Spatial Demography

Modelling the spatial distribution and the factors associated with under-five mortality in Nigeria

--Manuscript Draft--

Manuscript Number:	SDEM-D-20-00028R3
Full Title:	Modelling the spatial distribution and the factors associated with under-five mortality in Nigeria
Article Type:	Original Research
Funding Information:	
Abstract:	Globally, the risk of a child dying before celebrating their fifth birthday is still high at 5.3 million deaths in 2018 alone. Nigeria is among the few countries that are yet to achieve the Sustainable Development Goal Target of keeping under-5 death to as low as 25 deaths per 1000 live births by 2030. A recent study found that the under-5 mortality rate (U5MR) in Nigeria is still high with 1 in 8 Nigerian children dying before reaching the age of 5. In this study, the effect of a child's spatial location in Nigeria on their likelihood of dying before age 5 was examined alongside other key covariates. Bayesian geo-additive regression models were fitted to the 2018 Nigeria Demographic and Health Surveys data. Statistical inference was based on the Bayesian paradigm via Markov chain Monte Carlo simulation methods, and models were assessed using the Deviance Information Criterion (DIC). Under-five mortality rate varied significantly across spatial locations in Nigeria with Kebbi, Jigawa, Kaduna, Kogi and Gombe states having the highest rates. The likelihood of a child dying before age 5 increased among women with primary education and women aged 38 years and over. Other characteristics associated with high under-5 death are poverty, male child, low birth weight and multiple births. The current study has helped to identify geographical 'hotspots' as well as the key factors driving under-5 deaths in Nigeria to inform the effective design and implementation of timely and efficient interventions.
Corresponding Author:	Adeniyi Francis Fagbamigbe, BSc, MSc, MPDI, PhD University of Ibadan College of Medicine Ibadan, Oyo NIGERIA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of Ibadan College of Medicine
Corresponding Author's Secondary Institution:	
First Author:	Adeniyi Francis Fagbamigbe, BSc, MSc, MPDI, PhD
First Author Secondary Information:	
Order of Authors:	Adeniyi Francis Fagbamigbe, BSc, MSc, MPDI, PhD
	Chibuzor Christopher Nnanatu, BSc MSc PhD
Order of Authors Secondary Information:	
Author Comments:	We have addressed all issues raised. Figures 2 and 3 have been changed accordingly
Response to Reviewers:	We have addressed all issues raised. Figures 2 and 3 have been changed accordingly

Modelling the spatial distribution and the factors associated with under-five mortality in Nigeria

Adeniyi Francis Fagbamigbe[1,2,3*] & Chibuzor Christopher Nnanatu[4,5]

[1]Department of Epidemiology and Medical Statistics, Faculty of Public Health, College of Medicine, University of Ibadan, Ibadan, Nigeria.

[2]Division of Health Sciences, Populations, Evidence and Technologies Group, Warwick Medical School, University of Warwick, Coventry, United Kingdom.

[3]Health Data Science Group, Population Behavioural Sciences Unit, School of Medicine, St Andrews University, United Kingdom

[4]Department of Statistics, Nnamdi Azikiwe University, Awka, Nigeria.

[5]Department of Mathematics, Physics and Electrical Engineering, Northumbria University, Newcastle, United Kingdom

*correspondence: franstel74@yahoo,com, +234806134865, ORCID: 0000-0001-9184-8258

Modelling the spatial distribution and the factors associated with under-five mortality in Nigeria

Abstract

Globally, the risk of a child dying before celebrating their fifth birthday is still high at 5.3 million deaths in 2018 alone. Nigeria is among the few countries that are yet to achieve the Sustainable Development Goal Target of keeping under-5 death to as low as 25 deaths per 1000 live births by 2030. A recent study found that the under-5 mortality rate (U5MR) in Nigeria is still high with 1 in 8 Nigerian children dying before reaching the age of 5. In this study, the effect of a child's spatial location in Nigeria on their likelihood of dying before age 5 was examined alongside other key covariates. Bayesian geo-additive regression models were fitted to the 2018 Nigeria Demographic and Health Surveys data. Statistical inference was based on the Bayesian paradigm via Markov chain Monte Carlo simulation methods, and models were assessed using the Deviance Information Criterion (DIC). Under-five mortality rate varied significantly across spatial locations in Nigeria with Kebbi, Jigawa, Kaduna, Kogi and Gombe states having the highest rates. The likelihood of a child dying before age 5 increased among women with primary education and women aged 38 years and over. Other characteristics associated with high under-5 death are poverty, male child, low birth weight and multiple births. The current study has helped to identify geographical 'hotspots' as well as the key factors driving under-5 deaths in Nigeria to inform the effective design and implementation of timely and efficient interventions.

Keywords: Under-5 mortality, MCMC, Bayesian Model, DHS, Nigeria

Introduction

The global risk of a child dying before reaching the age of 5 is still high at 5.3 million deaths in 2018 alone (UNICEF, 2020). Although this represents an overall decline of 59% between 1990 and 2018, the African region accounts for the highest under-five mortality rate (U5MR) of 76 deaths per 1000 live births. Specifically, the Sustainable Development Goals (SDGs) Target 3 focuses on "ensuring healthy lives and promoting the well-being for all", with specific targets to "end preventable deaths of neonatal, infant and Under-5 by 2030 and to achieve universal health coverage (UHC), through access to quality, safe, effective, affordable and essential health care services" and to end preventable deaths of new-borns and children under 5 years of age (United Nations, 2015). The expectation is that all countries will have reduced under-5 deaths to at least as low as 25 deaths per 1000 live births by the year 2030 (United Nations, 2015).

Nigeria is one of the few countries that are yet to meet the SDGs Target 3 with a recent estimate showing that the rates have declined since 1990. Specifically, the most recent national population survey in Nigeria put the U5MR at 132‰ (per 1000 live births) (National Population Commission(NPC)[Nigeria] & ICF International, 2019). This translates to 4.6 million under-5 children not making it to their fifth birthday. It also means 920,000 deaths per year or 2,500 deaths per day on the average among this vulnerable population subgroup which constitutes about 17% (National Population Commission(NPC)[Nigeria] & ICF International, 2019) of the Nigeria population estimated at 205 million (United Nations Population, 2020). The high U5MR in Nigeria is an indication that health outcomes are generally poor in Nigeria because under-5 death is an indicator of the progress of societal value system in health care management of a country (Abir, Agho, & Page, 2015; Morakinyo & Fagbamigbe, 2017; Yaya, Bishwajit, Okonofua, & Uthman, 2018).

Although there are reported reducing trends in the burden of under-5 death in Nigeria, it remains a huge setback towards the attainment of SDGs 3 on good health and well-being and on the reduction of inequality within and among countries (United Nations, 2015) in the country. In Nigeria, the U5MR reduced from 201‰ in 2003 to 157‰ in 2008 to 128‰ in 2013 but rose slightly to 132‰ in 2018 (National Population Commission(NPC)[Nigeria] & ICF International, 2019). Nevertheless, according to the World Health Organisation (WHO), the pace of reduction in Nigeria is very slow at 32% reduction from 193‰ in 1990 to 132‰ in 2018 compared to a global reduction of 59% from 93‰ to 39‰ over the same period

(WHO, 2020). The overall reducing trend in Nigeria under-5 death in the last few decades could be ascribed to the concerted efforts made by stakeholders including governments at all levels, health professionals, and policymakers, aimed at reducing all forms of childhood deaths (Liu et al., 2015, 2016). Nonetheless, the slight increase between 2013 and 2018 is a major cause for concern.

Moreover, the burden of under-5 death is enormous in Nigeria which constitutes a gross inequality when compared with other countries. For instance, the current U5MR suggests that the risk of a child dying before attaining five years of age is 1 in every 8 children (132‰) in Nigeria, 1 in every 13 children (76‰) in WHO African Region, 1 in every 111 children (9‰) in the WHO European Region and 1 in every 26 children globally(WHO, 2020). The WHO asserted that inequities in child mortality between high-income and low-income countries remain large with an average U5MR of 68‰ in low-income countries compared with 5‰ average in high-income countries (WHO, 2020).

Furthermore, childhood deaths remain a major public health challenge in Nigeria in general. The deaths among under-5 children are mainly caused by Acute Respiratory Infections (ARIs), diarrhoea, malaria and chronic malnutrition. Others include measles, HIV/AIDS, neonatal conditions, and infections (WHO, 2020). Timely, adequate and efficient management of these diseases might reduce U5MR in Nigeria (Adeyele & Ofoegbu, 2015). Reinforced management of disease could drastically reduce the burden of under-5 death in Nigeria(WHO, 2020). The management should be in terms of effective and efficient prevention and control of childhood diseases, improved health care deliveries such as health education and promotion, vaccination, immunization and vitamin supplementation (Abir et al., 2015; Morakinyo & Fagbamigbe, 2017; Yaya et al., 2018).

The literature is replete with studies that have examined trends in under-5 death in various contexts in developed and developing countries from which several risk factors are identified to be associated with under-5 deaths. These factors include maternal age, rural-urban differentials in residence, household wealth status, educational attainment, employment status, marital status, religious background, birth type, birth order and interval, sex and weight at birth, place and mode of delivery (Akinyemi, Bamgboye, & Ayeni, 2015; Alkema, Chao, You, Pedersen, & Sawyer, 2014; Chao, You, Pedersen, Hug, & Alkema, 2018; Ezeh, Agho, Dibley, Hall, & Page, 2015; Fagbamigbe & Alabi, 2014; Morakinyo & Fagbamigbe, 2017; Yaya et al., 2018; Yaya, Uthman, Okonofua, & Bishwajit, 2019). For instance, Alkema et al. found substantial differentials tin children survivorship within the first five years of life among boys and girls with respect to survival up to the age of 5 years in many countries of the world (Alkema et al., 2014). The authors noted that sex ratios were higher among the boys than the girls but important exceptions exist in some countries (Alkema et al., 2014). Also, a systematic study reported an absolute disparity in the level of under-5 deaths among children from poorest and richest households in low- and middle-income countries (LMIC) (Chao et al., 2018).

Other important factors in the literature are region, residence (rural-urban), poverty, poor immunization coverage, access to basic health-care services, and high fertility risk amongst others (Ezeh, Agho, Dibley, Hall, & Page, 2014; Yaya et al., 2017). These factors have been reported to cut across the individual, household and community-level and sometimes country-level characteristics (Akinyemi, Bamgboye, et al., 2015; Bado, Susuman, & Nebie, 2016; Yaya et al., 2018, 2019). Other important factors that may affect childhood mortality are the affordability, availability, accessibility of health care services as well as the freedom a woman has to seek health care for herself and children.

Several intervention programmes have been developed over the years with change already happening. However, the reported change has been short of expectation and does not appear to truly reflect the number of efforts and resources so far deployed. Moreover, the intervention programmes may not have been comprehensive enough to take into account some key peculiarities, such as the effects of spatial location and individual- and community-level characteristics on the likelihood of childhood mortalities(Yaya et al., 2018). While geographical area differentials in the location of residence and socioeconomic inequalities have been linked to several health outcomes including under-5 death, studies on the spatial distribution, patterns and variations of under-5 death in Nigeria are not common in the literature (Fagbamigbe, Kandala, & Uthman, 2020a, 2020b; Faust, Yaya, & Ekholuenetale, 2017). This has hitherto limited a deep understanding of how States (regions) of residence influence under-5 death viz-a-viz children characteristics. For these reasons, the overarching aim of the study, therefore, is to simultaneously explore the roles of some key individual- and community-level risk factors and the spatial location in which a child lives on under-5 deaths at the disaggregated level of States in Nigeria and provoke evidence-based discussions on childhood mortality prevention using a very recent Demographic and Health Survey (DHS) data. Specifically, we seek to answer the following questions: what are the key demographic drivers of under-5 death in Nigeria? Is there a significant impact of a child's geographical location on their likelihood of dying before age 5?

The multistage sampling approach employed by the DHS uses cluster sampling to draw respondents and this implies that observational units are not independent. Thus, any statistical technique based on the assumption of independent observational units will no longer lead to unbiased estimates. To circumvent this analytical challenge and provide more precise estimates, in this paper, we used advanced statistical techniques to explore the key factors driving under-five mortality in Nigeria.

We used Bayesian hierarchical geo-additive regression to model the factors associated with under-five death in Nigeria. The model uses the Markov Chain Monte Carlo (MCMC) to estimate both random and spatial effects of factors associated with the outcome of interest. Kandala et al. has used the procedure to estimate factors associated with female genital mutilation in Africa (N.-B. Kandala, Nwakeze, & Ngianga, 2009; N. B. Kandala, Nnanatu, & Atilola, 2019). Similarly, Ayele et al. had used the procedure to estimate the factors associated with under-five death in Ethiopia (Ayele, Zewotir, & Mwambi, 2015). The Bayesian geo-additive regression modelling approach utilised here allowed us to account for the roles played by a child's geographical location on their likelihood of dying before their fifth birthday while simultaneously adjusting for other individual-level and community-level factors. The approach utilised here allowed us to explore the spatial patterns of the prevalence of under-five death in Nigeria as well as the nonlinear effects of continuous covariates such as maternal age and other fixed effects simultaneously, in a coherent Bayesian hierarchical geo-additive regression framework. The knowledge of the spatial structure of the prevalence of under-five death in Nigeria could serve a huge advantage for the design and implementation of tailored interventions. Moreover, the identification of high-risk geographical regions would guide the allocation of scarce resources in the fight against the scourge and facilitate the eradication of under-five mortality throughout the country.

The findings of this study would be useful for formulating evidence-based child health policy- and help the child and maternal health decision-makers to efficiently mobilize resources, plan strategies and accurately prioritise interventions targeted at turning the tides against childhood mortality in Nigeria. Our results could be very handy in designing and implementing appropriate state-specific and context-specific strategies and intervention programs aimed at preventing child death. The findings of this study can help improve researchers' understanding of the state-level childhood mortality and help Nigeria to reduce avoidable child deaths and drive the country towards the SDG 3 targets on reducing under-five mortality to at least as low as 25 per 1,000 live births.

Methods

Study Setting

In Nigeria, there are 36 states and the federal capital territory (FCT) which are grouped into 6 geopolitical zones namely, North-East (NE), North-West (NW), North-Central (NC), South-East (SE), South-South (SS), and South-West (SW) (Figure 1).

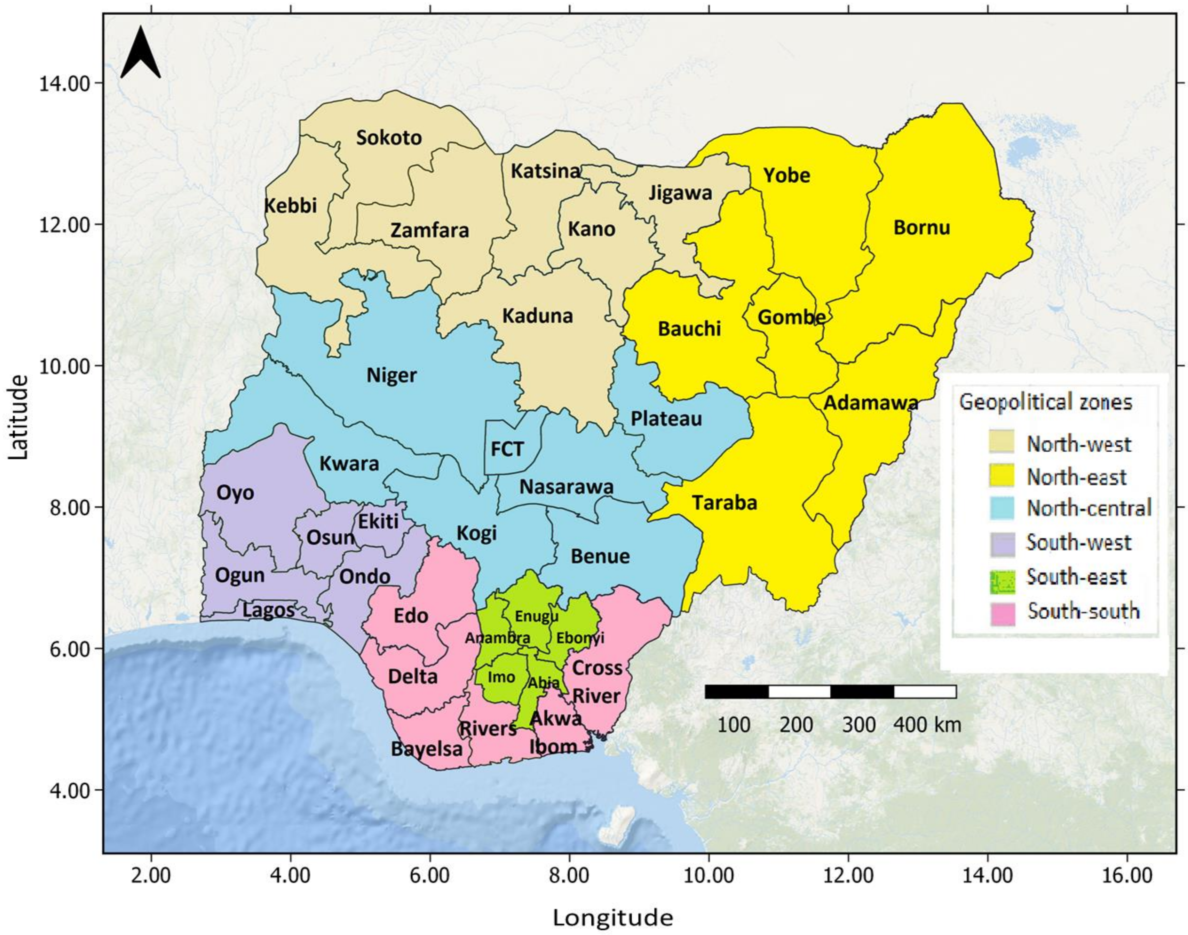

Figure 1: Map of Nigeria showing the 36 states and the Federal Capital Territory (FCT) and the 6 geopolitical zones of the country. *(Authors Drawings).*

Data source

The data analysed in this study were obtained from the most recent Nigeria Demographic and Health Surveys (NDHS) in 2018. The NDHS is nationally representative with respondents drawn from the Nigerian women population aged 15-49 years. Information on all children given birth to by the respondents within the last five years of the survey (National Population Commission(NPC)[Nigeria] & ICF International, 2019) is provided by the respondents. These data can be downloaded with permission from https:// dhsprogram.com

Sampling

The DHS uses a two-stage, stratified sampling design in all the 36 states in Nigeria and the FCT with the clusters as the primary sampling units. All eligible women of reproductive age (15-49 years) living in the selected households are interviewed. Sampling weights are added to account for unequal probability of selection at the cluster levels and to account for non-response since the samples are not self-weighting. Thus, these weights help to minimise non-response and selection biases. The questions asked included modules on primary information about households, sexual and reproductive health of the respondents and the birth history of the respondents.

Data

For this study, the NDHS “child recode data” which contained pregnancy, birth and post-birth morbidity and mortality history of all children born to the respondents within the last five years of the survey. After data cleaning, the data utilised in this study included a total sample size of 33,924 children aged 0-59 months.

Dependent variable

The outcome variable in this study is under-5 death and it is defined as a binary variable with one (1) indicating that the child died before attaining age 5 while zero (0) indicates that the child is alive. The U5MR is the measurement of the rate of under-5 death. It is the number of deaths among children aged 0-59 months per 1000 live births (National Population Commission(NPC)[Nigeria] & ICF International, 2019).

Explanatory Variables

Using the Mosley et al. conceptual framework which suggested that multiple factors including individual- and community-level factors should be used to examine a multitude of health outcomes among people of different ages including child survival (Mosley & Chen, 1984), the following explanatory variables were selected from the those that have been identified in earlier studies (Akinyemi, Bamgboye, et al., 2015; Alkema et al., 2014; Chao et al., 2018; Costa, Da

Silva, & Victora, 2017; Ezeh et al., 2015, 2014; Fagbamigbe & Alabi, 2014; Morakinyo & Fagbamigbe, 2017; Yaya et al., 2019, 2018, 2017). They are: Maternal age (15- 19, 20-24, 25-29, 30-39 and 40-49 years); maternal education (no education, primary, secondary or higher); Marital status (never married, living together/married and formerly married (widowed/divorced/separated)); Employment status (currently working or not working); Religion (Islam, Other Christians, Catholic and others); Ethnicity (Hausa/Fulani, Yoruba, Igbo and others); Sex of household head (male or female); Decision on mothers healthcare seeking (respondent alone, both, spouse alone); Problem in getting health care (big problem, not big problem); Media access (at least one of newspaper, magazine or radio); Sources of drinking water (unimproved and improved sources); Household wealth index (poorest, middle, and richest); House material (poor or good); Toilet type (improved and unimproved sources); Child sex (male or female); Birthweight (average/higher range, small, very small); Birth orders (1, 2-4, 4+); Birth intervals (1st birth, <36 month, 36 months+); Postnatal (No or Yes); Type of birth (singleton or multiple); Received tetanus Injection (No or Yes); and Place of residence (urban or rural).

We categorized the household wealth scores into three wealth tertiles (poorest, middle and richest). Whether a respondent encountered big problems in getting health care or not was aggregated from three factors (whether there are big problems in distance to health care, affordability of health care services and getting permission to go for health care). Any respondent that claims to have big problems in any of the three were regarded as having big problems accessing health care. We used the 2010 WHO and UNICEF guidelines as documented in the 2018 NDHS to determine whether or not housing materials and progress on sanitation and drinking water (Morakinyo & Fagbamigbe, 2017; National Population Commission(NPC)[Nigeria] & ICF International, 2019). We categorized whether housing materials are good or not from the flooring, wall and roofing materials used. The “source of drinking water” was grouped into either improved (piped into dwelling/yard/plot, public tap/standpipe, tube-well or borehole, protected well and spring, rainwater, and bottle water) while others are unimproved sources. The improved toilet types are “flush/pour flush to piped sewer system”, “flush/pour flush to septic tank”, “flush/pour flush to pit latrine”, “ventilated improved pit latrine”, “pit latrine with slab or composting toilet” while any other types are unimproved types.

Data analysis

The descriptive statistics of the maternal, children, biological and household characteristics were obtained using Stata Version 16. The U5MR was computed using the "ltable" command in Stata based on life tables for survival analysis. Inferential analysis was done using Bayesian geo-additive regression models.

Lifetable methods in Survival analysis for calculating childhood mortality rates

The event for children alive by their 5th birthday were right-censored and coded 0 at the censoring times T_i, while the events for children who died before attaining their 5th birthday were coded 1 at the failure time T_i. The "ltable" command treats censored observations as if they were withdrawn halfway through an interval q. The survival data are grouped into intervals given by $t_j,\ j = 1 \ldots\ldots\ldots J$, and $t_{j+1} = \infty$ for right censoring. Each interval contains counts for $t_j \leq \tau < t_{j+1}$. The number of deaths in distinct interval j is d_j, and m_j is the number of censored children within interval j, and N_j is the number alive at the beginning of interval j. The adjusted number at risk at the beginning of interval j is then defined as $n_j = N_j - m_j/2$, that is, we subtract half of the censored events. We estimated the survival function using the product-limit estimate

$$S_j = \prod_{k=1}^{j} \frac{n_q - d_q}{n_q}$$

where q is a specific interval. The U5MR is computed as $1000 * (1 - S_j)$ with corresponding asymptotic standard error computed from the "natural" units for the survivor function $\left(\log\left(-\log(S_j)\right)\right)$ as defined in equation (1)

$$\hat{S}_j = \sqrt{\frac{\sum d_q/\{n_q(n_q - d_q)\}}{[\sum \log\{(n_q - d_q)/n_q\}]^2}} \ldots\ldots\ldots\ldots (1)$$, (Kalbfleisch & Prentice, 2002).

The Bayesian geo-additive model

To simultaneously address the questions on the effects of key socio-economic and socio-demographic factors and the potential effects of geographical location on a child's likelihood of dying before age 5, we employed hierarchical Bayesian geo-additive regression models. Specifically, our model is a binomial regression in which the binary response y_{ij} takes the value of 0 if child (ij) aged < 5 years is alive or 1 if the child died before age 5 ($i =$

$1, \dots, S; j = 1, \dots, n$). Here, S $(= 37)$ is the number of states in Nigeria in addition to the federal capital territory (FCT) which are the geographical units of interest. Thus, y_{ij} is said to be Bernoulli distributed with a probability of success π_{ij}, where in this case, π_{ij} is the probability that a randomly selected child died before age 5. Mathematically, we write that $y_{ij} \sim Bernoulli(\pi_{ij})$ with $\mu_{ij} = E[Y_{ij}|\pi_{ij}] = \pi_{ij}$ and $Var(Y_{ij}|\pi_{ij}) = \pi_{ij}(1 - \pi_{ij})$. Also, the probability mass function (pmf) of the response is given by

$$f(y; \pi) = \pi^{y}(1 - \pi)^{1-y} \quad for \;\; y \in \{0, 1\} \qquad (2)$$

In the class of the semi-parametric geo-additive mixed models utilized in this study, the response variable y depends on a set of covariates through a linear predictor η_{ij} linked to a function of its mean with a link function $g(\mu_{ij})$ (Brezger, 2006; N. B. Kandala et al., 2019; Kneib & Fahrmeir, 2006) as defined in equation (3).

$$\eta_{ij} = f_1(x_{ij1}) + \cdots + \; f_p(x_{ijp}) + f_{spat}(s_i) \;\; z'_{ij}\gamma + \omega_i \qquad \ldots (3)$$

Such that $\mu_{ij} = g^{-1}(\eta_{ij})$ is the inverse logit link function, $f_1, \dots, f_p$ are the non-linear (not necessarily smooth) functions of continuous covariates $x_{ij1}, \dots, x_{ijp}$ (e.g., maternal age); $f_{spat}(s_i)$ is the (non-parametric) function of the spatial covariate $s_i \in \{1, \dots, S\}$ corresponding to the ith geographical location which accounts for the total unobserved effects of geographical locations.; $z_{ij}{'s}$ are individual-specific variables that are not continuous (e.g., Gender, Educational level, Wealth index, etc) and γ is the corresponding coefficients vector . The term ω_i is the cluster (state) level random effect which accounts for unobserved effects of the survey design not explained by $f_{spat}(.)$ and assumed to be zero mean Gaussian, that is, $\omega_i \sim Normal(0, \sigma_\omega^2)$ where the variance parameter σ_ω^2 is to be estimated. Examples of the usage are replete in the literature (Gelman & Little, 1997; Little, 1993, 2012; Malec, Davis, & Cao, 1999; Molina, Nandram, & Rao, 2014; Rao & Molina, 2015; Si, Pillai, & Gelman, 2015; Sugasawa, 2020; Zhang et al., 2014).

According to the first law of Geography which states that "Everything else is related to each other but near objects are more similar than the ones further apart" (Tobler, 1970), it makes sense that assume that the geographical locations (states) that are near to each other are more similar and it is no longer appropriate to assume that the observations in such locations are independent. On the other hand, it is reasonable to assume that the observations in the states that are further apart are independent and do not share common boundaries and characteristics. As a result, to simultaneously account for the inherent spatial autocorrelations between states that are neighbours and the spatial independence between states that are further apart, we split, the spatial effect f_{spat} in (2) into a spatially correlated (structured) $f_{str}(.)$ and an uncorrelated (unstructured) $f_{unstr}(.)$ effect as shown in Equation 4.

$$f_{spat}(s_i) = f_{str}(s_i) + f_{unstr}(s_i) \ldots\ldots\ldots\ldots\ldots\ldots.(4)$$

One key advantage of the decomposition in (4) is that it allows the quantification of spatial dependency in the data so the two effects can be compared. A higher unstructured effect suggests that spatial dependency is smaller and vice versa. All functions are centred on zero to enhance easy identification. We provide further details on these models including details on the Bayesian inference of the model parameters via Markov Chain Monte Carlo (MCMC) techniques in the Appendix.

The research questions outlined above were simultaneously addressed using equations (5) and (6). While equation (5) tests the unadjusted (without controlling for other covariates) effects of the spatial geography, equation (6) tests the adjusted (in addition to other key covariates) effects of the spatial location while simultaneously controlling for the effects of individual- and community-level covariates.

Unadjusted model:

$$u5m_i \sim f_{str}(state_i) + f_{unstr}(state_i) \qquad (5)$$

Adjusted model:

$$u5m_i \sim f_{str}(state_i) + f_{unstr}(state_i) + Ethnicity + Gender + \cdots + f(Age) \qquad (6)$$

where $u5m_i$ is the response variable which takes the value of 1 if the i^{th} child died before age 5, and 0, otherwise.

The models were then fitted in R statistical programming software version 3.6.1 using R2BayesX (Umlauf, Adler, Kneib, Lang, & Zeileis, 2015), the R interface BayesX, a popular statistical software for fitting various classes of generalized additive mixed models (Belitz, Brezger, Kneib, & Lang, 2011). Further details of these methods are provided as an Appendix.

Finally, model fit assessment and selection were based on the Deviance Information Criterion (DIC) (Spiegelhalter, Best, Carlin, & Van der Line, 2002) and the results based on the models with the smallest DIC (best fits) are presented and discussed.

Results

Of the 33,924 under-5 children included in our sample, about 39% of the children are from mothers aged 30-39 years, while up to 28% of children have mothers aged 25-29 years. Nearly half (46%) of the children are from mothers with no education, 61% are from mothers with access to media, while 96% are singletons as shown in Table 1. The overall U5MR was 131‰, highest (165‰) among teenage mothers and least among mothers aged 25-29 years (117‰). The U5MR among children whose mothers had no formal education was 170‰ compared with 63‰ among those with higher education; higher among male children (136‰) than female children (122‰). The rate was 312‰ among those from multiple births compared with 122‰ among singletons.

Table 1: Distribution of under-5 mortality rate by children family characteristics and health exposures in Nigeria

Characteristics	Weighted n	weighted %	U5MR per 1000 livebirths (‰)
Mother age			
15-19	1,449	4.3	*165
20-24	6,631	19.6	144
25-29	9,516	28.1	117
30-39	13,129	38.7	125
40-49	3,199	9.4	139
Mother education			
No formal education	15,734	46.4	*170
Primary	5,063	14.9	126
Secondary	10,331	30.5	85
Higher	2,796	8.2	63
Media access			
No	13,186	38.9	*157
Yes	20,738	61.1	110
Child sex			
Female	16,641	49.1	122
Male	17,283	51.0	136
Births			
Single	32,663	96.3	*122
Multiples	1,261	3.7	312
Household wealth tertiles			
Poorest	10,763	31.7	*169
Middle	11,133	32.8	139
Richest	12,029	35.5	78
Drinking-water sources			
Unimproved sources	11,379	34.0	*152
Improved sources	22,101	66.0	117
Toilet type			
Unimproved type	16,553	49.4	*146
Improved type	16,927	50.6	113
Ethnicity			
Hausa/fulani	15,629	46.1	*173

Yoruba	3,720	11.0	74
Igbo/ibiobio	4,722	13.9	83
Others	9,853	29.0	110
Religion			
Islam	21,536	63.5	*157
Other xtian	9,372	27.6	91
Catholics	2,836	8.4	78
Others	181	0.5	45
Marital status			
Never married	579	1.7	*81
Living together/married	32,350	95.4	129
Formerly married	995	2.9	157
Weight at birth			
Average/higher	28,742	86.1	*121
Small	3,695	11.1	166
Very Small	961	2.9	194
Birth orders			
1	6,573	19.4	*119
2-4	15,709	46.3	111
5+	11,642	34.3	160
Birth intervals			
1st Birth	6,573	19.4	*119
<36 months	17,282	51.0	149
36+ months	10,002	29.5	99
Postnatal care			
No	17,146	79.1	*110
Yes	4,525	20.9	65
Tetanus injection			
No	6,503	30.0	*131
Yes	15,184	70.0	87
Housing materials			
Poor	17061	51	*160
Good	16419	49	100
Mother employment			
Employed	22,930	67.6	*122
Unemployed	10,994	32.4	145
Region			
North Central	4,582	13.5	*110
North East	6,164	18.2	136
North West	12,459	36.7	187
South East	3,401	10.0	85
South South	2,945	8.7	70
South West	4,373	12.9	77
Location			
Urban	13067	38.5	*94
Rural	20857	61.5	148
Who Decide health care use			
Mothers alone	2985	9.3	*96
Both	9562	29.7	98
Spouse alone	19602	61.0	150
Accessing health care			
Not big problem	15868	46.8	*116
Big problem	18056	53.2	140
Total	33,924	100	131

*significant at 95% chi-square test

Figure 2 shows the spatial distribution of U5MR across Nigerian states in Nigeria and the FCT. The map shows that apart from Borno state, under-5 death is more prevalent among Northern states than Southern states with Kebbi and Jigawa states having the highest U5MR, while Ogun and Bayelsa states have the least rates.

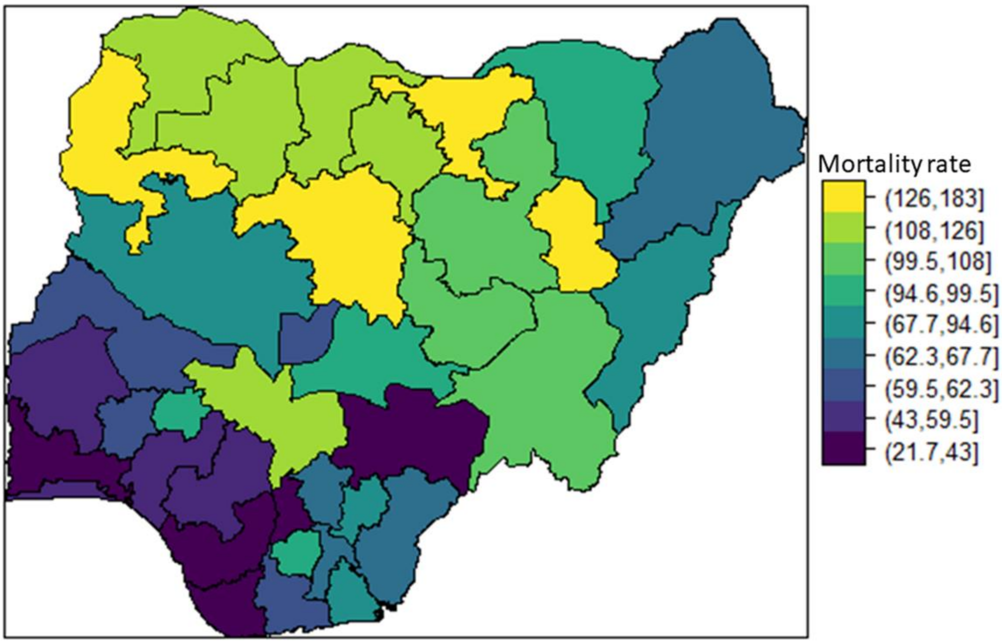

Figure 2: Spatial distribution of under-5 death across Nigerian states and the FCT. Dark blue to light yellow indicate lowest to highest rates.

Of the 33,924 children born within 5 years before the data collection in 2018, 6.0% are from Kano, 4.4% in Jigawa and lowest in Cross-Rivers with 1.3%. The overall estimated U5MR was 131‰ (95% CI: 127‰-135‰) per 1000 livebirths. The highest U5MR was in Kebbi (248‰), Jigawa (212‰), Kogi (191‰), and Kaduna (187‰) while the lowest U5MR was in Ogun (29‰), Bayelsa (37‰), Anambra (50‰) and Delta (53‰) as shown in Table 2 and Figure 1. Compared with Ogun that had the lowest U5MR, highest odds of under-5 death was 11 (POR=11.01, 95% CrI= 6.08 – 22.83) times higher in Kebbi, and 8 (POR=7.90, 95% CrI= 3.92 - 16.20) times higher in Jigawa as shown in Table 2.

Table 2: Distribution of under-5 death by states in Nigeria and the odds of under-5 death in each state

State	n (%)	U5MR Per 1000 live births (‰) (95% CI)	Unadjusted POR (95% CrI)
Ogun	508 (1.5)	29 (15 - 44)	Reference
Bayelsa	570 (1.7)	37 (23 - 59)	1.46 (0.64 - 3.62)
Anambra	856 (2.5)	50 (35 - 69)	1.95 (0.97 - 4.05)
Delta	508 (1.5)	53 (33 - 84)	1.94 (0.89 - 4.38)
Benue	908 (2.7)	60 (40 - 91)	*2.13(1.06 - 4.51)
Lagos	807 (2.4)	69 (52 - 91)	*2.99 (1.41 - 6.97)

Cross River	428 (1.3)	71 (49 - 102)	*3.22 (1.53 - 7.12)
Edo	465 (1.4)	71 (48 - 104)	*2.88 (1.37 - 6.16)
Osun	498 (1.5)	71 (49 - 103)	*2.98 (1.51 - 5.96)
Kwara	694 (2.1)	74 (55 - 98)	*3.09 (1.65 - 6.09)
Abia	641 (1.9)	75 (56 - 101)	*3.35 (1.67 - 7.03)
Oyo	656 (1.9)	76 (49 - 117)	*2.46 (1.23 - 5.01)
Rivers	667 (2.0)	77 (56 - 105)	*3.06 (1.55 - 6.44)
Enugu	561 (1.7)	78 (57 - 105)	*3.44 (1.69 - 7.20)
FCT, Abuja	803 (2.4)	79 (60 - 104)	*3.16 (1.64 - 6.45)
Borno	1099 (3.2)	86 (65 - 113)	*3.10 (1.38 - 6.52)
Ondo	542 (1.6)	96 (60 - 152)	*2.85 (1.48 - 5.72)
Ebonyi	1012 (3.0)	102 (75 - 137)	*3.56 (1.76 - 7.33)
Akwa Ibom	564 (1.7)	107 (81 - 140)	*4.71 (2.34 - 10.6)
Niger	1219 (3.6)	110 (90 - 133)	*4.40 (2.44 - 8.55)
Imo	728 (2.2)	114 (91 - 143)	*5.04 (2.47 - 10.9)
Ekiti	522 (1.5)	120 (91 - 156)	*5.06 (2.67 - 9.78)
Yobe	1252 (3.7)	127 (105 - 154)	*5.00 (2.3 - 10.15)
Adamawa	962 (2.8)	130 (102 - 164)	*4.93 (2.41 - 10.35)
Plateau	797 (2.4)	131 (105 - 164)	*5.28 (2.66 - 10.96)
Taraba	1112 (3.3)	139 (116 - 167)	*5.37 (2.83 - 10.57)
Nasarawa	834 (2.5)	140 (109 - 180)	*5.20 (2.79 - 10.29)
Bauchi	1442 (4.3)	149 (125 - 177)	*5.54 (2.90 - 10.95)
Zamfara	1226 (3.6)	151 (128 - 179)	*5.92 (3.20 - 11.91)
Kano	2037 (6.0)	168 (148 - 189)	*6.39 (2.66 - 12.92)
Katsina	1555 (4.6)	171 (146 - 200)	*6.08 (3.11 - 11.99)
Sokoto	1137 (3.4)	174 (146 - 207)	*7.14 (3.67 - 16.17)
Gombe	1344 (4.0)	175 (152 - 201)	*7.44 (3.52 - 14.88)
Kaduna	1451 (4.3)	187 (162 - 215)	*7.76 (4.33 - 15.06)
Kogi	620 (1.8)	191 (143 - 252)	*6.53 (3.54 - 12.33)
Jigawa	1502 (4.4)	212 (184 - 244)	*7.90 (3.92 - 16.20)
Kebbi	1397 (4.1)	248 (219 - 280)	*11.01 (6.08 - 22.83)
Total	33,924	131 (127 – 135)	

*significant at p<0.05, CI Confidence interval, ‰ per 1000, U5MR Under-5 death, CrI Credible Interval, POR Posterior Odds ratio

The frequentist unadjusted, individually spatial-adjusted and fully adjusted factors associated with under-5 death in Nigeria

The unadjusted odds ratios (ORs) from the bivariate frequentist logistic regression, the bivariate spatial-adjusted posterior odds ratios (PORs) and the fully adjusted PORs of the factors associated with under-5 death using Bayesian geo-additive regression model were presented in Table 3. In the unadjusted frequentist models (2nd column of Table 3), the factors associated with under-5 death were: from mothers aged 40-49 years (OR = 1.354, 95% CI= 1.189, 1.542), from mothers aged 15-19 years (OR = 1.230, 95% CI =1.023, 1.480), mother having no formal education (OR = 2.475, 95% CI = 2.073, 2.956), rural place of residence (OR = 1.522, 95% CI = 1.403, 1.652), from households in the poorest tertile (OR= 2.129, 95% CI = 1.935, 2.342) and from multiple births (OR = 3.623, 95% CI = 3.177, 4.132). Other significant factors are media access, sex of the child, source of drinking water, toilet type, ethnicity, religion, the zone of residence, marital status, receiving adequate tetanus injection, having postnatal care, weight at birth, birth order, preceding birth intervals, housing materials, the involvement of mothers in decisions regarding their health care and whether accessing health care was a big problem or not.

Bayesian spatial models

Here, we present the results obtained from the Bayesian spatial regression models fitted to the data. At the bivariate Bayesian geo-additive models (3rd column of Table 3), the posterior odds ratio (POR) of under-5 death were significantly higher among children from mothers aged 40-49 years (POR = 1.302, 95% Credible Interval (CrI)= 1.144, 1.483), from mothers aged 30-39 years (POR = 1.125, 95% CrI =1.023, 1.234), mother having no formal education (POR = 1.271, 95% CrI = 1.054, 1.537), secondary education (POR = 1.906, 95% CrI = 1.577, 2.316), rural place of residence (POR = 1.277, 95% CrI = 1.164, 1.401), from households in the poorest tertile (POR = 1.667, 95% CrI = 1.490, 1.884), with very small birthweight (POR = 2.032, 95% CrI = 1.721, 2.455) and from multiple births (POR = 3.793, 95% CrI = 3.313, 4.333). Other significant factors are media access, sex of the child, source of drinking water, toilet type, ethnicity, religion, the zone of residence, marital status, receiving adequate tetanus injection, having postnatal care, birth order, preceding birth intervals, housing materials, the involvement of mothers in decisions regarding their health care and whether accessing health care was a big problem POR not.

After adjusting for all other factors and spatial effect (4th column of Table 3), the likelihood of under-5 death increased with increasing maternal age with noticeable sharp increase among women older than 38 years. The odds of under-5 death was 44% higher (POR=1.442, CrI = 1.143-1.830) among children whose mothers had secondary education and 38% higher (POR=1.380, CrI =1.101-1.728) among mothers with only primary education than among those whose mothers had up to higher education. The odds of under-5 death among children from households in the poorest and middle wealth tertile were 36% (POR=1.362, CrI =1.192-1.555) and 43% (POR=1.426, CrI = 1.209-1.676) respectively higher than among those from households in the richest wealth tertile. Children from multiple births are about four times (POR=3.837, CrI =3.303-4.446) more likely to die before their 5th birthday than the singletons as odds of under-5 death was 16% (POR=1.162, CrI =1.075-1.257) higher among male children. The likelihood of under-5 deaths was 22% and 73% higher among children who had very small and small birth weight than those whose birthweights were average or higher. Odds of under-5 death doubled (POR=1.989, CrI =1.717-2.307) among firstborns and was 78% (POR=1.775, CrI =1.611-1.960) higher among those with less than 36 months preceding birth interval than those whose preceding birth intervals were 36 months or higher. The likelihood of under-5 death was 22% (POR=1.217, CrI =1.029-1.430) higher among children whose fathers are the sole decision-makers about their mothers' health care utilization compared with those where decisions are made by their mothers. Similarly, the odds of under-5 death was 9% (POR=1.091, CrI =1.001-1.191) higher among children whose mothers had big problems accessing health care facilities. However, the significant effects of drinking water sources, toilet type, ethnicity and rural-urban place of residence in the bivariate models disappeared in the fully adjusted model.

Table 3: Unadjusted and adjusted factors associated with under-5 death in Nigeria

Characteristics	**Frequentist approach**	**Bayesian Geo-additive model**	
	OR (95% CI)	**POR (95% CrI)**	**aPOR (95% CrI)**
Mother Age			
15-19	1.230(1.023, 1.480)*	1.117(0.925, 1.346)*	See Figure 4
20-24	1.195(1.073, 1.331)*	1.124(1.007, 1.251)*	
25-29	Reference		
30-39	1.095(0.997, 1.201)	1.125(1.023, 1.234)*	
40-49	1.354(1.189, 1.542)*	1.302(1.144, 1.483)*	
Maternal education			
No formal education	2.475(2.073, 2.956)*	1.271(1.054, 1.537)*	1.159(0.942, 1.431)
Primary	1.873(1.543, 2.274)*	1.702(1.401, 2.079)*	1.380(1.101, 1.728)*
Secondary	1.287(1.067, 1.551)*	1.906(1.577, 2.316)*	1.442(1.143, 1.830)*
Higher	Reference		
Media access			
No	1.458(1.356, 1.568)*	1.181(1.089, 1.281)*	0.986(0.898, 1.082)
Yes	Reference		
Child sex			
Female	Reference		
Male	1.127(1.048, 1.212)*	1.141(1.061, 1.228)*	1.162(1.075, 1.257)*
Births			
Single	Reference		
Multiples	3.623(3.177, 4.132)*	3.793(3.313, 4.333)*	3.837(3.303, 4.446)*
Household wealth tertiles			
Poorest	2.129(1.935, 2.342)*	1.501(1.347, 1.675)*	1.362(1.192, 1.555)*
Middle	1.750(1.586, 1.931)*	1.667(1.490, 1.884)*	1.426(1.209, 1.676)*
Richest	Reference		
Drinking-water sources			
Unimproved sources	1.290(1.198, 1.389)*	1.130(1.044, 1.222)*	1.021(0.934, 1.114)
Improved sources	Reference		
Toilet type			
Unimproved type	1.271(1.181, 1.368)*	1.174(1.083, 1.271)*	1.004(0.907, 1.108)

Improved type	Reference		
Ethnicity			
Hausa/Fulani	2.317(1.982, 2.709)*	1.330(1.025, 1.721)*	1.032(0.757, 1.395)
Yoruba	Reference		
Igbo/Ibiobio	1.151(0.956, 1.386)*	1.022(0.752, 1.394)	1.003(0.706, 1.388)
Others	1.436(1.220, 1.689)*	1.130(0.882, 1.447)	0.949(0.712, 1.256)
Religion			
Islam	1.664(1.525, 1.814)*	1.155(1.018, 1.314)*	1.058(0.909, 1.229)
Other Christian	Reference		
Catholics	0.807(0.679, 0.959)*	0.807(0.668, 0.971)*	0.745(0.602, 0.915)*
Others	0.550(0.300, 1.011)	0.478(0.244, 0.875)*	0.303(0.130, 0.637)*
Marital status			
Never married	Reference		^^Dropped
Living together/married	1.530(1.125, 2.081)*	1.146(0.840, 1.603)	
Formerly married	2.016(1.408, 2.888)*	1.641(1.133, 2.403)*	
Weight at birth			
Average/higher	Reference		
Small	1.432(1.283, 1.598)*	1.369(1.222, 1.536)*	1.223(1.080, 1.382)*
Very small	1.953(1.652, 2.308)*	2.032(1.721, 2.455)*	1.729(1.439, 2.079)*
Birth orders			
First birth	1.134(1.024, 1.256)*	1.160(1.047, 1.287)*	^^Dropped
2-4	Reference		
5+	1.461(1.347, 1.583)*	1.272(1.172, 1.380)*	
Birth intervals			
First birth	1.336(1.192, 1.497)*	1.409(1.256, 1.575)*	1.989(1.717, 2.307)*
<36 months	1.644(1.502, 1.799)*	1.566(1.429, 1.718)*	1.775(1.611, 1.960)*
36+ months	Reference		
Postnatal care			
No	1.818(1.548, 2.141)*	1.702(1.443, 2.019)*	$^{+}$Dropped
Yes	Reference		
Tetanus injection			
No	1.552(1.386, 1.737)*	1.434(1.271, 1.621)*	$^{+}$Dropped
Yes	Reference		
Housing materials			
Poor	1.596(1.480, 1.720)*	1.294(1.185, 1.415)*	^^Dropped
Good	Reference		
Mother employment			
Employed	Reference		
Unemployed	1.146(1.062, 1.236)*	0.944(0.871, 1.024)	^Dropped
Location			
Urban	Reference		
Rural	1.522(1.403, 1.652)*	1.277(1.164, 1.401)*	1.084(0.969, 1.211)
Who Decide health care use			
Respondent alone	Reference		
Both	1.026(0.872, 1.206)	1.139(0.963, 1.348)	1.165(0.974, 1.386)
Spouse	1.525(1.311, 1.774)*	1.234(1.052, 1.455)*	1.217(1.029, 1.430)*
Accessing health care			
Not a big problem	Reference		
Big problem	1.215(1.128, 1.308)*	1.226(1.129, 1.328)*	1.091(1.001, 1.191)*

CI Confidence Interval, CrI Credible Interval, OR Odds Ratio, POR Posterior Odds ratio, aPOR Adjusted Posterior Odds Ratio, *Significant at $p<0.05$, ^^Dropped due to multicollinearity, $^{+}$Captured for only last births, $^{\wedge}$insignificant at unadjusted level

Furthermore, in Figure 3, we show the posterior mean total spatial effects (top) for both unadjusted (left) and adjusted (right) models with the corresponding significance maps (bottom) for the estimates. For these maps, dark blue to light yellow represents a low risk to high risk. Also, black, white and grey correspond to significantly high risk, significantly low risk and states with non-significant spatial effects, respectively. Significantly high-risk states included Kebbi, Kaduna, Jigawa, Kaduna and Gombe states, while the states with the lowest likelihood of under-5 death are Ogun, Bayelsa, Anambra, Delta, and Benue.

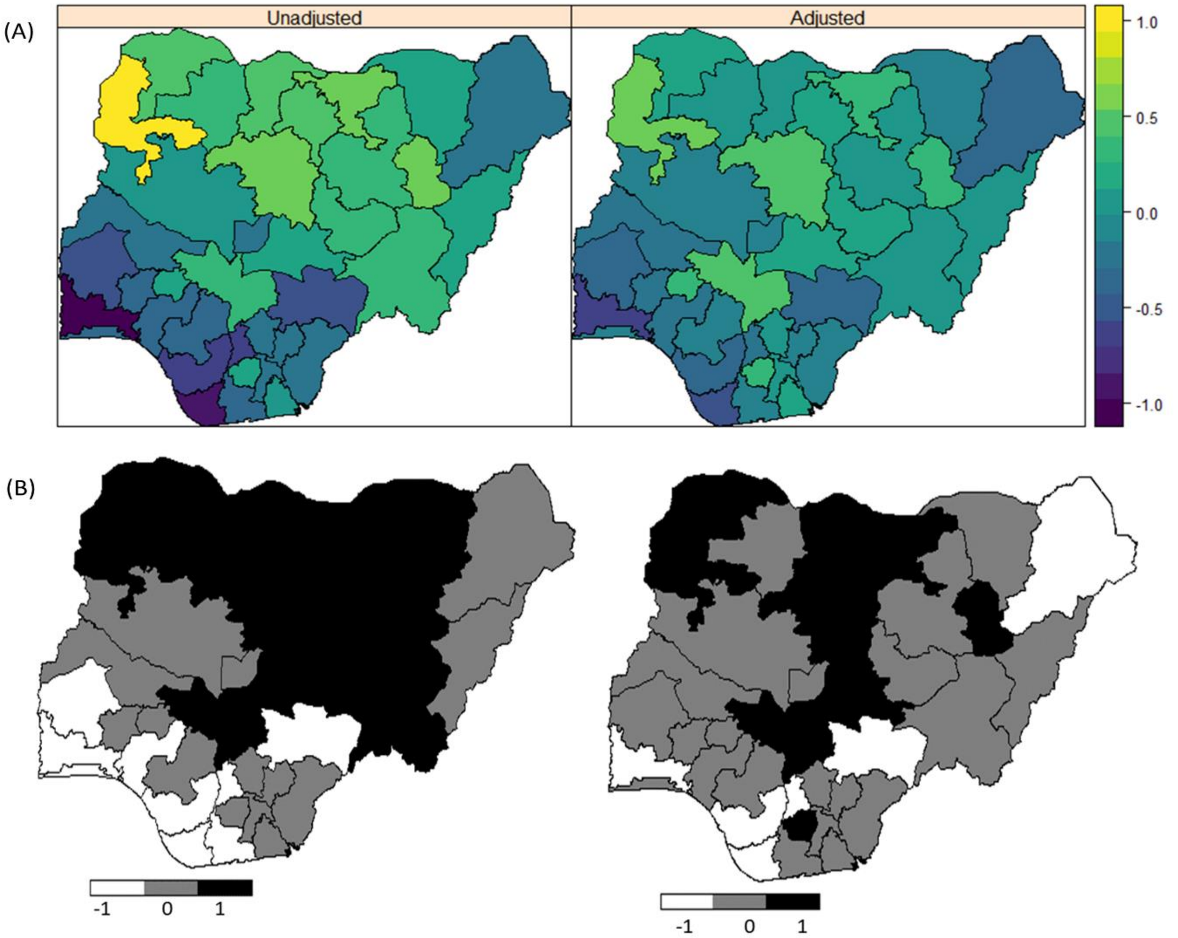

Figure 3: Unadjusted (left) and adjusted (right) total spatial effects (A) with the corresponding 95% posterior estimates significance map (B). Dark blue to light yellow indicate lowest to highest risk; black indicates states with a significantly high risk of under-5 death. White is significantly low risk and grey are non-significant.

Non-linear effects of maternal age are presented in Figure 4 which suggested that a child's likelihood of dying before the age of 5 increases as the mother's age increases. In particular, children born to younger mothers are less likely to die before age 5 than those born by mothers that are 38 years old and older.

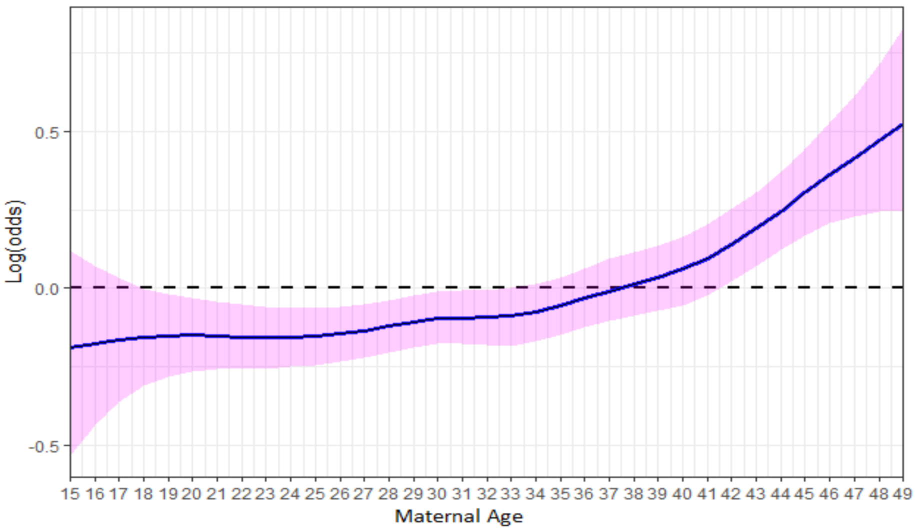

Figure 4: Posterior estimates of the non-linear effects (log-odds) of maternal age on under-5 death from the adjusted model. The blue line is the mean log(odds). while the band is the 95% credible interval width.

Discussions

In this study, we have used an advanced statistical approach which allowed for multiple adjustments of potential drivers of under-5 death in Nigeria while simultaneously controlling for the effects of the geographical location of the States where a child lived on the likelihood of the child dying before celebrating $5th$ birthday. Specifically, we used a unit-level Bayesian hierarchical regression model to estimate the parameters of interest conditional on the survey design variables while at the same time allowed for more precise aggregation of quantities at the state levels. We carried out statistical inference using via MCMC techniques allowing a straightforward prediction of unsampled locations. Thus, our approach has the advantage of flexibility, high precision and is devoid of the problem of benchmarking of estimates often associated with most area-level models as reported earlier (Little, 2012). Results show that the key drivers of under-5 death in Nigeria are –maternal age, maternal educational attainment, household wealth status, multiple births, birth intervals, who decides mothers' health care access and whether health care accessibility was a big problem or not as these factors have significant posterior odds ratio. Besides, the results show that a child born by a mother aged 38 and over is more likely to die before age 5 than another child born at a younger maternal age. Higher likelihoods of dying before age 5 were found among male children, children who lived in the northern part of the country, children who were born by an older mother, children who were from poorer households, children born with small birthweights, children born within 36 months birth interval, children who lived in the northern states, and children who were part of multiple births.

Our finding that childhood mortality is higher among males than the females is in agreement with existing literature. Besides, a systematic assessment of National, regional, and global sex ratios of infant, child, and under-5 mortality identified significant differences among boys and girls (Alkema et al., 2014). The authors reported that the likelihood of survival among under-5 children improved rapidly among girls than the boys as total mortality decreased. There are needs for in-depth qualitative studies on why male children die more than female children in Nigeria.

On the association between under-five deaths and household wealth tertiles, we found disparities in the survival of children among households from the poorest and richest wealth households. This finding was corroborated by the reports of Chao et al. relative differences exist in under-5 mortality rate between the poorest and richest households in LMIC (Chao et al., 2018). It is also in agreement with existing literature (Acácio et al., 2019; Fagbamigbe & Akinyemi, 2016; Fagbamigbe et al., 2015; UN Inter-agency Group for Child Mortality, 2019; You, New, & Wardlaw, 2010). A recent study by Morakinyo & Fagbamigbe, 2017) found that in Nigeria, children from poor households are more likely to have limited or no access to food and adequate care, and often live in unhealthy environments (Morakinyo & Fagbamigbe, 2017). Nigeria is one of the countries with the widest gaps in the study (Chao et al., 2018). It is particularly worse in Nigeria where most health care is paid for. Inability to pay could result in overreliance on self-medication or patronage of quacks thereby increasing the risk of a child who is in an urgent need of medical help dying before age 5. Parents from poor households may lack access and financial power to procure basic healthcare for their children since health insurance coverage in Nigeria is less than 20%. This finding suggests that poverty is one of the top causes of under-5 death in Nigeria. Targeted interventions aimed at improving the livelihood of people from poorest households are needed to narrow the rich-and-poor gap in under-5 mortality rate in Nigeria.

Furthermore, in terms of the effects of geographical location, evidence based on the adjusted model suggests that there is a significant effect of the location (states) in which a child lives on their likelihood of dying before age 5. Hotspots are identified as the states with a significantly high likelihood of under-5 death, and these states include Kebbi, Jigawa, Kaduna, Gombe, Kogi and Imo states. These states have significant effects on under-5 death.

These findings from this study are in line with previous studies (Adebowale et al., 2020; Adedini, Odimegwu, Imasiku, & Ononokpono, 2015; Akinyemi, Bamgboye, et al., 2015;

Dejene & Girma, 2013; Fagbamigbe & Akinyemi, 2016; Kayode, Adekanmbi, & Uthman, 2012; Morakinyo & Fagbamigbe, 2017; WHO, 2020; Yaya et al., 2018). Specifically, in the study of under-5 death on 5 sub-Sahara African (SSA) countries by Yaya et al., it was found that under-5 death varied significantly across Chad, Democratic Republic of Congo, Mali, Niger and Zimbabwe (Yaya et al., 2018). Also, the study by Adebowale et al. found that the U5MR differed across the 21 SSA countries considered in their study (Adebowale et al., 2020). They reported that under-5 death ranged from 56/1000 livebirths in South Africa to 190/1000 livebirths in Sierra-Leone. Similarly, a recent examination of trends and drivers of neonatal, infant and under-5 mortalities in Nigeria from 2003 to 2013 identified that childhood mortality differed across the 6 geopolitical zones in Nigeria (Morakinyo & Fagbamigbe, 2017). These studies used different methodologies. Yaya et al. used survival analysis method, Morakinyo et al. used probit regression model with associated marginal effects (Morakinyo & Fagbamigbe, 2017) while Adebowale et al. used Cox-proportional hazard model and Brass-adjusted model to identify risk factors associated to under-5 death (Adebowale et al., 2020). All these studies incorporated the regions where the children lived as one of the controlled variables in their models but none of them considered the spatial effects of the geographical location on under-5 death. Although the use of geo-additive regression models has been used for modelling prevalence of FGM among 0-14 years old girls and 15-49 years old women in the Nigerian context (N.-B. Kandala et al., 2009), its application in tackling the issue of under-5 death is still underdeveloped. We attempted to fill this gap by taking extra steps further to simultaneously account for both spatial independence and spatial autocorrelation in a coherent Bayesian geo-additive regression framework.

Maternal educational attainment had a significant effect on U5M. The odds of under-5 death was significantly higher among children whose mothers had lower educational attainment. Nonetheless, under-5 death was not significantly different among mothers with no formal education compared with mothers that had at least higher than secondary education. Overall, education remains a gateway to information, exposure and perhaps socio-economic well-being that could help reduce under-5 death (Akinyemi, Adebowale, Bamgboye, & Ayeni, 2015; Yaya et al., 2019).

Also, our finding that the odds of under-5 death was higher among male children than female children is interesting. Similar assertions have been made in an earlier study of 21 SSA countries (Adebowale et al., 2020). There may be a need for further research on biological differentials among male and female children that could help explain the differences. Besides, a qualitative study on mothers' perception and attitude to male and female children may help to better understand this.

Prominent among our findings is that odds of under-5 death was higher among children from multiple births compared with the singletons. The largest gap in U5MR across the explanatory variables considered in this study was in multiple/singleton divides (312/1000 livebirths versus 122/1000 livebirths) with nearly 300% higher POR in the adjusted inferential analysis. This suggests that multiple births are particularly endangered to under-5 death and should be given special attention in terms of parental support and health care as most multiple births have small birthweights (American Society for Reproductive Medicine, 2012; Mukabutera et al., 2016). Our study also established that children with small or very small birth weight are at higher odds of under-5 death. This was corroborated by an earlier study (Yaya et al., 2019).

Also, it was found that women autonomy is a major barrier to children survival in Nigeria. We found children whose fathers alone make decisions on their mothers' health care utilization to have 22% higher likelihood of under-5 death compared with when such decisions were made by the mothers alone. This is in agreement with the findings of Adhikari et al. (Adhikari & Sawangdee, 2011). Besides, Doku et al. have associated women's empowerment at both the individual and population levels with childhood mortality in LMICs (Doku, Bhutta, & Neupane, 2020). Closely related to this finding was the higher odds of under-5 death found among children whose mothers had big problems accessing health care facilities. The studied problems are health care accessibility, affordability and obtaining permission to go from spouses.

We found significant variations in the likelihood of under-five deaths across the various geographical locations in Nigeria. The odds of under-five deaths was 11 times higher in Kebbi than in Ogun state. Generally, the odds of under-five deaths are higher in the Northern states than in the Southern states. The 15 states with the highest burden of under-five deaths in Nigeria are all from the Northern part of Nigeria. These findings could be ascribed to the fact that the northern states have poorer utilization of maternal and child healthcare in Nigeria over the years (National Population Commission(NPC)[Nigeria] & ICF International, 2009, 2014, 2019). There are needs for these states with a high burden of under-five deaths to learn and adapt what is working in the states with a much lower burden. Although we strongly advocate intervention to mitigate under-five death across all the states in Nigeria.

In closing, these findings highlight key important points that require urgent attention: There is now an urgent need to extend more comprehensive interventions to these identified high-risk states targeting poor families, children from multiple births and those with low birth weights - There is also need for women empowerment and other programs aimed at educating families, especially the fathers, on the need to visit qualified medical experts for health care.

Finally, despite all concerted efforts by the Nigerian government, international organisations and civil society/non-governmental organisations in maternal and child health to improve childhood survival in Nigeria, under-5 death has remained higher than the global average. The current study has helped to identify geographical ‘hotspots’ as well as the key factors driving the under-5 mortality rate in Nigeria to inform the effective design and implementation of timely and efficient interventions.

Our study has identified the spatial pattern of under-5 deaths in Nigeria. In addition, we assessed the individual, household and state-level factors associated with under-5 deaths in the country. The knowledge of the hotspots of under-5 deaths in Nigeria will guide stakeholders in designing and channelling appropriate interventions that could help reduce avoidable deaths among under-5 children in Nigeria. Our findings and the suggested actions will aid Nigeria efforts to attain the SDG on health for all and to attain the specific target of reducing under-5 deaths to at least 25 per 1000 live births by 2030. This study is particularly important as we are not aware of any recent under-5 death study in Nigeria that applied geo-additive models to a recent Nigerian nationally representative under-5 data. More so, our study is a response to the United Nations call for multi-dimensional efforts to attain the several aspects of the SDG.

Strengths and limitations

A major strength of this study is the use of Bayesian geo-additive modelling framework that further revealed the place of spatial geographical locations in the burden of under-5 death in Nigeria. Besides, the use of a very recent nationally representative data made our findings on under-5 death in Nigeria generalizable. Nonetheless, a major drawback in this study is the cross-sectional study design, which lacks the power to establish causality. Also, the deaths and time of death were obtained from self-reported data which can blur the accuracy of results. For instance, stillbirths could have been mistaken for deaths within the first 24 hours of life and hence reduce the accuracy of the results. On the other hand, there might have been underreporting as some mothers may not wish to report such “unfortunate moments” in their lives and thereby rub “old injuries”. The secondary nature of the data used also limited our choices of explanatory variables.

Ethical clearance

The DHS publicly available data was used for the analysis. The Institutional review board granted ethical approval to ICF Macro to conduct the survey. While no further approval was required on the part of the authors, we obtained the express permission of the data owners (ICF, USA) to use the data. The data, as well as the ethical approval, is available at dhsprogram.com.

Conflict of Interest

The authors declare no conflict of interest

Abbreviations

Abbreviation	Full Meaning
CI	Confidence Interval
CrI	Credible Interval
FCT	Federal Capital Territory
GRF	Gaussian Random Field
NDHS	Nigeria Demographic Health Survey
DIC	Deviance Information Criteria
INMR	Infant Mortality Rate
IWLS	Iteratively Weighted Least Square
LMIC	Low- And Middle-Income Countries
MCMC	Markov Chain Monte Carlos
MRF	Markov Random Fields
NDHS	Nigeria Demographic Health Survey
NPC	National Population Commission
OR	Odds Ratio
POR	Posterior Odds Ratio
SDG	Sustainable Development Goal
UHC	Universal Health Coverage
U5MR	Under-five Mortality Rate

References

Abir, T., Agho, K. E., & Page, A. N. (2015). Risk factors for under-5 mortality: evidence from Bangladesh demographic and health survey, 2004–2011. *BMJ Open*, *5*(1), e006722. https://doi.org/10.1136/bmjopen-2014-006722.

Acácio, S., Mandomando, I., Nhampossa, T., Quintó, L., Vubil, D., Sacoor, C., … Bassat, Q. (2019). Risk factors for death among children 0-59 months of age with moderate-to-severe diarrhea in

Manhiça district, southern Mozambique. *BMC Infectious Diseases*, *19*(1), 1–14. https://doi.org/10.1186/s12879-019-3948-9

Adebowale, A. S., Fagbamigbe, A. F., Morakinyo, O., Obembe, T., Afolabi, R. F., & Palamuleni, M. E. (2020). Parental Educational Homogamy and Under-Five Mortality in Sub-Saharan Africa: Clarifying the Association's Intricacy. *Scientific African*, *7*(2020), e00255. https://doi.org/10.1016/j.sciaf.2019.e00255

Adedini, S. A., Odimegwu, C., Imasiku, E. N. S., & Ononokpono, D. N. (2015). Ethnic differentials in under-five mortality in Nigeria. *Ethnicity & Health*, *20*(2), 145–162. https://doi.org/10.1080/13557858.2014.890599

Adeyele, I. T., & Ofoegbu, D. I. (2015). Infant and Child Mortality in Nigeria : An Impact Analysis, *3*(2), 122–132.

Adhikari, R., & Sawangdee, Y. (2011). Influence of women ' s autonomy on infant mortality in Nepal. *Reproductive Health*, *8*(1), 7. https://doi.org/10.1186/1742-4755-8-7

Akinyemi, J. O., Adebowale, A. S., Bamgboye, E. A., & Ayeni, O. (2015). Child survival dynamics in Nigeria: Is the 2006 child health policy target met? *Nigerian Journal of Health Sciences*, *15*(1), 18. https://doi.org/10.4103/1596-4078.171378

Akinyemi, J. O., Bamgboye, E. A., & Ayeni, O. (2015). Trends in neonatal mortality in Nigeria and effects of bio-demographic and maternal characteristics. *BMC Pediatrics*, *15*, 36. https://doi.org/10.1186/s12887-015-0349-0

Alkema, L., Chao, F., You, D., Pedersen, J., & Sawyer, C. C. (2014). National, regional, and global sex ratios of infant, child, and under-5 mortality and identification of countries with outlying ratios: A systematic assessment. *The Lancet Global Health*, *2*(9), e521–e530. https://doi.org/10.1016/S2214-109X(14)70280-3

American Society for Reproductive Medicine. (2012). *Multiple Pregnancy and Birth : Twins , Triplets , and High-order Multiples*. Washington, DC. Retrieved from https://www.reproductivefacts.org/news-and-publications/patient-fact-sheets-and-booklets/documents/fact-sheets-and-info-booklets/multiple-pregnancy-and-birth-twins-triplets-and-high-order-multiples-booklet/

Ayele, D. G., Zewotir, T. T., & Mwambi, H. G. (2015). Structured additive regression models with spatial correlation to estimate under-five mortality risk factors in Ethiopia Biostatistics and methods. *BMC Public Health*, *15*(1), 1–11. https://doi.org/10.1186/s12889-015-1602-z

Bado, A. R., Susuman, A. S., & Nebie, E. I. (2016). Trends and risk factors for childhood diarrhea in sub-Saharan countries (1990-2013): assessing the neighborhood inequalities. *Global Health Action*, *9*, 30166. https://doi.org/10.3402/gha.v9.30166

Belitz, C., Brezger, A., Kneib, T., & Lang, S. (2011). BayesX - Software for Bayesian Inference in Structured Additive Regression Models: Version 2.0.1. Retrieved from http://www.bayesx.org

Besag, J. E., York, J. C., & Mollié, A. (1991). Bayesian image restoration, with two applications in spatial statistics (with discussion). *Ann Inst Stat Math*, *43*, 1–59.

Brezger, A. L. (2006). Generalized Structured Additive Regression Based on Bayesian P-Spline. *Computational Statistics & Data Analysis*, *50*, 947–991.

Chao, F., You, D., Pedersen, J., Hug, L., & Alkema, L. (2018). National and regional under-5 mortality rate by economic status for low-income and middle-income countries: a systematic assessment. *The Lancet Global Health*, *6*(5), e535–e547. https://doi.org/10.1016/S2214-109X(18)30059-7

Costa, J. C., Da Silva, I. C. M., & Victora, C. G. (2017). Gender bias in under-five mortality in low/middle-income countries. *BMJ Global Health*, *2*(2). https://doi.org/10.1136/bmjgh-2017-000350

Dejene, T., & Girma, E. (2013). Social determinants of under-five mortality in Ethiopia: Event history analysis using evidence from Ethiopian Demographic and Health Survey (EDHS). *Health*, *05*(05), 879–884. https://doi.org/10.4236/health.2013.55115

Doku, D. T., Bhutta, Z. A., & Neupane, S. (2020). Associations of women ' s empowerment with neonatal , infant and under-5 income mortality in low- and / middle- - countries : meta- - analysis of individual participant data from 59 countries. *BMJ Global Health*, *5*(e001558), 1–11. https://doi.org/10.1136/bmjgh-2019-001558

Eilers, P. H. C., & Marx, B. D. (1996). Flexible smoothing with b-splines and penalties. Statistical Science.

Ezeh, O. K., Agho, K. E., Dibley, M. J., Hall, J. J., & Page, A. N. (2015). Risk factors for postneonatal, infant, child and under-5 mortality in Nigeria: a pooled cross-sectional analysis. *BMJ Open*, *5*(3), e006779. https://doi.org/10.1136/bmjopen-2014-006779

Ezeh, O. K., Agho, K. E., Dibley, M. J., Hall, J., & Page, A. N. (2014). Determinants of neonatal mortality in Nigeria: evidence from the 2008 demographic and health survey. *BMC Public Health*, *14*(1), 521. https://doi.org/10.1186/1471-2458-14-521

Fagbamigbe, A. F., & Akinyemi, J. O. (2016). Modelling the survivorship of Nigeria children in their first 10 years of life. *The Nigerian Health Journal*, *16*(1), 1–19. Retrieved from http://www.tnhjph.com/index.php/tnhj/article/view/194/pdf_1

Fagbamigbe, A. F., & Alabi, O. (2014). Differentials and Correlates of Infants Mortality in Nigeria : A Comparative Survival Analysis between North East and South West Nigeria. *International Journal of TROPICAL DISEASE & Health*, *4*(8), 869–886.

Fagbamigbe, A. F., Bamgboye, E. A., Yusuf, B. O., Akinyemi, J. O., Issa, B. K., Ngige, E., … Abatta, E. (2015). The Nigeria wealth distribution and health seeking behaviour : evidence from the 2012 national HIV / AIDS and reproductive health survey. *Health Economics Review*, *5*(5), e1–e10. https://doi.org/10.1186/s13561-015-0043-9

Fagbamigbe, A. F., Kandala, N. B., & Uthman, O. A. (2020a). Decomposing the educational inequalities in the factors associated with severe acute malnutrition among under-five children in low- and middle-income countries. *BMC Public Health*, *20*(555), 1–14. https://doi.org/10.1186/s12889-020-08635-3

Fagbamigbe, A. F., Kandala, N. B., & Uthman, O. A. (2020b). Severe acute malnutrition among under-five children in low- and middle-income countries: A hierarchical analysis of associated risk factors. *Nutrition*, *75–76*(2020), 110768. https://doi.org/10.1016/j.nut.2020.110768

Faust, L., Yaya, S., & Ekholuenetale, M. (2017). Wealth inequality as a predictor of HIV- related knowledge in Nigeria. *BMJ Glob Health*, *12*, e000461. https://doi.org/10.1136/bmjgh-2017-000461

Gelman, A., & Little, T. (1997). Postratification into many categories using hierarchical logistic regression. *Survey Methodology*, *23*(2), 127–135. Retrieved from https://www150.statcan.gc.ca/n1/pub/12-001-x/1997002/article/3616-eng.pdf

Gilks, W. R., & Wild, P. (2006). Adaptive Rejection Sampling for Gibbs Sampling. *Journal of the Royal Statistical Society, Series C - Applied Statistics*, *41*(2), 337–348. https://doi.org/10.2307/2347565

Kalbfleisch, J. D., & Prentice, R. L. (2002). *The Statistical Analysis of Failure Time Data* (2nd ed). New York: Wiley.

Kandala, N.-B., Nwakeze, N., & Ngianga, S. K. I. (2009). Spatial distribution of female genital mutilation in Nigeria. *Am J Trop Med Hyg*, *81*(5), 784–92.

Kandala, N. B., Nnanatu, C. C., & Atilola, G. (2019). A Spatial Analysis of the Prevalence of Female Genital Mutilation/Cutting among 0-14-Year-Old Girls in Kenya. *Int J Environ Res Public Health*, *16*(21), 4155. https://doi.org/10.3390/ijerph16214155

Kayode, G. A., Adekanmbi, V. T., & Uthman, O. A. (2012). Risk factors and a predictive model for under-five mortality in Nigeria: evidence from Nigeria demographic and health survey. BMC Pregnancy and Childbirth, 12(1):10, dec 2012. *BMC Pregnancy & Childbirth*, *12*(1), 10.

Klein, N., Kneib, T., Lang, S., & Sohn, A. (2015). Bayesian structured additive distributional regression with an application to regional income inequality in germany. *Annals of Applied Statistics*, *9*(2), 1024–1052.

Kneib, T., & Fahrmeir, L. (2006). Structured Additive Regression for Multicategorical Space-Time Data: A Mixed Model Approach. *Biometrics*, *63*, 109=118.

Little, R. J. A. (1993). Post-Stratification: A Modeler's Perspective. *Journal of the American Statistical Association*, *88*(423), 1001. https://doi.org/10.2307/2290792

Little, R. J. A. (2012). Calibrated Bayes, an Alternative Inferential Paradigm for Official Statistics. *Journal of Official Statistics*, *28*(3), 309–334.

Liu, L., Oza, S., Hogan, D., Perin, J., Rudan, I., Lawn, J., … Black, R. (2015). Global, regional, and national causes of child mortality in 2000–13, with projections to inform post-2015 priorities: an updated systematic analysis. *The Lancet*, *385*(9966), 430–440. https://doi.org/10.1016/s0140-6736(16)31593-8

Liu, L., Oza, S., Hogan, D., Perin, J., Rudan, I., Lawn, J., … Black, R. (2016). Global, regional, and national causes of under-5 mortality in 2000–2015: an updated systematic analysis with implications for the sustainable development goals. *The Lancet*, *388*(10063), 3027–3035. https://doi.org/10.1016/s0140-6736(16)31593-8

Malec, D., Davis, W. W., & Cao, X. (1999). Model-based small area estimates of overweight prevalence using sample selection adjustment. In *Statistics in Medicine* (Vol. 18, pp. 3189–3200). John Wiley and Sons Ltd. https://doi.org/10.1002/(SICI)1097-0258(19991215)18:23<3189::AID-SIM309>3.0.CO;2-C

Molina, I., Nandram, B., & Rao, J. N. K. (2014). Small area estimation of general parameters with application to poverty indicators: A hierarchical bayes approach. *Annals of Applied Statistics*, *8*(2), 852–885. https://doi.org/10.1214/13-AOAS702

Morakinyo, O. M., & Fagbamigbe, A. F. (2017). Neonatal , infant and under-five mortalities in Nigeria : An examination of trends and drivers (2003-2013). *PLoS ONE*, *12*(8), e0182990. https://doi.org/10.1371/journal.pone.0182990

Mosley, W. H., & Chen, L. C. (1984). An Analytical Framework for the Study of Child Survival in Developing Countries. *Population and Development Review*, *10*, 25. https://doi.org/10.2307/2807954

Mukabutera, A., Thomson, D. R., Hedt-gauthier, B. L., Basinga, P., Nyirazinyoye, L., & Murray, M. (2016). Risk factors associated with underweight status in children under five : an analysis of the 2010 Rwanda Demographic Health Survey (RDHS). *BMC Nutrition*, *2*(40), 1–12. https://doi.org/10.1186/s40795-016-0078-2

National Population Commission(NPC)[Nigeria] & ICF International. (2009). *Nigeria Demographic and Health Survey, 2008*. DHS Measure Macro, New York and Nigeria Population Commission, Abuja, Nigeria.

National Population Commission(NPC)[Nigeria], & ICF International. (2014). *Nigeria Demograhic Health Survey, 2013*. Abuja.

National Population Commission(NPC)[Nigeria], & ICF International. (2019). *Nigeria Demographic and Health Survey 2018*. Abuja, Nigeria, And Rockville, Maryland, USA.

Rao, J. N. K., & Molina, I. (2015). *Small Area Estimation* (2nd ed., Vol. 1). Hoboken, New Jersey: Wiley. Retrieved from https://www.wiley.com/en-gb/Small+Area+Estimation%2C+2nd+Edition-p-9781118735787

Si, Y., Pillai, N. S., & Gelman, A. (2015). Bayesian Nonparametric Weighted Sampling Inference. *Bayesian Analysis*, *10*(3), 605–625. https://doi.org/10.1214/14-BA924

Spiegelhalter, D., Best, N., Carlin, B., & Van der Line, A. (2002). Bayesian measures of models complexity and fit. J R Stat Soc B 2002; 64:, *64*, 1–34.

Sugasawa, S. (2020). Small area estimation of general parameters: Bayesian transformed spatial prediction approach. *Japanese Journal of Statistics and Data Science*, *3*(1), 167–181. https://doi.org/10.1007/s42081-019-00067-7

Tobler, W. (1970). A computer movie simulating urban growth in the Detroit region. *Economic Geography*, *46*(Supp), 234–240.

Umlauf, N., Adler, D., Kneib, T., Lang, S., & Zeileis, A. (2015). Structured Additive Regression Models: An R Interface to BayesX. *Journal of Statistical Software*, *63211–46*. Retrieved from http://www.jstatsoft.org/v63/i21/

UN Inter-agency Group for Child Mortality. (2019). *Level and Trends in Child Mortality*. New York.

UNICEF. (2020). Child-Survival: Under-five Mortality. Retrieved April 23, 2020, from https://data.unicef.org/topic/child-survival/under-five-mortality/

United Nations. (2015). *Sustainable Development Goals (SDG)*. Washington, DC. Retrieved from http://www.un.org/sustainabledevelopment/sustainable-development-goals/

United Nations Population. (2020). United Nations World Population Prospects 2019. Retrieved May 9, 2020, from https://population.un.org/wpp/Download/Standard/Population/

WHO. (2020). Under-five mortality. Retrieved May 9, 2020, from https://www.who.int/gho/child_health/mortality/mortality_under_five_text/en/

Yaya, S., Bishwajit, G., Okonofua, F., & Uthman, O. A. (2018). Under five mortality patterns and associated maternal risk factors in sub-Saharan Africa: A multi-country analysis. *PLoS ONE*, *13*(10). https://doi.org/10.1371/journal.pone.0205977

Yaya, S., Ekholuenetale, M., Tudeme, G., Vaibhav, S., Bishwajit, G., & Kadio, B. (2017). Prevalence and determinants of childhood mortality in Nigeria. *BMC Public Health*, *17*(1), 485. https://doi.org/10.1186/s12889-017-4420-7

Yaya, S., Uthman, O. A., Okonofua, F., & Bishwajit, G. (2019). Decomposing the rural-urban gap in the factors of under-five mortality in sub-Saharan Africa? Evidence from 35 countries. *BMC Public Health*, *19*(1), 1–10. https://doi.org/10.1186/s12889-019-6940-9

You, D., New, J., & Wardlaw, T. (2010). Levels and trends in child mortality. Report 2012. Estimates developed by the UN inter-agency Group for Child Mortality Estimation.

Zhang, X., Holt, J. B., Lu, H., Wheaton, A. G., Ford, E. S., Greenlund, K. J., & Croft, J. B. (2014). Multilevel regression and poststratification for small-area estimation of population health outcomes: A case study of chronic obstructive pulmonary disease prevalence using the behavioral risk factor surveillance system. *American Journal of Epidemiology*, *179*(8), 1025–1033. https://doi.org/10.1093/aje/kwu018

Appendix

In the Bayesian paradigm, the unknown functions f_j and parameters γ and the variance σ^2 or the precision $\tau^2 = 1/\sigma^2$ are treated as latent and random variables which are to be estimated. In general, Bayesian inference is performed by evaluating the posterior distribution$\pi(\theta|\boldsymbol{y},\boldsymbol{x})$**,** which may be approximate as the product of the joint likelihood function, $L(\theta;\boldsymbol{y},\boldsymbol{x})$ and the joint prior distributions $\pi(\boldsymbol{\theta})$, where $\boldsymbol{\theta}$ is a vector of the unknown parameters.

Furthermore, for our purpose, we assign independent diffuse priors to the parameters $\gamma_j \propto \text{const}, \text{j} = 1, \dots, \text{r}$ of the r fixed effects covariates, $z_i = (z_{i1}, z_{i2}, \dots, z_{ir})$. Although, highly dispersed Gaussian priors could still be used. Following Kandala et al., (N. B. Kandala et al., 2019).and to reflect spatial neighbourhood structure, we assigned Markov random fields (MRF) priors to the correlated spatial effect $f_{str}(s), s = 1, \dots, S$,(Besag, York, & Mollié, 1991). Note that the MRF prior is the spatial extension of random walk models and is defined by equation S1

$$f_{str}(s) \mid f_{str}(r)\ , r \neq s \sim N\left(\sum_{r\epsilon\delta_s} \frac{f_{str}(r)}{N_s}, \frac{\tau_{str}^2}{N_s}\right) \dots \dots (S1)$$

where N_s is the number of adjoining states to state s, and $r\epsilon\delta_s$ denotes that region r is a neighbour of region s. Hence the (conditional) mean of $f_{str}(s)$ is the average of functions $f_{str}(s)$ of the neighbouring regions, where τ_{str}^2 is a smooth parameter. On the other hand, we assign zero-mean independent and identically distributed Gaussian priors to the uncorrelated (unstructured) spatial effect $f_{unstr}(s)$ as equation

$$f_{unstr}(s) \mid \tau_{unstr}^2 \sim N(0, \tau_{unstr}^2), \dots \qquad \text{(S2)}$$

As before, we assign inverse gamma-distributed priors to the smooth parameters such that $p(\tau_j^2) \sim IG(a_j, b_j)$, where j here is a generic subscript representing both str and $unstr$ and where a and b are hyperparameters. Usually, the hyperparameters are chosen to be vague and in our case, we chose $a = b = 0.001$.

Furthermore, to estimate the smooth functions, $f_1, \dots, f_p$, we used cubic splines which are twice continuously differentiable piecewise cubic polynomials. However, the spline can be written as a linear combination of B-spline basis functions $B_m(x)$, the Bayesian version of the Penalized–Splines (P–Splines) proposed by Eilers et al., (Eilers & Marx, 1996), such that $f(x) = \sum_{m=1}^{l} \beta_m B_m(x)$. In our approach, this corresponds to *2nd* order random walks given by equation S3

$$\beta_m = 2\beta_{m-1} - B_{m-2} + \mu_m \ldots \ldots . \ldots \qquad (S3)$$

with Gaussian increments $\mu_m \sim N(0, \tau^2)$ which is estimated from data and where the smoothness parameter τ is also estimated from the data.

For Bayesian inference, samples $\boldsymbol{\theta} = (\{\boldsymbol{f}\}, \boldsymbol{f}_{\boldsymbol{unstr}}, \boldsymbol{f}_{\boldsymbol{str}},, \boldsymbol{\tau}_{\boldsymbol{unstr}}, \boldsymbol{\tau}_{\boldsymbol{str}})$ are drawn from the posterior distribution of the latent parameters $\pi(\boldsymbol{\theta}|\boldsymbol{x}, \boldsymbol{y})$ using Markov chain Monte Carlo (MCMC) simulation (Gilks & Wild, 2006). For our purpose, we used iteratively weighted least square (IWLS) proposal (Klein, Kneib, Lang, & Sohn, 2015; Kneib & Fahrmeir, 2006).

The models were then fitted in R statistical programming software version 3.6.1 using R2BayesX (Umlauf et al., 2015), the R interface BayesX, a popular statistical software for fitting various classes of generalized additive mixed models (Belitz et al., 2011). For our study, 20,000 samples were simulated from the posterior distributions. Then, after a burn-in period of 4000 iterations which was discarded on the assumption that the 4000 initial chains may not have converged at the stationary distribution, we summarized the posterior after selecting only every 10^{th} of the remaining 16000 samples. This is also called thinning. Both the burn-in and thinning are used to ensure that the posterior samples are approximately independent.

Using sensitivity analysis, we investigated the appropriateness of the MRF priors by fitting the spatial model using Gaussian Random Field (GRF) priors. However, we found no evidence of a better fit with the GRF. Besides, the sparseness introduced by the neighbourhood structure of the MRF of a particular computational advantage and greatly reduces computational costs.