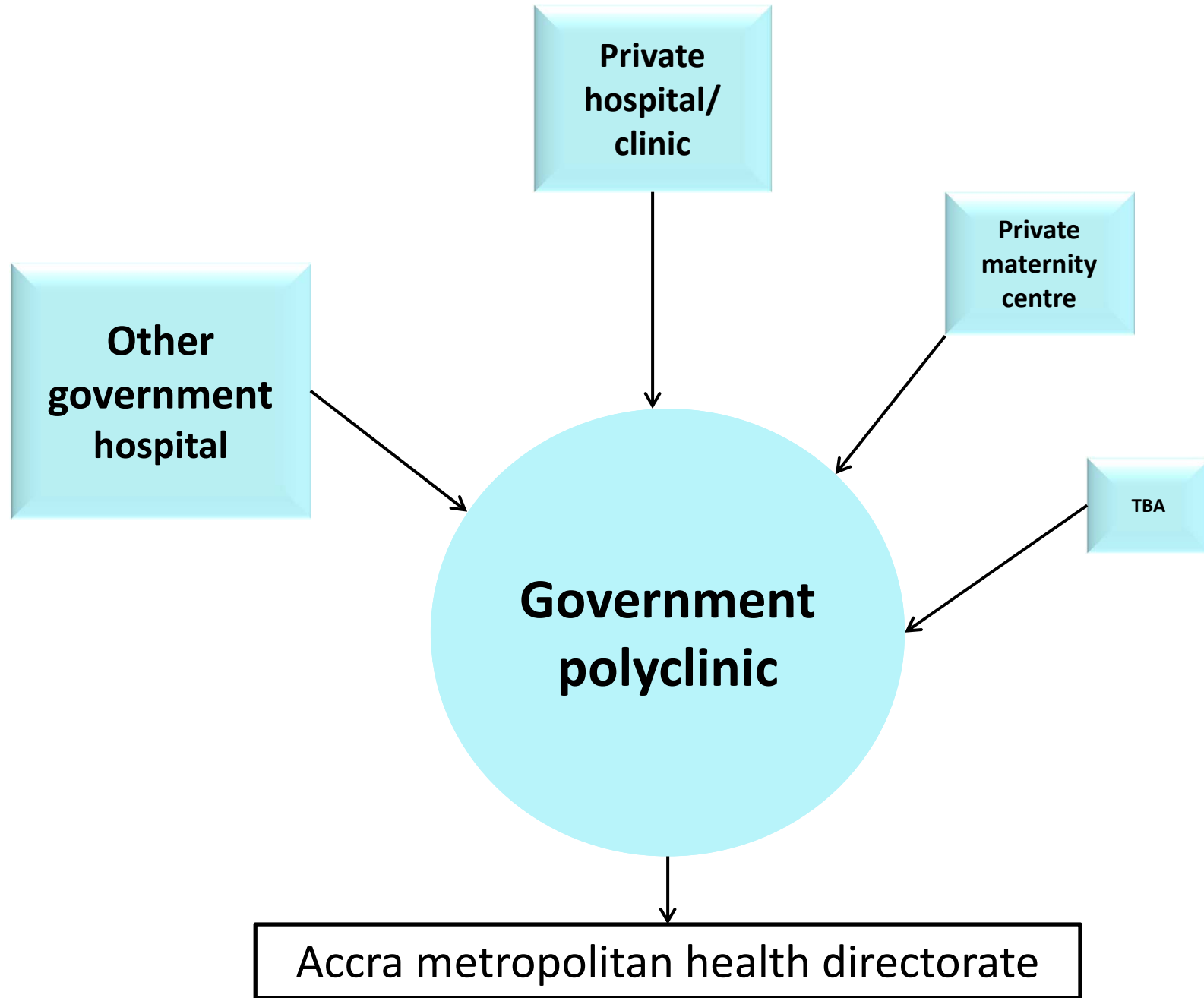


Figure 4: Administrative structure in each district for maternal and child health.



→ Movement of reports

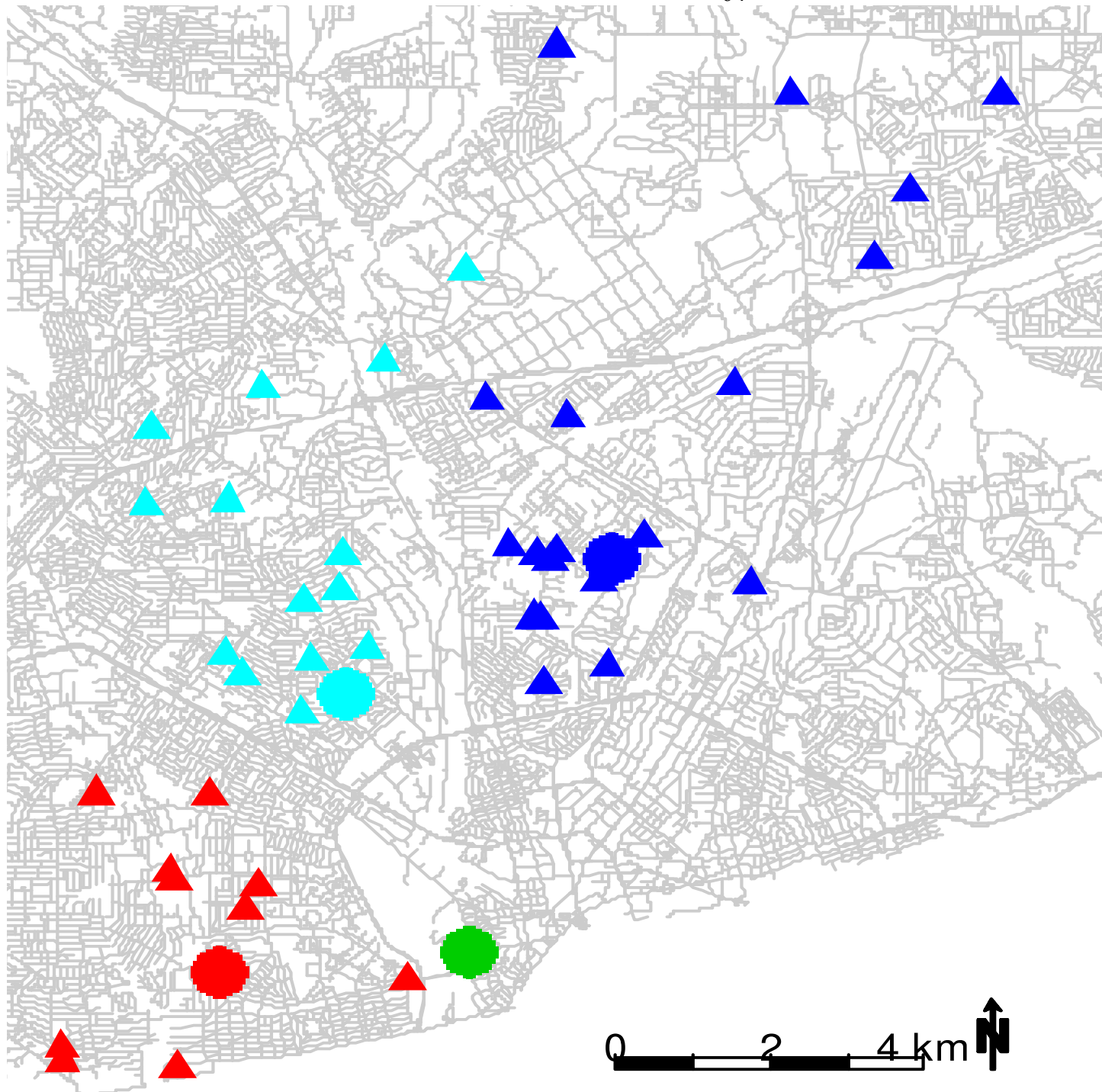
Figure 5: Health services provided in each district in relation to maternal and child health.

Type of service	Government polyclinic	Other government hospital	Private hospital/ clinic	Private maternity centre	TBA
Antenatal	X	X	X	X	X
Birth	X	X	X	X	X
Vaccines at birth	X	X	X		
Postnatal vaccines	X	X	X		

Time ↓

TBA = Traditional birth attendant

Figure 6: Locations of maternal and child care facilities in four districts.



Health facility

- ▲ Ablekuma
- ▲ Asiedu
- ▲ Okaikoi
- ▲ Ayawaso

Appendix 1: Maternal and child health record books.

