

Priority setting for achieving Universal Health Coverage in Nigeria:
A Spatial and Temporal Analysis and Cost-Benefit Analysis

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Abstract

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Universal Health Coverage (UHC) is an urgent global priority outlined in the Sustainable Development Goals (SDGs) to ensure the accessibility of health services for all people without causing financial hardship. If current progress continues to 2030, 37% to 61% of the global population will not be covered by essential health services.¹ Therefore, we need to accelerate the increase of service coverage to achieve the UHC target by 2030.

There are three specific aims of this dissertation; 1) To identify both individual and contextual factors that are consistently associated with utilization of nine essential maternal and child health services (i.e., ANC, facility-based delivery, modern contraceptive use, immunizations, and childhood illnesses), across survey years and household geolocations, using five national representative cross-sectional surveys in Nigeria; 2) To estimate grid-level coverage of selected essential MCH services in Nigeria using generalized additive models (GAMs) and Gradient Boosting (GB) 3) To estimate required costs and avoidable child deaths by increasing selected essential health service coverage in each community, and to identify the priority sub-national areas.

This dissertation emphasizes the importance of multi-dimensional priority setting in achieving Universal Health Coverage in Nigeria. By identifying the factors influencing health service utilization, assessing regional disparities, estimating required costs, and quantifying potential impacts, policymakers can make evidence-based decisions to maximize the efficiency and effectiveness of healthcare interventions. The findings and recommendations of this research contribute to the broader global agenda of achieving UHC and improving health outcomes for all populations, particularly in low- and middle-income countries.

Introduction

Universal Health Coverage (UHC) is an urgent global priority outlined in the Sustainable Development Goals (SDGs) to ensure the accessibility of health services for all people without causing financial hardship. According to World Health Organization (WHO) monitoring report published in 2019, the UHC service coverage index (SCI) increased from 45% in 2000 to 66% in 2017 globally.¹ Thanks to increasing the rapid intervention coverage of infectious disease and maternal and child health interventions, the progress in lower-income countries have been most significant. However, the percentages covered by essential health services in low-income and lower-middle-income countries are 12-27% and 21-38%, respectively. Also, if current progress continues to 2030, 37% to 61% of the global population will not be covered by essential health services.¹ Therefore, we need to accelerate the increase of service coverage to achieve the UHC target by 2030.

A more effective policy and strategy can be created by identifying the characteristics of the underserved population who do not have access to health services. According to the analytical framework developed by Jacobs et al.⁵, there are four dimensions of access barriers along supply and demand sides; geographic accessibility, availability, affordability, and acceptability. Most of the demand-side barriers to health services are socioeconomic statuses (SES) such as income, education, and occupation. SES is a major influence over not only access to health services but also environmental exposure and health behavior.⁶ SES is associated with access to maternal and child health (MCH) services^{7,8}, while strong evidence supports the association between SES and non-communicable diseases (NCD).⁹ In addition to SES, other barriers such as information barrier, lack of health awareness, cultural preferences, low self-esteem and availability of means of transportation were included in the analytical framework.⁵ However, there are a few studies to assess the significant factors influencing multiple health services regardless of the geography and time.

In addition, the national-level health service coverage masks the subnational and community-level variation, which makes the policymakers difficult to identify the underserved community and to prioritize the interventions matched with each community's situation. Revealing regional disparity in health service coverage becomes important for LMICs to develop an efficient implementation strategy for each community.

According to the High-Level Taskforce on Innovative International Financing for Health System²⁹, additional around 60 USD on average worldwide will be required in 2015 for a package that included a mix of health services for both communicable and non-communicable diseases. The Lancet article estimated the required budget for achieving UHC in each country by estimating outpatient and inpatient utilization and unit costs of these services over time.³⁰ While the study identified the financial challenge to attain true UHC, the reference country was the Netherlands that provides a high-quality and wide range of health services to the population. The Netherlands' standard of health care would be not a realistic short-term goal for most LMICs. WHO also estimates that 170 billion USD a year for achieving the UHC.¹ While the global and national required cost for achieving UHC is estimated, sub-national and community-level estimates are not available. In order for low- and middle-income countries to generate these necessary costs, it is necessary to raise domestic resources and increase public spending on health as well as to receive continuous external aid. The detailed estimates of the required cost and potential impact of achieving UHC in each community would be useful to raise the resources, to efficiently allocate the limited budget, and to maximize the impact. It will also a effective communication tool for policy makers to prioritize the UHC agenda.

Nigeria is the Africa's most populous country with 206 million people. Nigeria's gross domestic product in 2022 was the highest in Africa, but its per capita is low as around 2000 USD. Nigeria has been categorized as a lower middle-income country for several years. The percentage of GDP for the current health expenditure was 3.38% in 2020. The amount of development assistance for health (DAH) was the second largest (910 million USD). The Nigerian government faces the challenges of the transition period from donor-funded programs to government-funded programs and securing the required health budget to deliver essential health services. Additionally, the Service Coverage Index (SCI) in Nigeria was 44 in 2018. To efficiently reduce the gap between the current service coverage and the UHC target with the limited health budget, the government of Nigeria needs to set priorities in population, geography, and health interventions in each area. Identifying priority areas and estimating the required budget in each community enables the Nigerian government to distribute the budget efficiently and maximize the health benefits of using the limited health budget.

There are three specific aims in this dissertation;

- 1) To identify both individual and contextual factors that are consistently associated with utilization of nine essential maternal and child health services (i.e., ANC, facility-based delivery, modern contraceptive use, immunizations, and childhood illnesses), across survey years and household geolocations, using five national representative cross-sectional surveys in Nigeria.
- 2) To estimate grid-level coverage of selected essential MCH services in Nigeria using generalized additive models (GAMs) and Gradient Boosting (GB)
- 3) To estimate required costs and avoidable child deaths by increasing selected essential health service coverage in each community, and to identify the priority sub-national areas.

INNOVATION

Focusing on multiple health services is a unique approach that is able to identify the consistent individual and contextual characteristics associated with the utilization of each health service. Since the statistical model in this study includes not only spatial covariates but also socio-economic factors, it would generate more precise small-area estimates of each health service in Ghana. Also, this is the first study to estimate the required cost and potential impact of delivering the essential health services and achieving UHC. Also, since the methodology in this study can be adaptable in other African countries, we could extend the study areas to other African countries and help them to achieve UHC.

Aim 1:

Factors consistently associated with utilization of essential maternal and child health services in Nigeria: analysis of the five Nigerian national household surveys (2003 to 2018)

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Abstract

Objective: This study aims to identify the individual and contextual factors consistently associated with utilization of essential maternal and child health services in Nigeria across time and household geolocation.

Design, setting and participants: Secondary data from five nationally representative household surveys conducted in Nigeria from 2003 to 2018 were utilized in this study. The study participants are women and children depending on essential maternal and child health (MCH) services.

Outcome measures: The outcome measures were indicators of whether participants utilized each of the following essential MCH services: antenatal care (ANC), facility-based delivery, modern contraceptive use, childhood immunizations (BCG, DPT/PENTA and measles), and treatments of childhood illnesses (fever, cough and diarrhea).

Methods: We estimated generalized additive models (GAMs) with logit links and smoothing terms for households' geolocation and survey years.

Results: Higher maternal education and households' wealth were significantly associated with utilization of all types of essential MCH services ($p < 0.05$). On the other hand, households with more children under five years of age and in poor communities were significantly less likely to utilize essential MCH services ($p < 0.05$). Except for childhood immunizations, greater access to transport was positively associated with utilization ($p < 0.05$). Households with longer travel times to the most accessible health facility were less likely to utilize all types of essential MCH services ($p < 0.05$), except modern contraceptive use and treatment of childhood fever and/or cough.

Conclusion: This study adds to the evidence that maternal education and household wealth status are consistently associated with utilization of essential MCH services across time and space. To increase utilization of essential MCH services across different geolocations, interventions targeting poor communities and households with more children under five years of age should be appropriately designed. Moreover, additional interventions should prioritize to reduce inequities of essential MCH service utilization between the wealth quantiles and between education status.

Strengths and limitations of this study

- This study used representative data from five national household surveys conducted in Nigeria from 2003 to 2018, including over 150,000 households.
- Utilization of nine types of essential maternal and child health services were assessed under the same conceptual framework.
- We estimated generalized additive models smoothing over households' geolocation and survey years for each essential maternal and child health service.
- This is the first study to identify maternal, household, and geolocational factors consistently associated with essential MCH services across years and households' geolocations in Nigeria.
- Reported associations with service utilization do not necessarily reflect causal relationships, although we considered both temporal and geographic variations in our analysis.

INTRODUCTION

Universal health coverage (UHC) ensures that all people, regardless of where they live and how much they earn and spend, have access to quality health services with protection from financial hardship and risks. UHC serves as one of 13 targets for Sustainable Development Goal 3 (SDG 3). The World Health Organization (WHO), OECD, and World Bank jointly reported, in their UHC Global Monitoring Report 2021, that the UHC service coverage index (SCI) increased from 45% in 2000 to 68% in 2019 globally [1]. This is attributed largely to the rapid increase in coverage of treatments for infectious diseases and maternal and child health care. This progress in UHC has been particularly notable in low- and lower-middle income countries. However, using composite indexes such as SCI to measure progress in attaining universal health coverage obscures large discrepancies in service availability across both countries and types of services. For instance, service coverage for essential maternal and child health services in Nigeria ranged from just 6% for antenatal, peripartum, and postnatal care for mothers to 61% for measles vaccination [2]. At the same time, in low- and middle-income countries unequal coverage of essential maternal and child health services is often reported between rich and poor, the most and least educated, and urban and rural areas [3].

Development of an effective service delivery strategy must begin by identifying the characteristics of the underserved populations who are less likely to have access to essential maternal and child health services. A majority of earlier studies conducted in Nigeria identified and assessed the factors associated with utilization of only one or two types of essential maternal and child health services such as antenatal care (ANC) [4-6], facility-based delivery [6-8], family planning [9, 10], childhood immunization [11-13] and treatment of childhood illnesses [14, 15]. The factors identified in these studies include individual characteristics (e.g., age, education status, ethnic group, religion, occupation, pregnancy history, wealth status, access to media) and contextual characteristics (e.g., distance to a health facility, rurality, neighborhood socio-economic status, and ethnic diversity). While recognizing the importance of earlier studies in increasing utilization of specific services, in order to develop a comprehensive strategy across essential maternal and child health services -- and thereby advance UHC -- it is critical to identify factors consistently associated with utilization across a range of essential maternal and child health services.

Accordingly, this study aims to identify both individual and contextual factors that are consistently associated with utilization of all nine essential maternal and child health services (i.e., ANC, facility-based delivery, modern contraceptive use, immunizations, and childhood illnesses), across survey years and household geolocations, using five national representative cross-sectional surveys in Nigeria.

METHODS

Dataset

This study uses secondary data from national representative cross-sectional surveys of geolocated households conducted in Nigeria from 2003 to 2018. We combined publicly available data from four Nigeria Demographic Health Surveys (DHS) in 2003, 2008, 2013 and 2018 and Multiple Indicator Cluster Surveys (MICS) in 2016 - 17. DHS data were extracted from IPUMS DHS [16]. Detailed methodologies of the four DHS surveys are published elsewhere [17-21]. All surveys employed stratified two- or three-stage cluster sampling techniques. The primary sampling unit (PSU) for DHS 2003 was defined as one or more enumeration areas (EAs) used for Population and Housing Census 1991, while the primary sampling unit for DHS 2008, DHS 2013, DHS 2018, and MICS 2016/17 was defined as one or more EAs used for the Population and Housing Census 2006.

The counts of households interviewed in DHS 2003, DHS 2008, DHS 2013, DHS 2018, and MICS 2016/17 are shown in Table 1. In DHS 2018, 11 of 27 local government areas (LGAs) in Borno State were excluded from the sampling frame due to insecurity in those districts. Likewise, in MICS 2016/17, a total of 101 EAs in Borno, Yobe and Adamawa states were not surveyed due to insecurity.

Table 1 Total number of households interviewed in DHS 2003, 2008, 2013 and 2018 and MICS 2016/17

Surveys	Rural	Urban	Total
DHS 2003	2,931	4,294	7,225
DHS 2008	23,346	10,724	34,070
DHS 2013	22,663	15,859	38,522
DHS 2018	23,647	16,780	40,427
MICS 2016/17	22,797	11,104	33,901

DHS: Demographic health survey

MICS: Multiple indicator cluster survey

To protect the confidentiality of PSU geolocations, the GPS coordinates of urban PSU locations were randomly displaced within a 2 km buffer, and rural PSUs were displaced within a 5 km buffer (and in 1% of cases, a 10 km buffer). The direction and distance of the displacement for each PSU was randomly selected using a uniform distribution [22, 23]. Prior research found that the effect of random displacement across a 10 km² grid to be negligible for estimating measles vaccination coverage [24]. Geolocation data for 16 of 3,533 PSUs (0.5%) were missing across the four DHSs. Similarly, geolocation data for 1 of 2,239 PSUs (0.0004%) was missing in MICS 2016/17. After initial random displacement, fourteen PSUs (1 in DHS 2008 and 13 in MICS 2016/17) were “located” either in the sea or out of country’s boundaries. We resampled the random displacement of those PSUs until their displaced positions lay inside the relevant boundaries (using a 5 km buffer if possible, and a 10 km buffer if necessary). Of these 14 PSUs, eight were successfully resampled, and six cases that could not be appropriately displaced across 10,000 attempts were discarded.

Essential maternal and child health services

The essential maternal and child health services considered in this study consist of ANC, facility-based delivery, modern contraceptive use, childhood immunizations (BCG, 1st and 3rd DPT/PENTA, Measles) and treatments for childhood illnesses. The target group for ANC and facility-based delivery was women aged 15-49 years having given a live birth in the last 23 months, while that for modern contraceptive use was women aged 15-49 years not having wanted to have more children. Children aged 12–23 months and aged 0-59 months were the target groups for immunization and treatments of childhood illnesses, respectively. Table 2 provides further details on the definitions of and study populations for these essential services.

Table 2 Definitions and target populations of essential health services		
Health service	Definition	Study population
Four or more antenatal care visits	Four or more antenatal care visits with trained health personnel (i.e., doctor, nurse, midwife, auxiliary midwife) during pregnancy as of the time of survey	Women aged 15 to 49 years with a last birth in the last 23 months
Facility-based delivery	Delivery at a public or private health facility in the last 23 months as of the time of survey	Women aged 15 to 49 years with live births in the last 23 months
Modern contraceptive use	Utilization of modern contraceptives (i.e., the pill, IUD, injection, diaphragm, male condom, female condom, female sterilization, male sterilization, implants, foam/jelly, lactational amenorrhea, and emergency contraception) at the time of survey	Non-pregnant women aged 15 to 49 years who did not want to have more children, including those using sterilization methods.
Childhood immunization	Children who had received one dose of Bacillus Calmette-Guerin (BCG) vaccine	Children aged 12–23 months
	Children who had received first dose of DPT vaccine or Pentavalent vaccine	
	Children who had received third dose of DPT vaccine or Pentavalent vaccine	
	Children who had received first dose of measles vaccine	
Treatment for common childhood illness	Children under five with fever/cough and diarrhea in the last two weeks for whom care was sought at a health facility	Children aged 0–59 months

Conceptual framework and independent variables

Independent variables across essential maternal and child health services were selected based on three earlier studies [25-27]. We considered five types of explanatory variables that might influence health seeking behaviors: (i) individual characteristics; (ii) the built environment; (iii) neighborhood demographics; (iv) the social environment; and (v) the health care environment.

Maternal and households' characteristics include the explanatory variables of maternal age, household head, education level, marital status, possession of television and radio, possession of means of transport and household's wealth index. Possession of television and radio was categorized into three groups: (i) households possessing both a television and a radio; (ii) households possessing either of them; and (iii) households possessing neither of them. Possession of means of transport means was generated using possession of car, motorcycle, and bike and categorized into three groups: (i) No means of transport; (ii) one means of transport; and (iii) 2-3 means of transport. The household wealth index was the first principal component estimated by a principal components analysis (PCA) on the household assets, sources of drinking water, sanitation facilities, type of fuel for cooking, and materials of floors for housing units.

Gridded estimates of population density provided by WorldPop were used as a proxy for the built environment [28]. The proportion of households in a PSU living under the poverty line was used as a proxy for neighborhood demographics and the social environment. As proxy for the health care environment, we measured each PSU's travel time to the most accessible health facility using the friction surface developed by the Malaria Atlas Project [29]. Geolocations of health facilities managed by government, community-based organizations and faith-based organizations in Nigeria were provided by the Nature Scientific database, which records locations of health facilities as of 2018[30]. We assume these facilities were present in all years surveyed by DHS; however, because Nature Scientific does not provide the date on which each facility was established, some health facilities may not have existed at the time of some of the five surveys, a possible limitation of our analysis. Finally, the number of health facilities within a 20 km buffer around each PSU was employed as the proxy for the health care environment, indicating the availability of accessible health facility options.

In analyses of the utilization of childhood immunizations and treatments of childhood illnesses, we added additional explanatory variables related to child characteristics (i.e., age, sex, and birth month). Children's ages were rounded to whole months.

Data analysis

In addition to descriptive analyses, we estimated generalized additive models (GAMs) with logit links to identify factors associated with the utilization of essential service v by the i^{th} individual in the d^{th} PSU in the j^{th} state at the t year. The systematic component of the model of v_{idjt} is:

$$\begin{aligned} \text{logit}(v_{idjt}) = & \beta_0 + \beta_1 DHS_{djt} + \beta_2 Head_{idjt} + \beta_3 \log(U5_{idjt}) + \beta_4 Poverty_{djt} + \beta_5 Access_{dj} \\ & + \beta_6 \log(Choice_{dj}) + \beta_7 \log(PopDensity_{djt}) + Age_{idjt}\gamma + Education_{idjt}\delta \\ & + Marital_{idjt}\theta + Transport_{idjt}\phi + Wealth_{idjt}\eta + s(long_{idj}, lat_{idj}) \\ & + s(month_t) \end{aligned}$$

$s(long_{idj}, lat_{idj})$	Smooth function of longitude and latitude using isotropic smooths on the sphere to account for spatial autocorrelation.
$s(month_year_t)$	Smooth function of time trends.
DHS_{djt}	Binary indicator recording 1 if the data source for year t is DHS and 0 if not.
$Head_{idjt}$	Binary indicator recording 1 if the household head in year t was a mother and 0 if not.
Age_{idjt}	Maternal age of the mother in a household in year t .
$U5_{idjt}$	The number of children under five years of age in a household in year t .

<i>Education</i> _{idjt}	The education level of the mother in year <i>t</i> .
<i>Wealth</i> _{idjt}	The wealth quantile of the household in year <i>t</i> .
<i>Marital</i> _{idjt}	The marital status of the mother in year <i>t</i> .
<i>Media</i> _{idjt}	Possession of TV and/or radio by the household in year <i>t</i> .
<i>Transport</i> _{idjt}	Possession of means of transport by the household in year <i>t</i> .
<i>Poverty</i> _{djt}	Proportion of the households living below the poverty line in the <i>d</i> th PSU of the <i>j</i> th state in year <i>t</i> .
<i>Access</i> _{dj}	Travel time in minutes from the household's PSU to the most accessible health facility.
<i>Choice</i> _{dj}	The number of health facilities within 20 km from the household's PSU.
<i>PopDensity</i> _{djt}	Population density in the <i>d</i> th PSU of the <i>j</i> th state in year <i>t</i> .

We included childhood covariates *ChildAge*_{ijt} and *ChildSex*_{ijt} (child's age and sex, respectively) in the models of childhood immunization and care seeking for common childhood illnesses. We log-transformed population density, the number of health facilities and the number of children under five to improve model fit and to account for diminishing marginal effects of these variables. Two of these variables -- the count of health facilities within 20 km and the count of children under five years of age -- could in some cases have a value of precisely zero, posing a problem for taking logs. Rather than adding an arbitrary positive quantity to these count variables, we directly estimate the effect of having zero children (or zero health facilities) by including dummy variables in the model to indicate cases where each is precisely zero. In turn, and without loss of generality, before logging the count of health facilities (or children), we replaced zeros with ones, so that cases in which there are zero health facilities within 20km (or no children under five years of age) affect the outcome only through the dummy variable for that case [31, 32].

We listwise deleted missing data, which accounted for <2% of total cases. Because the guidelines for DHS 2018 recommend against using weights for estimating relationships, we do not use sampling weights in estimating the GAMs [33]. However, sampling weights were used for estimating health service coverage reported in Table 3.

Finally, we estimated an additional eight models for each outcome as sensitivity analyses to check the robustness of our findings:

- Model 0a through 0d explore the association between health utilization outcomes and each of the four consistent factors separately, with only the potential confounders of (smoothed) household geolocation and time controlled.
- Model 1 estimates the association between health utilization outcomes and the four consistent factors taken together, controlling for (smoothed) household geolocation and time controlled.
- Model 2 builds on Model 1 to add controls for other individual characteristics.
- Model 3 builds on Model 1 to add controls for population density and proportion of poor households in a community, which proxy for the built environment and neighboring demographics.
- Model 4 builds on Model 1 to add controls for time to the accessible health facility and number of health facilities within 20 km, which proxy for the health care environment.

Patient and public involvement

None.

RESULTS

Table 3 shows the observed levels of coverage of essential maternal and child health services in 2003, 2008, 2013, 2016/17 and 2018. Overall, essential health service coverage increased from 2003 to 2018. Weighted service coverage of ANC rose from 44.2% to 51.7% over this period, whereas facility-based delivery and modern contraceptive use rose from 34.2% to 40.9% and 17.7% to

19.4%, respectively. Coverage for all four types of childhood immunization was below 50% in 2003, and exceeded that threshold for all types in 2018. 62.8% of children having fever and/or cough symptoms visited health facilities for their treatments, while 54.4% of children having diarrhea symptoms visited health facilities in 2018, more than double the rates of 2003. MICS 2016/17 reported approximately 30 to 40% lower coverage of treatment for childhood illnesses than DHS 2018. Table 4 and 5 show the descriptive statistics of the respondents' characteristics for each outcome.

Table 3. Essential health service coverage from 2003 to 2018 in Nigeria

Essential health services	2003	2008	2013	2016/17	2018
	%	%	%	%	%
Four or more antenatal care visits	44.24	44.95	48.90	48.17	51.74
Facility-based delivery	34.19	35.82	37.91	37.12	40.87
Modern contraceptive use	17.72	19.74	23.86	19.18	19.40
BCG vaccination	49.03	50.29	51.62	53.33	66.71
1 st pentavalent vaccination	42.71	52.45	51.00	49.53	64.96
3 rd pentavalent vaccination	22.95	36.65	38.93	34.08	50.81
Measles vaccination	37.03	42.61	42.88	41.85	53.96
Treatment for fever/cough	29.07	30.83	58.46	22.02	62.83
Treatment for diarrhea	19.07	28.28	55.91	24.99	54.44

Table 4. Descriptive statistics of maternal and contraceptive service utilization and independent variables in Nigeria

	4 th ANC N=47433	Facility-based delivery N=50398	Modern contraceptive use N=26931
Independent variables			
Data source			
DHS	37425 (78.8%)	40448 (80.2%)	19937 (74.0%)
MICS	10063 (21.2%)	10005 (19.8%)	6994 (26.0%)
Maternal and households' characteristics			
Household head			
Self	45173 (95.1%)	47922 (95.0%)	22353 (83.0%)
Others	2315 (4.9%)	2531 (5.0%)	4578 (17.0%)
Maternal Age (Mean (SD))	28.3 (6.89)	28.3 (6.86)	39.5 (7.19)
Maternal education level			
No education	22205 (46.8%)	23147 (45.9%)	8981 (33.3%)
Primary	8638 (18.2%)	9331 (18.5%)	7298 (27.1%)
Secondary	13528 (28.5%)	14610 (29.0%)	7934 (29.5%)
Higher	3117 (6.6%)	3365 (6.7%)	2718 (10.1%)
Marital status			
Never married	1183 (2.5%)	1227 (2.4%)	988 (3.7%)
Married or live together with a partner	45311 (95.4%)	48170 (95.5%)	22764 (84.5%)
Others	994 (2.1%)	1056 (2.1%)	3179 (11.8%)
Possession of TV and radio			
None	13743 (28.9%)	14388 (28.5%)	6058 (22.5%)
At least one	18297 (38.5%)	19379 (38.4%)	9018 (33.5%)
Both of them	15448 (32.5%)	16686 (33.1%)	11855 (44.0%)
Possession of transport means			
No transport means	21606 (45.5%)	22960 (45.5%)	12795 (47.5%)
1 transport means	19843 (41.8%)	21088 (41.8%)	10279 (38.2%)
2-3 transport means	6039 (12.7%)	6405 (12.7%)	3857 (14.3%)
Wealth quantile			
Poorest	8882 (18.7%)	9352 (18.5%)	5389 (20.0%)
Poor	9620 (20.3%)	10077 (20.0%)	5375 (20.0%)
Middle	9628 (20.3%)	10214 (20.2%)	5399 (20.0%)
Rich	9607 (20.2%)	10250 (20.3%)	5330 (19.8%)
Richest	9751 (20.5%)	10560 (20.9%)	5438 (20.2%)
Number of children under 5 (Mean (SD))	2.18 (1.14)	2.21 (1.16)	0.962 (1.11)
Geolocational characteristics			
Proportion of poorest households in a PSU	0.187 (0.285)	0.185 (0.284)	0.200 (0.317)
Population density (Mean (SD))	1690 (4480)	1720 (4520)	2350 (5240)
Time to the most accessible health facility (Mean (SD))	15.1 (22.8)	14.9 (22.7)	11.5 (19.6)
Number of health facilities within 20 km (Mean (SD))	51.3 (39.8)	51.9 (40.2)	61.5 (42.7)

Table 5. Descriptive statistics of utilization of child health services and independent variables in Nigeria

Independent Variables	BCG N=22982	1st Pentavalent N=22909	3rd Pentavalent N=22860	Measles N=22903	Fever/Cough treatment (N=28589)	Diarrhea treatment (N=13876)
Data source						
DHS	17596 (76.6%)	17564 (76.7%)	17558 (76.8%)	17544 (76.6%)	19697 (68.9%)	10409 (75.0%)
MICS	5386 (23.4%)	5345 (23.3%)	5302 (23.2%)	5359 (23.4%)	8892 (31.1%)	3467 (25.0%)
Maternal and households' characteristics						
Household head						
Self	1250 (5.4%)	1252 (5.5%)	1251 (5.5%)	1251 (5.5%)	1438 (5.0%)	525 (3.8%)
Others	21732 (94.6%)	21657 (94.5%)	21609 (94.5%)	21652 (94.5%)	27151 (95.0%)	13351 (96.2%)
Maternal Age (Mean (SD))	28.8 (6.85)	28.8 (6.85)	28.8 (6.85)	28.7 (6.84)	29.4 (7.00)	28.8 (7.11)
Maternal education level						
No education	10462 (45.5%)	10429 (45.5%)	10417 (45.6%)	10416 (45.5%)	13727 (48.0%)	8164 (58.8%)
Primary	4153 (18.1%)	4140 (18.1%)	4125 (18.0%)	4143 (18.1%)	5373 (18.8%)	2397 (17.3%)
Secondary	6696 (29.1%)	6676 (29.1%)	6660 (29.1%)	6680 (29.2%)	7866 (27.5%)	2805 (20.2%)
Higher	1671 (7.3%)	1664 (7.3%)	1658 (7.3%)	1664 (7.3%)	1623 (5.7%)	510 (3.7%)
Marital status						
Never married	535 (2.3%)	531 (2.3%)	531 (2.3%)	534 (2.3%)	538 (1.9%)	230 (1.7%)
Married or live together with a partner	21865 (95.1%)	21796 (95.1%)	21749 (95.1%)	21789 (95.1%)	27178 (95.1%)	13295 (95.8%)
Others	582 (2.5%)	582 (2.5%)	580 (2.5%)	580 (2.5%)	873 (3.1%)	351 (2.5%)
Possession of TV and radio						
None	6526 (28.4%)	6501 (28.4%)	6486 (28.4%)	6503 (28.4%)	9041 (31.6%)	4808 (34.6%)
At least one	8623 (37.5%)	8607 (37.6%)	8592 (37.6%)	8598 (37.5%)	11087 (38.8%)	5726 (41.3%)
Both of them	7833 (34.1%)	7801 (34.1%)	7782 (34.0%)	7802 (34.1%)	8461 (29.6%)	3342 (24.1%)
Possession of transport means						
No transport means	10406 (45.3%)	10384 (45.3%)	10368 (45.4%)	10377 (45.3%)	12719 (44.5%)	6086 (43.9%)
1 transport means	9658 (42.0%)	9617 (42.0%)	9596 (42.0%)	9618 (42.0%)	11884 (41.6%)	5961 (43.0%)
2-3 transport means	2918 (12.7%)	2908 (12.7%)	2896 (12.7%)	2908 (12.7%)	3986 (13.9%)	1829 (13.2%)
Wealth quantile						
Poorest	4459 (19.4%)	4451 (19.4%)	4447 (19.5%)	4440 (19.4%)	5830 (20.4%)	3421 (24.7%)
Poor	4443 (19.3%)	4432 (19.3%)	4426 (19.4%)	4432 (19.4%)	5989 (20.9%)	3335 (24.0%)
Middle	4628 (20.1%)	4614 (20.1%)	4597 (20.1%)	4614 (20.1%)	5987 (20.9%)	2959 (21.3%)
Rich	4526 (19.7%)	4506 (19.7%)	4499 (19.7%)	4509 (19.7%)	5760 (20.1%)	2450 (17.7%)
Richest	4926 (21.4%)	4906 (21.4%)	4891 (21.4%)	4908 (21.4%)	5023 (17.6%)	1711 (12.3%)
Number of children under 5 (Mean (SD))	2.10 (1.11)	2.10 (1.10)	2.10 (1.10)	2.10 (1.10)	2.21 (1.18)	2.29 (1.21)
Child characteristics						
Sex						
Male	11713 (51.0%)	11673 (51.0%)	11653 (51.0%)	11671 (51.0%)	14604 (51.1%)	7178 (51.7%)
Female	11269 (49.0%)	11236 (49.0%)	11207 (49.0%)	11232 (49.0%)	13985 (48.9%)	6698 (48.3%)
Month age (Mean (SD))	17.0 (3.44)	17.0 (3.44)	17.0 (3.44)	17.0 (3.45)	27.5 (16.3)	24.1 (15.3)
Geolocational characteristics						
Proportion of poorest households in a PSU	0.194 (0.287)	0.194 (0.288)	0.194 (0.288)	0.194 (0.287)	0.204 (0.296)	0.249 (0.321)
Population density (Mean (SD))	1800 (4690)	1800 (4690)	1800 (4690)	1800 (4690)	1560 (4160)	1360 (3750)
Time to the most accessible health facility (Minutes: Mean (SD))	14.7 (22.4)	14.8 (22.5)	14.8 (22.5)	14.7 (22.5)	15.5 (23.1)	17.0 (24.3)
Number of health facilities within 20 km (Count: Mean (SD))	52.4 (40.5)	52.4 (40.5)	52.4 (40.5)	52.4 (40.5)	50.0 (39.0)	45.1 (37.1)

Table 6 summarizes the results of nine GAMs for each essential maternal and child health service. More educated and wealthier mothers were significantly more likely to utilize all nine types of essential maternal and child health services. Similarly, older mothers were significantly more likely to utilize ANC, modern contraceptive use, childhood immunization, treatment of fever and/or cough and of diarrhea. In addition, having a greater number of means of transport was positively associated with essential service utilization, with the exception of childhood immunization. On the other hand, both having more children under five of age and living in poorer communities were negatively associated with utilization of essential maternal and child health services. Households with longer travel times to the most accessible health facility were significantly less likely to utilize all types of essential maternal and child health services, with the exception of modern contraceptive use and treatment of fever and/or cough, and diarrhea. Absence of health facilities within 20 km from a household was negatively associated with utilization of childhood immunization and treatment of fever and/or cough, and diarrhea.

Detailed results of all analyses for each health service are presented in Supplement files 1-4. Supplement file 5 shows the smooth fitting of time, longitude and latitude in the final models for each health service. Also, Supplement file 6.1 – 6.9 shows the results of sensitivity analyses for each outcome. The results of the full models from Table 6 in the main paper are also added in the supplement files for convenient comparison. The effects of four variables consistently associated with health service utilization in our main result did not change significantly in the sensitivity analyses.

Table 6. Results summary of generalized additive models for essential health services using five national-representative data from 2003 to 2018 in Nigeria.

Variables	ANC	Facility-based delivery	Modern contraceptive use	BCG vaccine	1st Pentavalent vaccine	3rd Pentavalent vaccine	Measles vaccine	Treatment of fever/cough	Treatment of diarrhea
Data source: DHS	1.151	0.948	1.176	1.608	1.204	1.098	1.416	10.540	5.066
Household head	1.056	1.162	0.751	1.123	1.117	1.171	0.944	1.058	1.051
Maternal Age (Ref. Less than 20 years old)									
20 – 24 years old	1.181	0.935	4.875	1.358	1.383	1.317	1.495	1.057	1.032
25 – 29 years old	1.251	0.914	6.786	1.508	1.512	1.505	1.731	1.079	1.138
30 – 34 years old	1.295	0.957	7.235	1.502	1.515	1.468	1.785	1.086	1.120
35 – 39 years old	1.237	1.031	7.316	1.685	1.735	1.607	1.924	0.989	1.063
40 or older	1.191	1.017	4.370	1.631	1.639	1.619	1.907	1.141	1.014
Maternal education level (Ref. No education)									
Primary	1.701	1.714	2.187	1.780	1.764	1.587	1.661	1.427	1.306
Secondary	2.402	2.857	2.476	3.237	3.071	2.558	2.523	1.588	1.361
Higher	5.690	8.990	2.779	7.853	6.790	4.616	6.053	1.809	1.562
Marital status (Ref. Never married)									
Married or live together with a partner	1.411	1.274	2.445	1.015	1.075	1.217	1.001	1.003	1.225
Others	1.313	1.166	1.209	1.040	1.057	0.990	1.009	0.925	0.954
Possession of TV and radio (Ref. None)									
At least one	1.000	1.016	0.909	0.995	1.061	0.985	0.984	1.084	1.104
Both	1.110	1.119	0.976	1.105	1.101	1.059	1.006	1.138	1.223
Possession of transport (Ref. No means of transport)									
1 means of transport	1.091	1.103	1.142	0.992	0.945	0.999	1.008	1.049	1.090
2-3 means of transport	1.198	1.111	1.241	1.019	0.980	1.030	1.000	1.170	1.133
Wealth quantile (Ref. Poorest)									
Poor	1.126	0.967	0.938	1.069	1.053	1.167	1.095	1.119	1.055
Middle	1.380	1.224	1.097	1.193	1.180	1.264	1.259	1.163	1.207
Rich	1.677	1.583	1.296	1.520	1.471	1.624	1.479	1.218	1.268
Richest	2.614	2.737	1.435	2.432	2.309	2.281	2.261	1.250	1.430
No children under 5 ¹			0.854						
Number of children under 5 in households [^]	0.795	0.763	0.693	0.762	0.774	0.819	0.839	0.942	0.877
Child characteristics									
Child sex: Female				1.015	0.998	1.022	1.010	0.952	0.962
Child age: Months				1.004	1.009	0.999	1.038	0.999	1.002
Geolocational characteristics									
Proportion of poorest households in a PSU	0.366	0.431	0.566	0.429	0.495	0.439	0.585	0.487	0.536
Population density [^]	1.066	1.094	1.010	1.060	1.019	1.013	1.016	0.991	1.014
Time to the most accessible health facility	0.997	0.998	1.000	0.997	0.997	0.996	0.998	1.000	0.998
No health facilities within 20 km	0.511	0.655	1.964	0.419	0.158	0.142	0.186	0.392	0.313
Number of health facilities within 20 km [^]	1.006	1.085	1.051	1.073	1.093	1.102	1.104	0.985	0.887

Entries are adjusted odds ratios (AORs) estimated by generalized additive models with logistic links and smoothing over time and households' geolocations. Blue shading indicates statistically significant AORs greater than one at the 0.05 level, red shading indicates significant AORs less than one, and unshaded entries are not significantly different from AORs of one.

[^]: log-transformed

¹: This variable is only included for models of modern contraceptive use, as the study population for other essential services (mothers aged 15-49 years with a last birth in the last 23 months and children aged 12-23 months) had at least one child under 5 in their households.

DISCUSSION

Using data from the five most recent nationally representative health surveys in Nigeria, this study identified individual- and community-level factors consistently associated with utilization of essential maternal and child health services in Nigeria. The sensitivity analyses confirmed the robustness of our findings. The identified factors consistently associated are maternal education, household economic status, having more children under five and living in poorer communities. Longer travel time to the most accessible health facility was not significantly associated with all, but a majority of essential maternal and child health services. These factors would be important characteristics across states and time to identify the underserved populations who are less likely to have access to multiple essential maternal and child health services rather than a single health service.

The results of our study reconfirmed that maternal education and household economic status are cross-cutting factors significantly associated with the utilization of essential maternal and child health services of households in Nigeria. Several earlier studies conducted in Nigeria reported women's education attainment and household economic status as factors significantly associated with utilization of essential health services such as ANC [4], facility-based delivery [7, 8, 34, 35], child immunizations [12], and treatment of childhood illnesses [14]. Meta-analyses have confirmed the importance of maternal education and household economic status for childhood immunization [36] and child mortality [37-39], as well. While the Health Equity Assessment Toolkit (HEAT) also provide useful information on inequalities of essential health service coverages within a country using five dimensions of inequity including wealth and education status [40], this study included more individual and contextual factors than HEAT such as marital status, possession of transportation, population density, and time to the most accessible health facility.

Moreover, this study found that having more children under five and living in poorer communities were negatively associated with utilization of the full range of essential maternal and child health services. Earlier systematic reviews reported that women with higher parity less frequently utilized ANC and facility-based delivery in developing countries [41-43]. A previous study conducted in Nigeria also reported childbirth order was significantly associated with the uptake of vaccinations [12]. On the other hand, it was reported that primigravidae could be more likely to seek advice and assistance for their deliveries [44]. Mothers in the households with a greater number of children under five years of age could need to spend more time and other resources taking care of the children. It could be difficult for them to find someone who takes care of children during their absence while receiving health services. They may also face additional logistical challenges in accessing health facilities. Some may have negative stereotypes about the quality of essential health services due to their previous dissatisfying experiences that could discourage them from utilizing health services [45]. This study also found that mothers living in poorer communities were less likely to utilize all essential maternal and child health services, even after adjusting for distance to and availability of health facilities and household economic status. Another study in Nigeria reported that not only poverty level but also the infrastructure level of communities in which mothers live were important determinants of child mortality [46]. Poorer communities tend to lack basic infrastructure, including paved roads and public transport, that enable timely and inexpensive access to essential health services. In addition, some mothers in poor rural communities might be either directly or indirectly influenced by the anti-immunization resistance movement observed in Northern Nigeria State [47, 48]. On the other hand, those living in urban poor communities, particularly slum dwellers, may have language barriers to accessing health services in addition to financial and geographic barriers [8].

Consistent with several earlier studies, longer travel times to the most accessible health facility were significantly associated with the utilization of most, though not all, essential maternal and child health services [43, 49, 50]. In addition, households with at least one health facility within 20 km were significantly more likely to utilize child immunization services and treatments of fever and/or cough, and diarrhea, suggesting the opportunity and/or financial cost of travel matters for utilization.

Similarly, those having means of transport can more easily access health facilities in the search of essential health services, with the possible exception of child immunization services, which are provided not only at most private and public health facilities, but also through outreach services and house-to-house campaigns. It is thus unsurprising that possession of means of transport did not significantly increase utilization of child immunization services.

As shown in Supplement file 5, temporal trends in the models of essential maternal and child health services varied. Spatial trends varied by health services, too. For example, the northern parts of Nigeria had generally lower coverage areas than other states.

The data source variable (i.e., DHS or MICS) would partially account for systematic differences between the surveys, while other covariates such as a smoothing function of longitude and latitude could also reflect the portion of the differences. As shown in Table 3, the service coverage in MICS 2016/17 were similar to that in DHS 2018 except for treatment for childhood fever/cough and diarrhea. The possible reasons for this include differences in sampling methodology, translated questionnaires in local languages, or may reflect true differences in outcomes due to different data collection periods or changes in trends over time.

The results of this study suggest several policy implications. In the short-term, service delivery points (e.g., health facilities and outreach service points) should be located closer to inhabitants in a community by: (i) ensuring availability and readiness of essential health services at existing service delivery points; and (ii) establishing additional primary health care centers; and (iii) strategically implementing outreach services such as campaigns. These interventions would mitigate physical barriers to access to essential health services, especially for among poor households who live far from current service delivery points. In the middle- and long-term, education attainment of pregnant women and mothers is one of the key determinants potentially modifiable by future interventions. Policy makers and program managers should place a greater emphasis on increasing enrollment rates in primary and secondary education among females not only to improve education outcomes themselves, but also to enhance health service utilization. Moreover, poorer households and communities should be prioritized to mitigate discrepancies in utilization of essential health services between the poor and the rich.

In addition, our study focused on the relationship between social conditions and healthcare utilization. Healthcare utilization, however, is only one of the factors that influence health outcomes. Further study is needed to fully illuminate the relationships between the drivers of healthcare utilization, utilization itself, and health outcomes.

LIMITATIONS OF THE STUDY

There are four types of limitations of the study. First, causality between service utilizations and the independent variables could not be established, although we considered both temporal and geographic variations into our analysis. Second, our analytical framework does not capture the full complexity of interactions between the independent variables. Third, immunization status is vulnerable to recall bias. Although it is preferable to use more reliable data from home-based records (e.g., child vaccination cards and maternal and child health cards), since these records are often not missing, especially in households with vulnerable mothers, reliance on parental recall is often unavoidable. Notably, studies in Tanzania and South Africa reported a high level of agreement in data between parental recall and home-based records [49, 50]. Finally, the two variables of health care environment “travel time to the most accessible health facility using friction surface” and “the number of health facilities within 20 km from local residence” were assumed as the time-invariant variables in this study, due to its poor data availability, although the relationship between these variables and service utilization might vary over time.

CONCLUSIONS

This study identified factors consistently associated with utilization of essential maternal and child health services in Nigeria. Higher female education attainment and wealthier households were positively associated with utilization of all the essential health services. Living in poorer communities and having more children under five years of age were negatively associated with utilization. Appropriate prioritization and intervention aimed at these factors should be implemented by the government and its development partners. As a short-term intervention, increasing service delivery points for poor communities would mitigate the negative effect of several factors identified here.

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Contributorship

YK performed the data analysis, interpretation and visualization and wrote the manuscript. JM, CA, DA, and KS contributed to the study concept and design. JM, and CA accessed and verified data analysis and visualization. PB and FC provided technical insights on data interpretation. JM, CA, and HA contributed to the critical revision of the manuscript for important intellectual content. KS supervised all the process of this manuscript. All authors read and approved the final manuscript.

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Competing interest

None declared.

Disclaimer

The information expressed in this paper authors' personal views and does not necessarily represent the corporate views of UNICEF.

Ethical consideration

This study is based on publicly available DHS and MICS datasets. Permission to access and use these datasets is provided by the DHS Programme (<http://www.dhsprogram.com>) and Unicef/MICS (<http://mics.unicef.org/surveys>).

Data availability statement

MICS and DHS data are available at the DHS Programme (<http://www.dhsprogram.com>) and Unicef/MICS website (<http://mics.unicef.org/surveys>).

REFERENCES

1. World Health Organisation, World Bank. Tracking Universal Health Coverage : 2021 Global Monitoring Report. World Health Organization and World Bank, 2021.
2. Lozano R, Fullman N, Mumford JE, Knight M, Barthelemy CM, Abbafati C, et al. Measuring universal health coverage based on an index of effective coverage of health services in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*. 2020;396(10258):1250-84. doi: 10.1016/S0140-6736(20)30750-9.

3. World Health Organization. State of inequality: reproductive, maternal, newborn and child health. Geneva: World Health Organization; 2015 2015.
4. Nwosu CO, Ataguba JE. Socioeconomic inequalities in maternal health service utilisation: a case of antenatal care in Nigeria using a decomposition approach. *BMC Public Health*. 2019;19(1):1493. Epub 2019/11/11. doi: 10.1186/s12889-019-7840-8. PubMed PMID: 31703734; PubMed Central PMCID: PMC6842188.
5. Stella B, Adesegun F. Determinants of use of maternal health services in Nigeria - looking beyond individual and household factors. *BMC Pregnancy and Childbirth*. 2009;9(43).
6. Ononokpono DN, Odimegwu CO, Imasiku E, Adedini S. Contextual determinants of maternal health care service utilization in Nigeria. *Women & health*. 2013;53(7):647-68. Epub 2013/10/08. doi: 10.1080/03630242.2013.826319. PubMed PMID: 24093448.
7. Adedokun ST, Uthman OA. Women who have not utilized health Service for Delivery in Nigeria: who are they and where do they live? *BMC Pregnancy Childbirth*. 2019;19(1):93. Epub 2019/03/15. doi: 10.1186/s12884-019-2242-6. PubMed PMID: 30866841; PubMed Central PMCID: PMC6416870.
8. Kawakatsu Y, Aiga H, Ubani O, Adesina AO, Honda S, Otaki J, et al. Socioeconomic barriers to facility-based delivery in urban poor communities of Lagos: Wealth, linguistic capacity, and residential area. *Health Policy OPEN*. 2020;1:100019. doi: <https://doi.org/10.1016/j.hpopen.2020.100019>.
9. Ajaero CK, Odimegwu C, Ajaero ID, Nwachukwu CA. Access to mass media messages, and use of family planning in Nigeria: a spatio-demographic analysis from the 2013 DHS. *BMC Public Health*. 2016;16(1):427. doi: 10.1186/s12889-016-2979-z.
10. Ogundele OJ, Pavlova M, Groot W. Inequalities in reproductive health care use in five West-African countries: A decomposition analysis of the wealth-based gaps. *International Journal for Equity in Health*. 2020;19(1):44. doi: 10.1186/s12939-020-01167-7.
11. Adeloye D, Jacobs W, Amuta AO, Ogundipe O, Mosaku O, Gadanya MA, et al. Coverage and determinants of childhood immunization in Nigeria: A systematic review and meta-analysis. *Vaccine*. 2017;35(22):2871-81. doi: <https://doi.org/10.1016/j.vaccine.2017.04.034>.
12. Oleribe O, Kumar V, Awosika-Olumo A, Taylor-Robinson SD. Individual and socioeconomic factors associated with childhood immunization coverage in Nigeria. *The Pan African medical journal*. 2017;26:220-. doi: 10.11604/pamj.2017.26.220.11453. PubMed PMID: 28690734.
13. Ataguba JE, Ojo KO, Ichoku HE. Explaining socio-economic inequalities in immunization coverage in Nigeria. *Health Policy and Planning*. 2016;31(9):1212-24. doi: 10.1093/heapol/czw053.

14. Adedokun ST, Adekanmbi VT, Uthman OA, Lilford RJ. Contextual factors associated with health care service utilization for children with acute childhood illnesses in Nigeria. *PloS one*. 2017;12(3):e0173578. Epub 2017/03/16. doi: 10.1371/journal.pone.0173578. PubMed PMID: 28296905; PubMed Central PMCID: PMC5351867.
15. Omondi D, Ogol C, Otieno S, Macharia I. Parental awareness of hearing impairment in their school-going children and healthcare seeking behaviour in Kisumu district, Kenya. *International Journal of Pediatric Otorhinolaryngology*. 2007;71(3):415-23. [dataset] 16. Elizabeth Heger Boyle, Miriam King, Matthew Sobek. IPUMS Demographic and Health Surveys. Version 8 [dataset]. In: ICF Ia, editor. Minneapolis, MN2020.
17. National Population Commission - NPC/Nigeria, ORC Macro. Nigeria Demographic and Health Survey 2003. 2004.
18. National Population Commission - NPC/Nigeria, ICF Macro. Nigeria Demographic and Health Survey 2008. Abuja, Nigeria: NPC/Nigeria and ICF Macro, 2009.
19. National Population Commission (NPC) N, International I. Nigeria Demographic and Health Survey 2013. Abuja, Nigeria, and Rockville, Maryland, USA: NPC and ICF International, 2014.
20. National Population Commission - NPC, ICF. Nigeria Demographic and Health Survey 2018 - Final Report. Abuja, Nigeria: NPC and ICF, 2019.
21. National Bureau of Statistics (NBS), United Nations Children's Fund (UNICEF). Nigeria - Multiple Indicator Cluster Survey 2016-2017. Abuja, Nigeria: 2018.
22. Perez-Heydrich Carolina, Joshua L. Warren, Clara R. Burgert, Emch ME. Guidelines on the Use of DHS GPS Data. Spatial Analysis Reports No. 8. Calverton, Maryland, USA: ICF International, 2013.
23. Biostat Global Consulting, NBS/Nigeria NBoS-. MICS/NICS 2016-17 Cluster GPS Coordinates - Displaced for Public Use. Abuja, Nigeria: National Bureau of Statistics - NBS/Nigeria, 2019.
24. Takahashi S, Metcalf CJE, Ferrari MJ, Tatem AJ, Lessler J. The geography of measles vaccination in the African Great Lakes region. *Nature communications*. 2017;8(1):15585. doi: 10.1038/ncomms15585.
25. Ryvicker M. A Conceptual Framework for Examining Healthcare Access and Navigation: A Behavioral-Ecological Perspective. *Social theory & health : STH*. 2018;16(3):224-40. Epub 2019/04/23. doi: 10.1057/s41285-017-0053-2. PubMed PMID: 31007612; PubMed Central PMCID: PMC6474407.
26. Jacobs B, Ir P, Bigdeli M, Annear PL, Van Damme W. Addressing access barriers to health services: an analytical framework for selecting appropriate interventions in low-income

- Asian countries. *Health Policy Plan*. 2012;27(4):288-300. Epub 2011/05/14. doi: 10.1093/heapol/czr038. PubMed PMID: 21565939.
27. Andersen R, Newman J. Societal and individual determinants of medical care utilization in the United States. *Milbank Memorial Fund Quarterly*. 1973;51:95 - 124. PubMed PMID: doi:10.2307/3349613.
28. World Population Review. Lagos Population 2018. Available from: <http://worldpopulationreview.com/world-cities/lagos-population/> (Accessed 10th Dec 2018).
29. Weiss DJ, Nelson A, Gibson HS, Temperley W, Peedell S, Lieber A, et al. A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature*. 2018;553(7688):333-6. doi: 10.1038/nature25181.
30. Maina J, Ouma PO, Macharia PM, Alegana VA, Mitto B, Fall IS, et al. A spatial database of health facilities managed by the public health sector in sub Saharan Africa. *Scientific Data*. 2019;6(1):134. doi: 10.1038/s41597-019-0142-2.
31. Adolph C, Amano K, Bang-Jensen B, Fullman N, Magistro B, Reinke G, et al. Governor Partisanship Explains the Adoption of Statewide Mask Mandates in Response to COVID-19. *State Politics & Policy Quarterly*. 2021:1-26. Epub 2021/10/20. doi: 10.1017/spq.2021.22.
32. Adolph C, Amano K, Bang-Jensen B, Fullman N, Magistro B, Reinke G, et al. The Pandemic Policy U-Turn: Partisanship, Public Health, and Race in Decisions to Ease COVID-19 Social Distancing Policies in the United States. *Perspectives on Politics*. 2021:1-23. Epub 2021/10/01. doi: 10.1017/S1537592721002036.
33. Croft TN, Aileen M. J. Marshall, Courtney K. Allen. *Guide to DHS Statistics*. Rockville, Maryland: ICF, 2018.
34. Agunwa CC, Obi IE, Ndu AC, Omotowo IB, Idoko CA, Umeobieri AK, et al. Determinants of patterns of maternal and child health service utilization in a rural community in south eastern Nigeria. *BMC Health Serv Res*. 2017;17(1):715. Epub 2017/11/15. doi: 10.1186/s12913-017-2653-x. PubMed PMID: 29132329; PubMed Central PMCID: PMC5683234.
35. Ononokpono DN, Odimegwu CO. Determinants of Maternal Health Care Utilization in Nigeria: a multilevel approach. *The Pan African medical journal*. 2014;17 Suppl 1(Suppl 1):2-. doi: 10.11694/pamj.supp.2014.17.1.3596. PubMed PMID: 24643545.
36. Forshaw J, Gerver SM, Gill M, Cooper E, Manikam L, Ward H. The global effect of maternal education on complete childhood vaccination: a systematic review and meta-analysis. *BMC Infectious Diseases*. 2017;17(1):801. doi: 10.1186/s12879-017-2890-y.

37. Balaj M, York HW, Sripada K, Besnier E, Vonen HD, Aravkin A, et al. Parental education and inequalities in child mortality: a global systematic review and meta-analysis. *The Lancet*. doi: 10.1016/S0140-6736(21)00534-1.
38. O'Hare B, Makuta I, Chiwaula L, Bar-Zeev N. Income and child mortality in developing countries: a systematic review and meta-analysis. *Journal of the Royal Society of Medicine*. 2013;106(10):408-14. Epub 2013/07/05. doi: 10.1177/0141076813489680. PubMed PMID: 23824332; PubMed Central PMCID: PMC3791093.
39. Jahan S. Poverty and infant mortality in the Eastern Mediterranean region: a meta-analysis. *Journal of Epidemiology and Community Health*. 2008;62(8):745-51. doi: 10.1136/jech.2007.068031.
40. Hosseinpoor AR, Nambiar D, Schlottheuber A, Reidpath D, Ross Z. Health Equity Assessment Toolkit (HEAT): software for exploring and comparing health inequalities in countries. *BMC Medical Research Methodology*. 2016;16(1):141. doi: 10.1186/s12874-016-0229-9.
41. Simkhada B, Teijlingen ERV, Porter M, Simkhada P. Factors affecting the utilization of antenatal care in developing countries: systematic review of the literature. *Journal of Advanced Nursing*. 2008;61(3):244-60. doi: <https://doi.org/10.1111/j.1365-2648.2007.04532.x>.
42. Gabrysch S, Campbell OMR. Still too far to walk: Literature review of the determinants of delivery service use. *BMC Pregnancy and Childbirth*. 2009;9:34.
43. Moyer CA, Mustafa A. Drivers and deterrents of facility delivery in sub-Saharan Africa: a systematic review. *Reproductive Health*. 2013;10(1):40. doi: 10.1186/1742-4755-10-40.
44. Pell C, Meñaca A, Were F, Afrah NA, Chatio S, Manda-Taylor L, et al. Factors Affecting Antenatal Care Attendance: Results from Qualitative Studies in Ghana, Kenya and Malawi. *PloS one*. 2013;8(1):e53747. doi: 10.1371/journal.pone.0053747.
45. Onyeneho NG, Amazigo UV, Njepuome NA, Nwaorgu OC, Okeibunor JC. Perception and utilization of public health services in Southeast Nigeria: Implication for health care in communities with different degrees of urbanization. *International Journal for Equity in Health*. 2016;15(1):12. doi: 10.1186/s12939-016-0294-z.
46. Adedini SA, Odimegwu C, Imasiku ENS, Ononokpono DN, Ibisomi L. REGIONAL VARIATIONS IN INFANT AND CHILD MORTALITY IN NIGERIA: A MULTILEVEL ANALYSIS. *Journal of Biosocial Science*. 2015;47(2):165-87. Epub 2014/01/10. doi: 10.1017/S0021932013000734.
47. Oku A, Oyo-Ita A, Glenton C, Fretheim A, Eteng G, Ames H, et al. Factors affecting the implementation of childhood vaccination communication strategies in Nigeria: a qualitative study. *BMC Public Health*. 2017;17(1):200. doi: 10.1186/s12889-017-4020-6.

48. McArthur-Lloyd A, McKenzie A, Findley SE, Green C, Adamu F. Community Engagement, Routine Immunization, and the Polio Legacy in Northern Nigeria. *Global Health Communication*. 2016;2(1):1-10. doi: 10.1080/23762004.2016.1205887.
49. Tegegne TK, Chojenta C, Loxton D, Smith R, Kibret KT. The impact of geographic access on institutional delivery care use in low and middle-income countries: Systematic review and meta-analysis. *PloS one*. 2018;13(8):e0203130. doi: 10.1371/journal.pone.0203130.
50. Geleto A, Chojenta C, Musa A, Loxton D. Barriers to access and utilization of emergency obstetric care at health facilities in sub-Saharan Africa: a systematic review of literature. *Systematic Reviews*. 2018;7(1):183. doi: 10.1186/s13643-018-0842-2.

Aim 2:

High-resolution mapping of essential maternal and child health service coverage in Nigeria: A machine learning approach

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Abstract

Background: National-level coverage estimates of maternal and child health (MCH) services mask district- and community-level geographical inequities. The purpose of this study is to estimate grid-level coverage of essential MCH services in Nigeria using machine learning techniques.

Methods: Essential MCH services in this study included antenatal care (ANC), facility-based delivery, childhood vaccinations, and treatments of childhood illnesses. We estimated generalized additive models (GAM) and gradient boosting regressions (GB) for each essential MCH service using data from five national representative cross-sectional surveys in Nigeria from 2003 to 2018 and geospatial socio-economic, environmental, and physical characteristics. Using the best-performed model for each service, we map predicted coverage at 1 km² and 5 km² spatial resolutions in urban and rural areas respectively.

Results: GAMs for essential MCH services were selected as the best fitting models. High-resolution spatial estimates produced by GAMs highlight geographic inequalities of essential MCH service coverage within states and LGAs. Inequalities between LGAs vary by state and service type.

Conclusion: High-resolution spatial estimates can guide geographic prioritization and help develop better strategies for implementation plans, allowing limited resources to be targeted to areas with lower coverage of essential MCH services.

1. Background

National and subnational coverage of essential maternal and child health (MCH) services in low- and middle-income countries (LMICs) are typically estimated using nationally representative cross-sectional surveys, including Demographic and Health Surveys (DHS) and Multiple Indicator Cluster Surveys (MICS). Because these surveys are generally designed to produce estimates at the national and sub-national levels (e.g., administrative level 1) exclusively, these estimates can mask district- and community-level inequities in service coverage. As a result, it can be difficult for policymakers to identify underserved geographic locations and prioritize interventions that match each community's context and needs.

Although estimates of essential MCH service coverage are rarely available at the lowest administrative level in LMICs, several earlier studies reported service coverage of diphtheria-pertussis-tetanus (DPT) vaccination, measles vaccinations, and contraceptive use at sub-district or community levels in LMICs.¹⁻⁴ Prevalence rates of HIV⁵ and plasmodium falciparum⁶ were also estimated at the subnational level in some LMICs. Finally, the DHS Program Map Surfaces provides grid-level estimates of coverage for multiple health service estimated using a Bayesian geostatistical approach with a standardized set of covariates across countries.^{7,8} However, these studies focus only on a single survey or a single indicator, whereas studies combining data from multiple surveys to investigate multiple indicators over time are lacking. The DHS Program Map Surfaces reports recommend use of additional geospatial covariates and integrated data from multiple surveys to further improve their methodologies and monitor progress towards UHC at sub-national level.⁷

There is a critical need for district- and community-level data on coverage of essential MCH services, so that countries may effectively target interventions, including new health facilities and outreach services, to communities with low coverage of multiple MCH services. Therefore, this study is aimed at estimating grid-level coverage of essential MCH services (i.e., antenatal care (ANC), facility-based deliveries, childhood vaccinations, and treatments of childhood illnesses) in Nigeria using machine learning methods. We further compare the prediction precision of two machine learning techniques, generalized additive models (GAMs) and Gradient Boosting (GB). We then use these methods to create high-resolution maps to visualize inequities in MCH service coverage across specific locations in Nigeria.

2. Methods

2.1. Survey data in Nigeria

This study use data from five nationally representative cross-sectional surveys administered in Nigeria between 2003 and 2018 that include geolocation data of primary sampling units (PSUs) (i.e., DHS 2003, DHS 2008, DHS 2013, and DHS 2018 and MICS 2016–2017). DHS data were extracted from IPUMS DHS.⁹ Methodological details on the conduct of these five surveys is published elsewhere.¹⁰⁻¹⁴ All five surveys employed stratified two- or three-stage cluster sampling. Each PSU for DHS 2003 was composed of one or more enumeration areas (EAs) developed for the 1991 Population Census. PSUs for other DHS and MICS surveys from 2016–2017 consisted of one or more EAs developed for the Population and Household Census 2006. MICS 2016–2017 excluded 101 PSUs located in Borno, Yobe, and Adamawa States due to insecurity in those regions. For the same reason, DHS 2018 excluded 11 of 27 local government areas (LGAs) in Borno State.

To protect confidentiality of personal geoinformation, the public versions of all five surveys' data randomly displaced Global Positioning System (GPS) coordinates of the locations of

respondents' PSUs. Geolocations of urban PSUs were randomly displaced within 2 km buffers, whereas rural PSUs (99%) were displaced within either 5 km buffers (in 99% of cases) or 10 km buffers (in 1% of cases representing extremely remote PSUs). The direction and distance of displacement for each household was randomly determined.^{15,16} A previous study reported that errors in direction and distance due to random household displacement were sufficiently negligible to estimate measles vaccination coverage in a 10 km² grid.¹⁷ Geolocation data for 16 of 3,533 PSUs (0.5%) were missing across the four DHSs. Similarly, geolocation data for 1 of 2,239 PSUs (0.0004%) was missing in MICS 2016/17. After initial random displacement, fourteen PSUs (1 in DHS 2008 and 13 in MICS 2016/17) were "located" either in the sea or outside country boundaries. We resampled those PSUs by conducting random displacement again within 5 km until they were within Nigeria's land boundaries. If there was no appropriate point within 5 km from the original PSUs' locations, we resampled those PSUs within 10 km. Of these 14 PSUs, eight were successfully resampled, and six cases that could not be appropriately displaced across 10,000 attempts were discarded. Supplement file 1 shows the locations of PSUs with at least one target population for ANC and facility-based delivery.

2.2. Essential MCH services

Twelve essential MCH services were included in this study: (i) ANC; (ii) facility-based delivery; (iii - x) childhood vaccinations (BCG, 1st, 2nd, and 3rd DPT/pentavalent (Penta) and Oral Polio (OPV), and first dose of measles); and (xi-xii) treatments of childhood illnesses for fever/cough and diarrhea. The definitions and study population of essential services are shown in Table 1. The target population for ANC and facility-based delivery are women 15–49 years of age having given a livebirth during the last 23 months. Children 12–23 months of age are the study population for childhood vaccinations.

The outcome variables for this study are the grid-level utilization rates for each essential MCH service. First, we created a map with 1 km x 1 km cells in urban areas and 5 km x 5 km cells in rural areas. (We define an urban area as having a population density of at least 300 inhabitants per km² and a minimum population of 5000 across all cells; all other areas are classified as rural.¹⁸) Then, for each essential MCH service, survey year, and grid cell, we constructed a utilization rate using the count of children 12–23 months of age (or women 15–49 years of age) who utilized that service as the numerator, and the number of individuals categorized into the study population (children 12–23 months of age or women 15–49 years of age, depending on the indicator) as the denominator.

Table 1 Definitions and target populations of essential health services		
Health service	Definition	Target population
Four or more antenatal care visits	Antenatal care four or more times by trained health personnel (i.e., doctor, nurse, midwife, auxiliary midwife) during pregnancy at the point of survey	Women aged 15 to 49 years with a last birth in the last 23 months
Facility-based delivery	Delivery at public or private health facility in the last 23 months at the point of survey	Women aged 15 to 49 years with live births in the last 23 months
Childhood immunization	Children who had received one dose of Bacillus Calmette-Guerin (BCG) vaccine	Children aged 12–23 months
	Children who had received 1 st , 2 nd and 3 rd dose of DPT vaccine or Pentavalent vaccine	
	Children who had received 1 st , 2 nd and 3 rd dose of oral polio vaccine	
	Children who had received 1 st dose of Measles vaccine	
Treatment for common childhood illness	Children under five with fever/cough and diarrhea in the last two weeks for whom care was sought at a health facility	Children aged 0–59 months

2.3. Covariate data

Several earlier studies found geospatial socio-economic, environmental, and physical factors to be associated with the spatial distribution of under-five mortality cases and geographical heterogeneity in MCH service coverage.^{2,19,20} Table 2 shows the geospatial covariates employed in this study (except for longitude and latitude). Household poverty and female and male education attainment by grid cell were extracted from high-resolution data published in earlier studies.^{21,22} Population density and total population data were extracted from the WorldPop database.²³ Road density data were extracted from the Global Roads Inventory Project (GRIP).²⁴ Metrological data (precipitation and evapotranspiration) and night time light data were extracted from TerraClimate²⁵ and High Resolution Electricity Access (HREA).²⁶ We also created three spatial covariates: (i) travel time to the most accessible health facility; (ii) travel time to the nearest city; and (iii) the number of major roads crossing the household's grid cell. Travel time to the most accessible health facility was estimated by using the geolocations of health facilities run by state governments, community-based organizations, and faith-based organizations in Nigeria²⁷ with the friction surface developed by Malaria Atlas Project.²⁸ Similarly, travel time to the nearest city was estimated by using geolocational data of cities (extracted from OpenStreetMap) and the same friction surface.²⁹ We counted the number of major roads (i.e., primary, secondary, and tertiary roads, motorway, track grade 1, 2, and 3) in each cell using OpenStreetMap. In addition, we used high-resolution spatial data on the prevalence of *Plasmodium falciparum* malaria, lower respiratory infections, and childhood diarrheal morbidity^{6,30,31} as disease-related covariates.

Table 2. Description of spatial covariates for modeling in this study

Category	Year*	Data type	Data description	Grid size	Data source
Poverty	2010	Continuous	Estimates of proportion of people per grid square living in poverty, as defined by \$1.25 a day	1 km ²	https://www.worldpop.org/geodata/listing?id=23
Female education	2003 – 2017	Continuous	Pixel-level estimates of mean educational attainment among female 15-49	5 km ²	https://cloud.ihme.washington.edu/index.php/s/CTnfWYaZxc7ZENc?path=%2FData%20%5BGeoTIFF%5D
Male education			Pixel-level estimates of mean educational attainment among male 15-49		
Population density	2003 – 2018	Continuous	Estimated population density per grid-cell (1 km)	1 km ²	https://www.worldpop.org/geodata/listing?id=77
Total population	2003 – 2018	Continuous	Estimated total population per grid-cell (1 km)	1 km ²	https://www.worldpop.org/geodata/listing?id=75
Time to health facility	2015	Continuous	Time to the most accessible health facility using the health facility locations and the friction surface	5 km ² for rural and 1 km ² for urban	NA
Time to city	2015	Continuous	Time to the most accessible city using the city locations and the friction surface		NA
Number of main roads crossing a grid	2021	Continuous	Number of main roads crossing a grid using OpenStreetMap data		OpenStreetMap; http://download.geofabrik.de/africa.html
Road density	2018	Continuous	Total road density	8 km ²	https://www.globio.info/download-grip-dataset
Precipitation	2003 – 2018	Continuous	High-spatial resolution (1/24°, ~4-km) map of cumulative precipitation	4 km ²	http://thredds.northwestknowledge.net:8080/thredds/catalog/TERRACLIMATE_ALL/data/catalog.html
Evapotranspiration	2003 – 2018	Continuous	High-spatial resolution (1/24°, ~4-km) map of cumulative evapotranspiration		
Night time lights	2012 – 2018	Continuous	Nighttime light annual composite	450 m ²	http://www-personal.umich.edu/~brianmin/HREA/data.html
Malaria prevalence	2003 – 2018	Continuous	Pixel-level Age-standardized parasite prevalence rate for <i>Plasmodium falciparum</i> malaria for children two to ten years of age	5 km ²	https://cloud.ihme.washington.edu/s/teDKnPGcJnBjJ5F?path=%2F5%20-%20Prevalence%3A%20Plasmodium%20falciparum%20%5BGeoTIFF%5D%2FRate
Lower respiratory infection	2003 – 2017	Continuous	Pixel-level prevalence of lower respiratory infections (LRIs) among children under 5	5 km ²	http://ghdx.healthdata.org/record/ihme-data/africa-under-5-lri-incidence-prevalence-mortality-geospatial-estimates-2000-2017
Childhood diarrhea	2003 – 2017	Continuous	Pixel-level estimates of under-5 diarrhea prevalence rate	5 km ²	https://cloud.ihme.washington.edu/s/fGpEZwJetEJdxG

* Data availability between 2003 - 2018

2.4 Prediction modeling and High-resolution map creation

We compared the prediction performances of two models, Generalized additive models (GAMs) and Gradient Boosting (GB) models. These models are described in section 2.4.1. For each service, we identify the best prediction model based on each model's performance on four indicators described in section 2.4.2. Finally, we create high-resolution coverage maps for each essential MCH service using the best prediction model for that service. We also estimated the aggregated service coverage at various administrative levels and in rural and urban areas. Section 2.4.3 provides methods of creating high resolution maps and estimating aggregated service coverage.

2.4.1 The prediction models: Generalized additive models (GAMs) and Gradient Boosting (GB) models

We consider two modelling strategies from machine learning – generalized additive models (GAMs) and gradient boosting (GB) models – for predicting essential maternal and child health service coverage. Both models rely on the same set of covariates, but employ different estimation techniques: GAMs emphasize non-parametric estimation of flexible functional forms, whereas gradient boosting involves prediction from a weighed ensemble of sequentially-constructed models, each of which attempts to better predict cases that were poorly predicted by the previous model in the sequence.

Generalized Additive Models. We estimated grid-level quasi-binomial GAMs for each essential MCH service using the `mgcv` package in R.³³ The functional form of this model is allows for non-parametric smooth relationships between the outcome and covariates, and is given by:

$$\begin{aligned} \log\left(\frac{y_{ijt}}{Pop_{ijt}}\right) = & \beta_0 + \beta_1 Urban_{ij} + State_{ij}\gamma + s(year_t) + s(long_{ij}, lat_{ij}) + s(Poverty_{ij}) + s(Female_edu_{ijt}) \\ & + s(Male_edu_{ijt}) + s(Pop_den_{ijt}) + s(Pop_total_{ijt}) + s(No_road_{ij}) + s(Road_den_{ij}) \\ & + s(Time_city_{ij}) + s(Time_HF_{ij}) + s(Rain_{ijt}) + s(Dry_{ijt}) + s(Light_{ijt}) + s(Malaria_{ijt}) \\ & + s(LRI_{ijt}) + s(Diarrhea_{ijt}) \end{aligned}$$

y_{ijt} represents the number of eligible individuals utilizing essential MCH services in the i^{th} grid of the j^{th} state in year t . Pop_{ijt} indicates the number of eligible individuals in the i^{th} grid of the j^{th} state in year t . $Urban_{ij}$ is a binary indicator for whether the i^{th} grid of the j^{th} state is urban or rural. $State_{ij}$ is a vector of dummy variables indicating states of Nigeria. $s(year)$ is a two-dimensional thin plate regression spline of years. $s(lat, long)$ is an isotropic smooth of latitude and longitude on the sphere with second derivative penalty³³. In all other cases, $s(\cdot)$ indicates a cubic spline smoothing function of the given covariate.

$Poverty_{ij}$ denotes estimated proportion of people living in poverty, defined as living on less than US\$1.25 a day, in the i^{th} grid of the j^{th} state. $Female_edu_{ijt}$ and $Male_edu_{ijt}$ represent mean educational attainment among female and male aged 15 – 49 years in the i^{th} grid of the j^{th} state in year t , respectively. Pop_den_{ijt} and Pop_total_{ijt} represent population density and total population in the i^{th} grid of the j^{th} state in year t . No_road_{ij} and $Road_den_{ij}$ denote the number of main roads crossing and total road density in the i^{th} grid of the j^{th} state. $Time_city_{ij}$ and $Time_HF_{ij}$ denote time to the most accessible health facility and city in the i^{th} grid of the j^{th} state. $Rain_{ijt}$, Dry_{ijt} and $Light_{ijt}$ represent cumulative precipitation, cumulative evapotranspiration, and annual composite nighttime light, respectively, in the i^{th} grid of the j^{th} state in year t . $Malaria_{ijt}$, LRI_{ijt} and

$Diarrhea_{ijt}$ represent prevalence of Plasmodium falciparum malaria, lower respiratory infections and diarrhea in the i^{th} grid of the j^{th} state in year t .

We employed a shrinkage approach to smoothing functions in the GAM model with all covariates, since the best-subset selection approach was not computationally feasible. A simulation study found that the shrinkage approach performed better in terms of predictive ability than other methods, such as backward selection.³⁴

Gradient Boosting. We also estimated Gradient Boosting regression models for each essential MCH service using the XGBoost package in R.³⁵ We used the same set of the covariates as listed in section 2.3, and assumed service coverage outcomes followed the Tweedie distribution. We tested a sequence of variance power between 1 and 2 by running iterative models and selected the best power based on the negative log-likelihood. Moreover, we conducted a grid search to select the best set of hyper-parameters based on negative log-likelihood for Tweedie regression. In the grid search, we tested the following parameters and their ranges: (i) the maximum depth of a tree, 2 – 10 by increments of 2; (ii) the minimum sum of instance weight needed in a child, 1 – 3 by increments of 0.5; (iii) the subsample ratio of columns when constructing each tree, 0.5 – 1.0 by increments of 0.1; (iv) the subsample ratio of the training instances, 0.5 – 1.0 by increments of 0.1; and (v) step size shrinkage used in update to prevent overfitting, 0.01 – 0.3 (specifically, we tested 0.01 – 0.1 by increments of 0.01, as well as 0.2 and 0.3).

2.4.2 Model performance indicators and selection of final models

We compared the performance of the GAM and GB models for each MCH service on four performance criteria, each of which was computed using 5-fold cross-validation: weighted root-mean-squared error (WRMSE) of proportions of essential MCH service utilizations,

$WRMSE = \sum(d_i \times \sqrt{((P_i - \hat{P}_i)^2) / \sum d_i})$; mean bias error, $MBE = \frac{1}{n} \sum_{i=1}^n (P_i - \hat{P}_i)$; mean squared error, $MSE = \frac{1}{n} \sum_{i=1}^n (P_i - \hat{P}_i)^2$; and nominal coverage of 95% prediction intervals, $nCoverage = 100 \times \sum_{i=1}^n I(l_i \leq \hat{y}_i \leq u_i) / n$. P_i and \hat{P}_i denote observed and predicted proportions at grid i , d_i is the size of the study population at grid i , and n is the count of grid locations with non-zero study populations. l_i and u_i are the lower and upper limits of the prediction interval and $I(\cdot)$ is an indicator function. Nominal coverage indicates the proportion of the estimated numbers of study population having utilized essential maternal and child services (\hat{y}_i) within 95% confidence intervals (CIs) of predicted services coverage. Due to erratic behavior around the endpoints (i.e., 0 and 1) using binomial probabilities³², whenever observed values were exactly 0 or 1, we set the estimated lower and upper confidence intervals in GAMs to either 0 or 1, respectively. We employed methods employed in an earlier study on grid-level estimates of measles vaccinations² to calculate the nominal coverage of 95% prediction intervals.

To determine a final model for each MCH service, we first checked whether either the GAM or GB model was dominant on all the four measures of goodness of fit. If either model was uniformly superior on these four metrics, we selected it as the prediction model for the service. When the results of the four metrics disagreed on the best model, we further examined whether one of the models had WRMSE at least 0.01 units lower, MSE at least 0.005 units lower, MBE at least 0.01 units lower, or nCoverage at least 1% closer to 95%. Whichever model met a greater number of these criteria than the others was selected as the prediction model for that

service. (In no cases did we observe a tie in which both the GAM and GB model met the same number of these criteria.)

2.4.3 High-resolution map creation

Using best predicting model (either GAM or GB) for each service, we created high-resolution coverage maps for essential MCH services from 2003 to 2018. We also computed 95% confidence intervals (CIs) of predicted grid-level service coverage using the estimated standard error for each predicted value (for GAMs) or bootstrapped standard errors (GB models). We estimated aggregate predicted proportions aggregated at various administrative levels by calculating weighted mean values and using as weights in each grid location the proxy target population from WorldPop.²³ For ANC and facility-based delivery, we used the sum of the number of children 0 – 12 months of age in the year of estimation and in the prior year as a proxy for the number of women 15 – 49 years of age with a livebirth during the last 23 months. For childhood vaccinations, we used the total number of children 0 – 12 months of age in the prior year as a proxy for the number of children aged 12–23 months. To estimate gaps in MCH service coverage between rural and urban areas over time, the difference-in-difference (DiD) estimator for each essential MCH service was calculated by taking the difference in an MCH service coverage of urban areas between 2018 and 2003, and subtracting the difference for rural areas between 2018 and 2003. 95% CIs for the DiD estimates were computed using bootstrapped standard errors. A bivariate choropleth map is used to display mean MCH coverage.

Following previous work,³⁰ we discarded (treated as missing) estimated values of MCH service coverage for the grid locations which include either lakes or very low population (less than 10 people per km²). We did not estimate predicted values for grid locations lacking covariate data. To check model fitting, we further compared the observed and estimated share of study populations utilizing essential MCH services (see Supplement file 3). Supplement file 4 provides plots of smoothed functional forms from the GAMs. GB model estimates of the importance of each feature for predicting each MCH service based are provided in Supplement file 5.

Patient and public involvement

Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research.

Results

Model selection and validation

Supplement file 2 reports the performance of the GAMs and GB models. Across a range of essential MCH services, GAMs matched or outperformed GB models based on all four performance indicators, as shown in Supplement file 2. In particular, for ANC, facility-based delivery, BCG, 1st 2nd and 3rd Penta, GAMs performed better than GB models on all four measures (MBEs, MSEs, WRMSEs, and nominal 95% coverage). For 2nd and 3rd OPV and measles vaccinations, GAMs outperformed GB models in terms of MBE and the nominal coverage, while obtaining similar MSEs and WRMSEs. For 1st OPV, GAMs outperformed GB

models on MBE, while MSE, WRMSE and nominal coverage were similar across both approaches. Finally, due to low predictive power and wide prediction intervals in both GAM and GB models, we did not select final models or create coverage maps for treatments of childhood illnesses.

The final predictive models had uniformly low systematic prediction error, with a range of MBE from 0.001 to 0.016 across 10 essential MCH services. The range of MSEs was similarly narrow (0.057 – 0.068). As shown in Supplement file 4, smoothers fitted by the GAMs show different slopes by MCH service types. Supplement file 6 compares high-resolution maps of coverage of six essential MCH services based on GAMs and GB models.

Geographic inequality in essential MCH service coverage

High-resolution maps of coverage from 2003 to 2018 of 10 essential MCH services, excepting treatments of childhood illnesses, have been stored online [here](#). High-resolution maps of six of 10 essential MCH services (ANC, facility-based delivery, BCG, 1st Penta, 3rd Penta and measles vaccination) as of 2018 are shown in Figure 1 to highlight geographic inequality in service coverage across states and LGAs. Overall, MCH service coverage in rural areas was lower than urban areas across service types. Likewise, MCH service coverage was also lower in northern parts of Nigeria, though higher coverage can be found in some major cities and towns in those states.

Figure 2 shows LGA-level coverage estimates for eight of 10 essential MCH services by state as of 2018. (We omitted coverage of 2nd OPV and 2nd Penta doses, which tend to fall between the coverage levels of 1st and 3rd doses.) Overall, the LGA-level inequalities of 3rd OPV, 3rd Penta and measles were narrower, compared to BCG, 1st OPV and 1st Penta. For ANC and facility-based delivery, the states with higher average coverage rates tended to have narrower inequities between LGAs. The three states with the greatest LGA-level inequality in terms of ANC were Kwara (Interquartile range [IQR]: 54.2% to 82.6%), Borno (IQR: 16.6 % to 40.8%), and Bayelsa (IQR: 23.4% to 46.3%), whereas the top three states for LGA-level inequality in BCG vaccination were Kaduna (IQR: 53.4 % to 88.1%), Gombe (IQR: 45.3 % to 78.4%) and Borno (IQR: 35.7% to 60.4%). Overall, we find that Borno, Gombe, Kaduna, Kwara, and Niger states showed consistently high inequality across LGAs, with each of these states ranking among the top three states in terms of interquartile range for at least four of eight MCH services. In terms of inequality across the 10 MCH services shown in Figure 2, we find the highest LGA-level interquartile range for facility-based delivery coverage, followed by BCG, 1st OPV and ANC. The LGA-level IQR for measles vaccination was the lowest of the eight services, although its mean coverage was the lowest, as well.

Trends in essential MCH service coverage

The mean LGA-level service coverage for essential MCH services increased during the period from 2003 to 2018. The annual mean increase in service coverage was higher for 3rd Penta (1.4%), 1st Penta (1.3%), BCG (1.3%), and 3rd OPV (1.2%), and lower for measles vaccination (0.7%), 1st OPV (0.7%), facility-based delivery (0.6%), and ANC (0.5%). However, trends in LGA-level essential MCH service coverage between 2003 and 2018 varied by type of service

and by state. Although most LGAs are trending towards better essential MCH service coverage, some are stagnating or even decreasing over time.

Trends in mean MCH coverage for urban and rural LGAs are shown in Supplement file 7. On average, service coverage in both urban and rural areas increased over time. Difference-in-difference estimates of the change in the urban-rural gap find no significant evidence that this gap has change over time for any service. Specifically, between 2003 and 2018, the gap between urban and rural areas changed by -2.3% (95% CI: -14.3 % to 10.6%) for ANC, -3.8% (-16.2% to 8.6%) for facility-based delivery, 7.6% (95% CI: -22.9% to 7.0%) for BCG, -6.4% (-19.3% to 6.3%) for 1st pentavalent, -2.6% (-17.2 % to 11.9%) for 1st OPV, and -1.8 % (-13.5 % to 9.5%) for measles vaccination. In no case was the difference-in-difference statistically significant.

Priority LGAs with lower coverage of essential MCH services

Figure 3 is an LGA-level bivariate choropleth map that two-dimensionally shows service coverage of childhood vaccinations (BCG, 1st, 2nd, and 3rd DPT/pentavalent (Penta) and Oral Polio (OPV), and first dose of measles) and maternal health (ANC and facility-based delivery). Coverage level was classified by tertile (i.e., higher 33%, middle 33% and lower 33%). The map indicates that a majority of LGAs located in northern part of the country had lower childhood vaccination and maternal health service coverage, excepting some urban LGAs which had higher coverage for either or both types of services. The southwest, including districts in Ogun and Oyo states, had higher maternal health service coverage and lower childhood vaccination coverage. In contrast, the southeastern and central areas of the country had lower maternal service coverage and higher childhood vaccination coverage. Finally, those states in which 80% of LGAs were categorized as high coverage for both types of services (the dark purple areas in Figure 3, comprising Abia, Anambra, Edo, Ekiti, Enugu, Imo, Lagos, and Osun) can be found in the southern part of Nigeria and had relatively greater population sizes and density than other areas. Supplement file 8 provides LGA-level mean coverage of childhood vaccinations and maternal health services as of 2018, by state.

Discussion

The global movement for universal health coverage (UHC) highlights the importance of identifying subnational inequities in health service coverage in order to better understand the characteristics of underserved populations and thereby correct maldistribution of health resources and services. This movement has led researchers to conduct studies on the heterogeneity of health service coverage within and between subnational levels and to identify the most vulnerable areas for priority setting. Responding to this need, this study estimated grid-level coverage of essential MCH services in Nigeria using publicly available geographic datasets and comparing the performance of two statistical approaches (GAMs and GB).

Cross-validation performance confirms the strong predictive power of the final models of essential service coverage, with the exception of treatments for childhood illnesses. MSE and MBE values of the final model for measles vaccination were slightly better than those reported in an earlier study on grid-level coverage estimates of measles vaccination that employed

Bayesian multivariate spatial-temporal modeling.² GAM with a shrinkage approach might be applied to a multicounty or global model, to simultaneously account for differing drivers and non-linear relationships. GAM estimation is also less computationally intensive than GB models, particularly to find the best set of hyper-parameters.

The importance of each feature for predicting MCH service coverage, shown in Supplement file 5, varied by MCH service types. This suggests that further study may need to select an appropriate set of geospatial covariates for predicting coverage of specific health services. Additionally, the results for some predictors should be interpreted with caution. For example, education attainment is a model-based estimate generated using geospatial covariates such as night light, access to roads, population, and aridity. The consistent importance of male and female education attainment in predicting coverage in GB models might therefore reflect the influence of the other geospatial covariates that were used to generate education status estimates, rather than educational status itself.

One avenue for increasing predictive power is to use health administrative data on essential MCH service utilizations reported from health facilities. Almost all countries have health management information systems (HMIS) that store time-series data on the delivery of key health services from public and (in some cases) private health facilities. For example, Nigeria launched the web-based software District Health Information System version 2 (DHIS2) in 2010. Childhood vaccination data have been collected on a monthly basis since 2014.³⁶ National-level health administrative data were used for estimating national coverage of childhood vaccination services by the WHO and UNICEF³⁷ and by a recent publication in the *Lancet*.³⁸ In addition, DHIS2 contains the aggregated count of clients/patients who receive respective health services at the lowest administrative level every month. Using these lower-level health administrative data may increase predictive power. However, the quality of health administrative data from health facilities is questionable in many countries at present.³⁹

This study clarifies that national and sub-national MCH service coverage measures mask significant spatial heterogeneity within Nigeria, which may result in poor decision making on geographical prioritization at the LGA level. Likewise, inequities in MCH service coverage between LGAs varied by state and type of service. However, the distribution and use of health resources in Nigeria remain suboptimal in terms of demography, disease burden, and pre-existing endowments of health resources.^{41 42} The high-resolution maps generated by this study could be an input into the decision making process for better geographical prioritization of health resources. Whereas prioritizing based on a single indicator may make sense for achieving specific goals, such as the Immunization Agenda 2030, broader agendas, such as the Sustainable Development Goals (SDGs), require prioritization based on multiple indicators. Accordingly, we recommend that criteria for prioritizing geographic locations should not rely on a single indicator of coverage, but rather consider coverage rates for multiple health services in order to ensure optimal provision. In particular, the study highlights within-locality differences in coverage of childhood vaccinations and maternal health services, with some localities performing markedly better in one area or the other.

According to the Lancet Commissions,⁴² Nigeria needs to distribute available health resources more equitably through increasing resource management and strategic purchasing capacities. Routinely updated high-resolution maps could also support micro-planning of supplementary activities such as outreach services and childhood vaccination, especially if such mapping is connected with a health information management system such as DHIS2. Specifically, mapping can help estimate the number of individuals in need of services at the community level and thereby inform budgeting and resource allocation.

There are several limitations to this study. Our modelling approach is less applicable to estimating the coverage of health services like treatments of childhood illnesses, which are more associated with individual and contextual characteristics than spatial covariates.⁴⁴⁻⁴⁶ Inequalities between relatively affluent urban areas and their adjacent peri-urban areas suffering higher poverty rates were not captured in the maps we created due to limitations of the available input data. Moreover, our study investigated inequality not by income, educational status, and other factors, but by geospatial conditions only.

Conclusion

This study visualized significant geographical inequities of essential MCH service utilizations in Nigeria. The high-resolution maps herein provide health policymakers/planners with guidance for geographic prioritization of specific MCH services. These estimates serve as a resource to further develop implementation strategies for maximizing limited resources. Strengthening routine MCH service delivery and its supplementary activities should be implemented in the priority areas with low coverage of essential MCH services.

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Contributors

As a guarantor, YK performed and interpreted data analyses and visualizations, and wrote the manuscript. JM, CA, DA, and KS contributed to the study concept and design. JM and CA also verified data analysis and visualization. PB and FC provided technical insights on data interpretation. JM, CA, and HA contributed to the critical revision of the manuscript for intellectual content. KS supervised the process of this manuscript. All authors read and approved the final manuscript.

Declaration of Competing Interest

None declared.

Disclaimer

The information expressed in this paper is the authors' personal views and does not necessarily represent the corporate views of UNICEF.

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None

Data availability statement

Data are available in DHS and MICS website.

Figure 1. Predicted service coverage of (A) antenatal care, (B) facility-based delivery, (C) BCG vaccination, (D), 1st pentavalent vaccination, (E) 3rd pentavalent vaccination, and (F) Measles vaccination in 2018.

Figure 2. Predicted LGA-level coverage of eight essential MCH services in 2018 by state. Orange dots mark the mean coverage within each state. Gray dots show service coverage for each LGA within the state. The distribution of these gray dots is summarized by a violin plot.

Figure 3. Service coverage distribution of essential maternal health services (ANC and facility-based delivery) and immunization services in 2018 as a bivariate choropleth map. Mixtures of the colors red and blue indicate coverage levels in each LGA. Areas with high levels of maternal service coverage but low levels of immunization coverage are shown in red. Areas with high levels of immunization coverage but low levels of maternal service coverage are shown in blue. Areas with similar levels of coverage across both services are shown in shades of purple ranging from lilac (low coverage of both services) to plum (high coverage of both services).

References

1. Mosser JF, Gagne-Maynard W, Rao PC, et al. Mapping diphtheria-pertussis-tetanus vaccine coverage in Africa, 2000–2016: a spatial and temporal modelling study. *The Lancet* 2019;393(10183):1843-55. doi: 10.1016/S0140-6736(19)30226-0
2. Utazi CE, Thorley J, Alegana VA, et al. High resolution age-structured mapping of childhood vaccination coverage in low and middle income countries. *Vaccine* 2018;36(12):1583-91. doi: 10.1016/j.vaccine.2018.02.020 [published Online First: 2018/02/20]
3. Utazi CE, Thorley J, Alegana VA, et al. A spatial regression model for the disaggregation of areal unit based data to high-resolution grids with application to vaccination coverage mapping. *Statistical methods in medical research* 2019;28(10-11):3226-41. doi: 10.1177/0962280218797362 [published Online First: 2018/09/20]
4. Bosco C, Alegana V, Bird T, et al. Exploring the high-resolution mapping of gender-disaggregated development indicators. *Journal of the Royal Society, Interface* 2017;14(129) doi: 10.1098/rsif.2016.0825 [published Online First: 2017/04/07]
5. Dwyer-Lindgren L, Cork MA, Sligar A, et al. Mapping HIV prevalence in sub-Saharan Africa between 2000 and 2017. *Nature* 2019;570(7760):189-93. doi: 10.1038/s41586-019-1200-9

6. Weiss DJ, Lucas TCD, Nguyen M, et al. Mapping the global prevalence, incidence, and mortality of *Plasmodium falciparum*, 2000-17: a spatial and temporal modelling study. *Lancet* 2019;394(10195):322-31. doi: 10.1016/s0140-6736(19)31097-9 [published Online First: 2019/06/24]
7. Gething P, Tatem A, Bird t, et al. Creating spatial interpolation surfaces with DHS data. DHS Spatial Analysis Reports No 11. Rockville, Maryland, USA: ICF International, 2015.
8. Burgert-Brucker CR, Dontamsetti T, Mashall A, et al. Guidance for use of The DHS Program modeled map surfaces. DHS Spatial Analysis Reports No 14. Rockville, Maryland, USA: ICF International, 2016.
9. Elizabeth Heger Boyle, Miriam King, Matthew Sobek. IPUMS Demographic and Health Surveys. Version 8 [dataset]. In: ICF Ia, ed. Minneapolis, MN, 2020.
10. National Population Commission - NPC/Nigeria, ORC Macro. Nigeria Demographic and Health Survey 2003, 2004.
11. National Population Commission - NPC/Nigeria, ICF Macro. Nigeria Demographic and Health Survey 2008. Abuja, Nigeria: NPC/Nigeria and ICF Macro, 2009.
12. National Population Commission (NPC) N, International I. Nigeria Demographic and Health Survey 2013. Abuja, Nigeria, and Rockville, Maryland, USA: NPC and ICF International, 2014.
13. National Population Commission - NPC, ICF. Nigeria Demographic and Health Survey 2018 - Final Report. Abuja, Nigeria: NPC and ICF, 2019.
14. National Bureau of Statistics (NBS), United Nations Children's Fund (UNICEF). Nigeria - Multiple Indicator Cluster Survey 2016-2017. Abuja, Nigeria, 2018.
15. Perez-Heydrich Carolina, Joshua L. Warren, Clara R. Burgert, et al. Guidelines on the Use of DHS GPS Data. Spatial Analysis Reports No. 8. Calverton, Maryland, USA: ICF International, 2013.
16. Biostat Global Consulting, NBS/Nigeria NBoS-. MICS/NICS 2016-17 Cluster GPS Coordinates - Displaced for Public Use. Abuja, Nigeria: National Bureau of Statistics - NBS/Nigeria, 2019.
17. Takahashi S, Metcalf CJE, Ferrari MJ, et al. The geography of measles vaccination in the African Great Lakes region. *Nature communications* 2017;8(1):15585. doi: 10.1038/ncomms15585
18. Lewis Dijkstra, Poelman H. A harmonised definition of cities and rural areas: the new degree of urbanisation. Regional Working Paper 2014: European Commission, 2014.

19. Fagbamigbe AF, Nnanatu CC. Modelling the Spatial Distribution and the Factors Associated with Under-Five Mortality in Nigeria. *Spatial Demography* 2021 doi: 10.1007/s40980-021-00078-7
20. Metcalf CJ, Tatem A, Bjornstad ON, et al. Transport networks and inequities in vaccination: remoteness shapes measles vaccine coverage and prospects for elimination across Africa. *Epidemiol Infect* 2015;143(7):1457-66. doi: 10.1017/s0950268814001988 [published Online First: 2014/08/15]
21. Tatem AJ GP, Bhatt S, Weiss D and Pezzulo C. Pilot high resolution poverty maps. In: Southampton/Oxford Uo, ed., 2013.
22. Graetz N, Woyczynski L, Wilson KF, et al. Mapping disparities in education across low- and middle-income countries. *Nature* 2020;577(7789):235-38. doi: 10.1038/s41586-019-1872-1
23. WorldPop. [Available from: <https://www.worldpop.org/> accessed Access Date: 15th August 2021.
24. Meijer JR, Huijbegts, M.A.J., Schotten, C.G.J. and Schipper, A.M. Global patterns of current and future road infrastructure. In: 13-064006 ERL, ed., 2018.
25. Abatzoglou JT, Dobrowski SZ, Parks SA, et al. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data* 2018;5(1):170191. doi: 10.1038/sdata.2017.191
26. Min BaOK, Zachary. High Resolution Electricity Access Indicators Dataset. In: Center for Political Studies UoM, ed., 2021.
27. Maina J, Ouma PO, Macharia PM, et al. A spatial database of health facilities managed by the public health sector in sub Saharan Africa. *Scientific Data* 2019;6(1):134. doi: 10.1038/s41597-019-0142-2
28. Weiss DJ, Nelson A, Gibson HS, et al. A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature* 2018;553(7688):333-36. doi: 10.1038/nature25181
29. OpenStreetMap contributors. [Available from: <http://download.geofabrik.de/africa.html> accessed Access Date: 15 Aug 2021.
30. Reiner RC, Jr., Wiens KE, Deshpande A, et al. Mapping geographical inequalities in childhood diarrhoeal morbidity and mortality in low-income and middle-income countries, 2000–2013;17: analysis for the Global Burden of Disease Study 2017. *The Lancet* 2020;395(10239):1779-801. doi: 10.1016/S0140-6736(20)30114-8

31. Reiner RC, Welgan CA, Casey DC, et al. Identifying residual hotspots and mapping lower respiratory infection morbidity and mortality in African children from 2000 to 2017. *Nature microbiology* 2019;4(12):2310-18. doi: 10.1038/s41564-019-0562-y [published Online First: 2019/10/02]
32. Brown LD, Cai TT, DasGupta A. Interval Estimation for a Binomial Proportion. *Statistical Science* 2001;16(2):101-33, 33.
33. Wood SN. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* 2011;73(1):3-36. doi: <https://doi.org/10.1111/j.1467-9868.2010.00749.x>
34. Marra G, Wood SN. Practical variable selection for generalized additive models. *Computational Statistics & Data Analysis* 2011;55(7):2372-87. doi: <https://doi.org/10.1016/j.csda.2011.02.004>
35. Chen T, Guestrin C. XGBoost: A Scalable Tree Boosting System. Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining. San Francisco, California, USA: Association for Computing Machinery, 2016:785–94.
36. Shuaib F, Garba AB, Meribole E, et al. Implementing the routine immunisation data module and dashboard of DHIS2 in Nigeria, 2014–2019. *BMJ Global Health* 2020;5(7):e002203. doi: 10.1136/bmjgh-2019-002203
37. Burton A, Monasch R, Lautenbach B, et al. WHO and UNICEF estimates of national infant immunization coverage: Methods and processes. *Bulletin of the World Health Organization* 2009;87(7):535-41. doi: Cited By (since 1996) 29

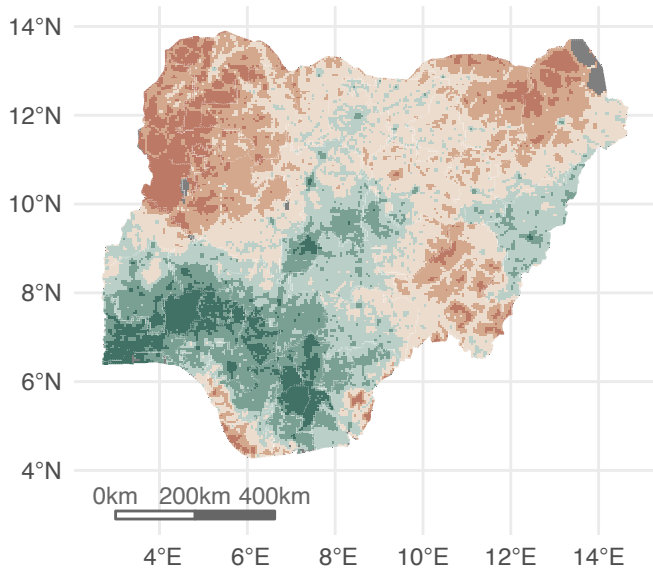
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38. Galles NC, Liu PY, Updike RL, et al. Measuring routine childhood vaccination coverage in 204 countries and territories, 1980–2019: a systematic analysis for the Global Burden of Disease Study 2020, Release 1. *The Lancet* 2021;398(10299):503-21. doi: 10.1016/S0140-6736(21)00984-3
39. Maïga A, Jiwani SS, Mutua MK, et al. Generating statistics from health facility data: the state of routine health information systems in Eastern and Southern Africa. *BMJ Global Health* 2019;4(5):e001849. doi: 10.1136/bmjgh-2019-001849
40. Begum T, Khan SM, Adamou B, et al. Perceptions and experiences with district health information system software to collect and utilize health data in Bangladesh: a qualitative exploratory study. *BMC Health Services Research* 2020;20(1):465. doi: 10.1186/s12913-020-05322-2

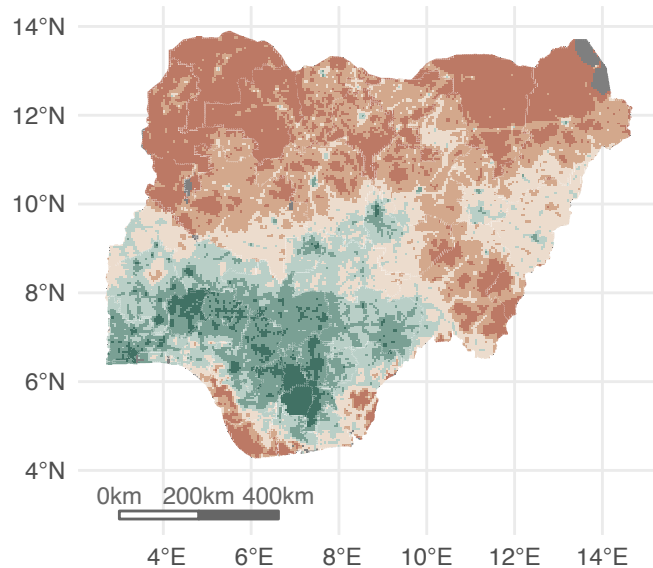
41. Onwujekwe O, Ezumah N, Mbachu C, et al. Exploring effectiveness of different health financing mechanisms in Nigeria; what needs to change and how can it happen? *BMC health services research* 2019;19(1):661-61. doi: 10.1186/s12913-019-4512-4
42. Abubakar I, Dalglish SL, Angell B, et al. The *Lancet* Nigeria Commission: investing in health and the future of the nation. *The Lancet* 2022;399(10330):1155-200. doi: 10.1016/S0140-6736(21)02488-0
43. Okafor J. Local government financial autonomy in Nigeria: the state joint local government account. *Commonwealth Journal of Local Governance* 2010(6):127-31.
44. Kawakatsu Y, Tanaka J, Ogawa K, et al. Community unit performance: factors associated with childhood diarrhea and appropriate treatment in Nyanza Province, Kenya. *BMC Public Health* 2017;17(1):202. doi: 10.1186/s12889-017-4107-0 [published Online First: 2017/02/18]
45. Dougherty L, Gilroy K, Olayemi A, et al. Understanding factors influencing care seeking for sick children in Ebonyi and Kogi States, Nigeria. *BMC Public Health* 2020;20(1):746. doi: 10.1186/s12889-020-08536-5 [published Online First: 2020/05/26]
46. Ugboko HU, Nwinyi OC, Oranusi SU, et al. Risk Factors of Diarrhoea among Children Under Five Years in Southwest Nigeria. *Int J Microbiol* 2021;2021:8868543-43. doi: 10.1155/2021/8868543

Figure 1. Predicted service coverage of essential health services in 2018.

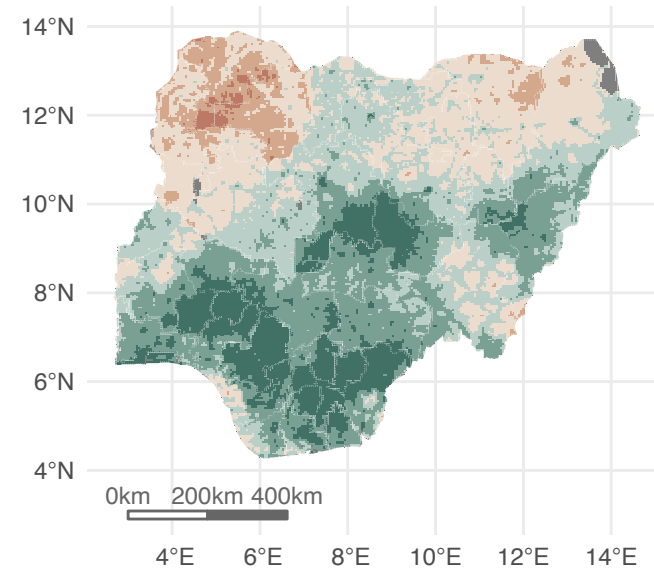
A. Antenatal care



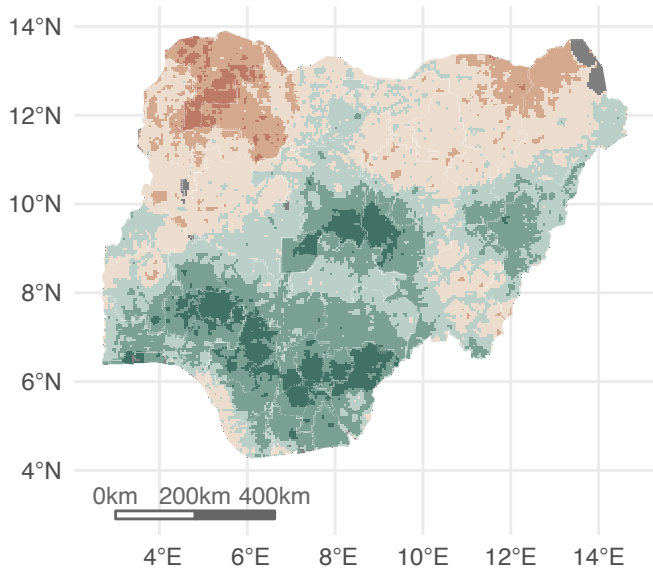
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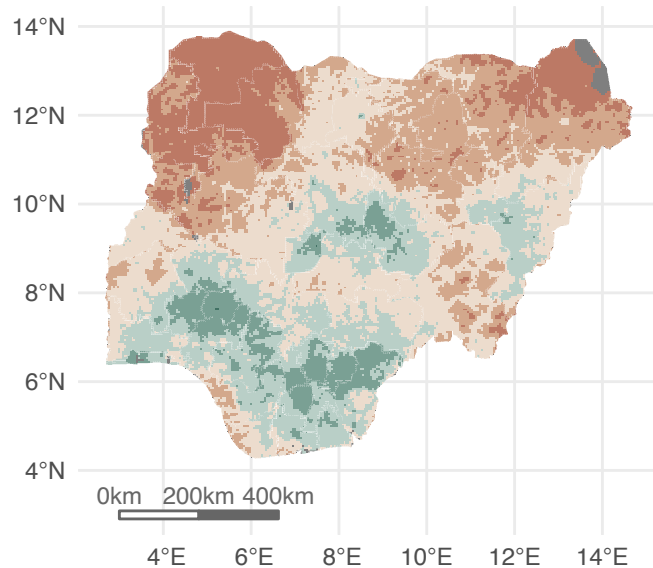
C. BCG vaccination



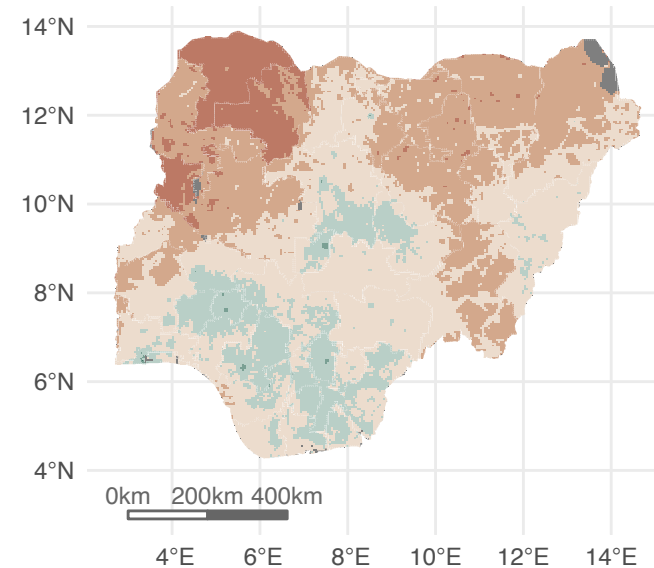
D. 1st pentavalent vaccination



E. 3rd pentavalent vaccination



F. Measles vaccination



% received

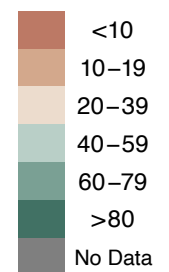


Figure 2. Predicted LGA-level coverage of eight essential MCH services in 2018 by state.

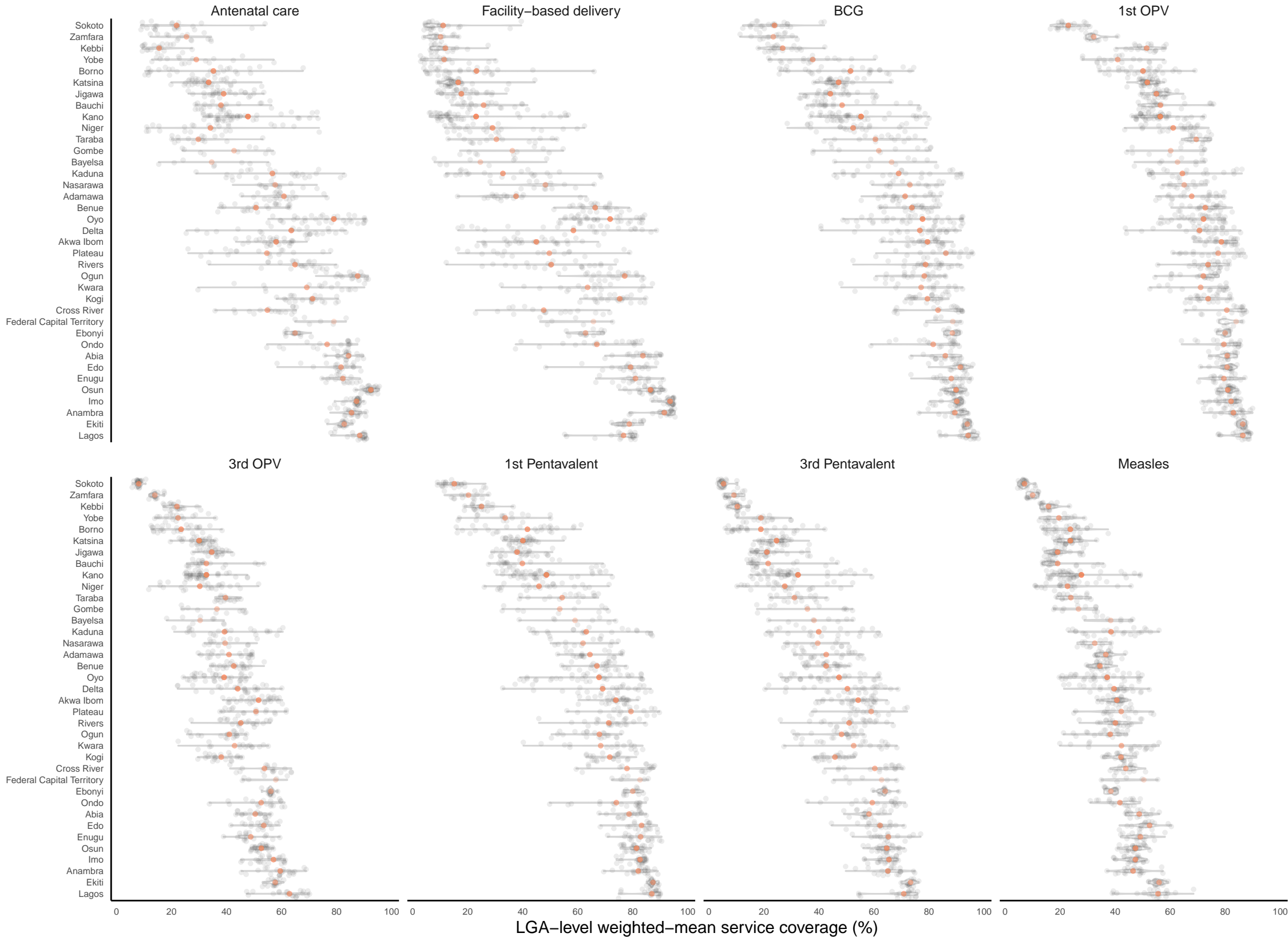
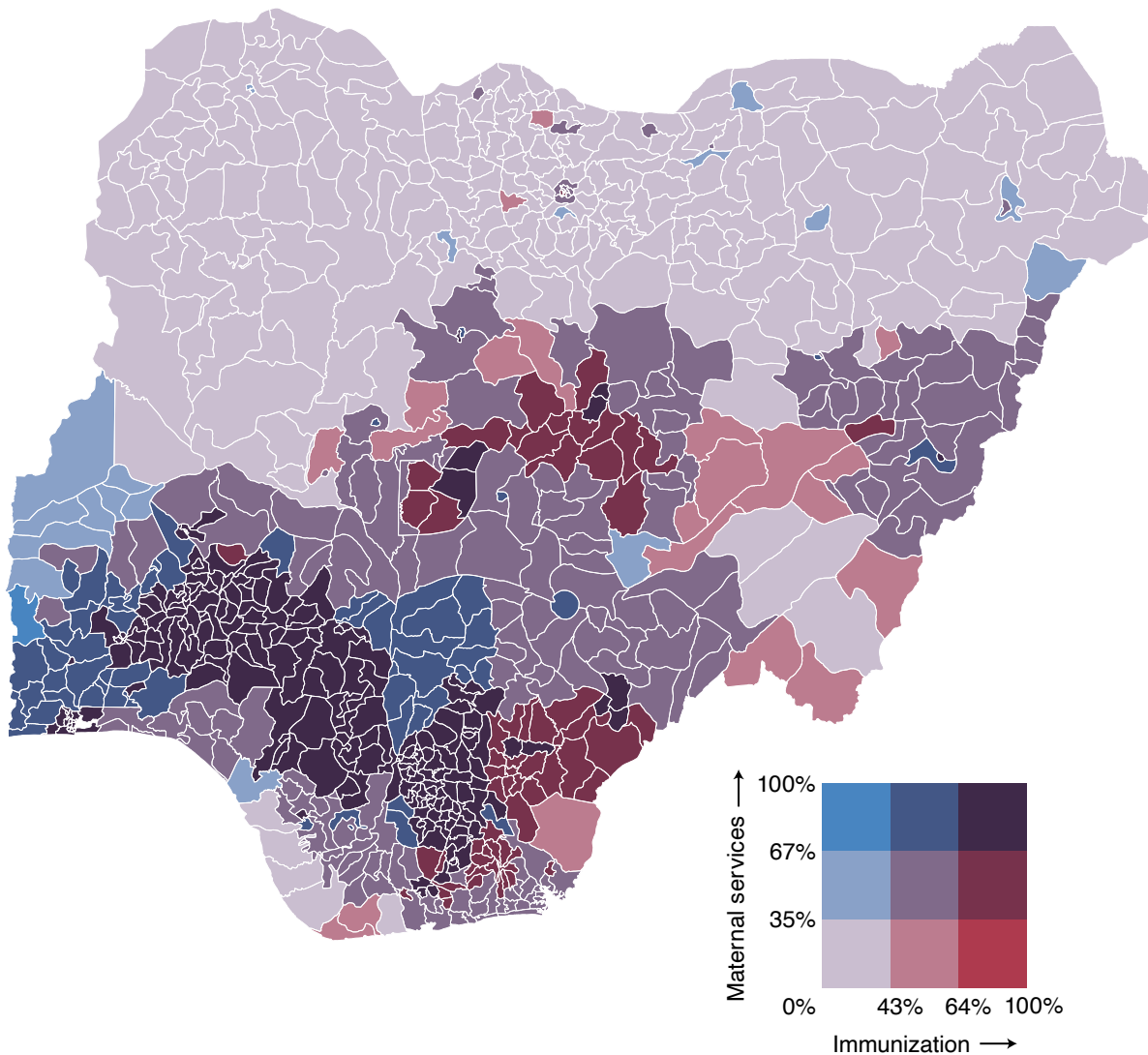


Figure 3. Service coverage distribution of essential maternal health services (ANC and facility-based delivery) and immunization services in 2018 as a bivariate choropleth map.



Aim 3:

High-resolution mapping of incremental cost and avoidable death estimation for achieving universal health coverage in Nigeria

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1. Introduction

Universal Health Coverage (UHC) is a global priority outlined in the Sustainable Development Goals 3.8. According to World Health Organization (WHO) in 2019,¹ the UHC service coverage index (SCI) increased from 45% in 2000 to 66% in 2017 globally, which was mainly contributed by the rapid increase of health service coverage for infectious disease and maternal and child health. However, the percentages covered by essential health services in low-income and lower-middle-income countries are 12-27% and 21-38%, respectively. Also, if current progress continues to 2030, 37% to 61% of the global population will not be covered by essential health services.¹ We need to accelerate the increase of essential health service coverage to reach the UHC target by 2030.

A recent study estimated that the annual required spending on essential UHC interventions in low-income countries (LICs) and in lower-middle-income countries (LMICs) would need to be USD 79 and 130 per capita respectively.² Another study reached similar conclusions by estimating outpatient and inpatient utilization and unit costs over time.³ Finally, Stenberg and colleagues⁴ estimated that an additional 41 USD per person would be needed per year to progress towards the SDG 3. While all these studies indicate that significant additional investment in health is needed to achieve UHC, none reported sub-national and community-level resources required, which could vary considerably by population size, service coverage and distance to health facilities in various communities. Policy makers and health ministries need to guide sub-national administrations and communities on how to use additional resources for maximal impact.

This study aims to estimate the potential gains in child health and additional costs required to increase the coverage of selected essential health services in Nigeria, with a focus on sub-national areas where the greatest investment is needed.

2. Methods

2.1 Overview

We estimated the additional required cost and the avoidable childhood mortality in 5 km² grid locations in Nigeria associated with delivering essential health services to 95% of the population. Based on that, we also estimated the incremental cost-effective ratio (ICER) by grid location and local government area (LGA). The essential health services we selected in this study are antenatal care (ANC), facility-based delivery, pentavalent and measles vaccinations. These services were defined as essential health services even during the COVID-19 pandemic.⁵⁻⁷ In addition, the costs and effectiveness of these services were reported in the previous studies and the OneHealth tool. Table 1 shows the list of health interventions in the essential health services, which are based on the OneHealth tool (ver. 6.24). In this study, we have three types of facility-based delivery since each type has a different set of health interventions: skilled delivery, Basic Emergency Obstetric Care (BEmOC), and Comprehensive Emergency Obstetric Care (CEmOC).

ICER (O_{ijst}) is calculated using the following formula:

$$O_{ijst} = \frac{\sum_{n=0}^s R_{ijst}}{\sum_{n=0}^s L_{ijst}}$$

$\sum_{n=0}^s R_{ijst}$ represents the sum of incremental costs to increase s^{th} service coverage from the baseline to 95% in the i^{th} grid location of the j^{th} state in year t . $\sum_{n=0}^s L_{ijst}$ denotes the sum of deaths avoidable

by increasing the coverage of s^{th} service to 95% in the i^{th} grid location of the j^{th} state in year t . The details of each component are explained in the following sections (2.2 and 2.3).

2.2 Incremental cost (R_{ijst})

The simplified formula for calculating total (E_{ijst}), baseline (B_{ijst}) and incremental cost (R_{ijst}) to increase coverage of the s^{th} essential health service to 95% is as follows:

$$E_{ijst} = B_{ijst} + R_{ijst}$$

$$E_{ijst} = (P_{ijst} \times U_{ijs}) \times ce_{ijst} + oe_{ijst}$$

$$B_{ijst} = (P_{ijst} \times U_{ijs}) \times cb_{ijs} + ob_{ijst}$$

E_{ijst} denotes the total cost to achieve the expected coverage (ce_{ijst}) of the s^{th} health service in the i^{th} grid location of the j^{th} state in year t . P_{ijst} represents the target population for the s^{th} health service in the i^{th} grid location of the j^{th} state in year t . oe_{ijst} represents the total cost of outreach services for the s^{th} health service in the i^{th} grid location of the j^{th} state in year t . Similarly, B_{ijst} and ob_{ijst} denote the baseline cost and outreach service cost to achieve base coverage (cb_{ijs}). R_{ijst} indicates the incremental cost for the s^{th} health service in the i^{th} grid location of the j^{th} state in year t , which is calculated by subtracting B_{ijst} from E_{ijst} . We exclude oe_{ijst} and ob_{ijst} for antenatal care and facility-based delivery, since both services should be provided at health facilities.

2.2.1 Target Population (P_{ijst})

We calculated the size of the target population that should receive the s^{th} essential health service in the i^{th} grid location of the j^{th} state in year t . The target population for antenatal care is pregnant women and for facility-based delivery and vaccinations is live births. The number of pregnancies and births per 1 km² in 2015 were extracted from the WorldPop database.⁸ We estimated the population growth rate in the i^{th} grid location by calculating the annual change in total population between 2015 and 2019 in that grid location. We forecast the target population in the i^{th} grid location of the j^{th} state from 2023 to 2030 using the population growth rate since there was no data available on age-specific fertility rates and all-cause age-specific mortality rates.

2.2.2 Mean costs of essential health service per target population (U_{ijs})

We used the OneHealth tool (ver. 6.24) developed by Avenir Health to estimate the mean costs and time required to provide essential health services per target population, as shown in Table 2. Supplement files 1 and 2 provide the annual salary of health personnel and expected time required to provide each intervention by health personnel. Supplement file 3 provides the percentage of population in need, the list and cost of required medicines/supplies per case and per target population, and the human resource cost and required time by type of health personnel.

In addition, we added 50% of medicines/supplies costs as indirect facility-level costs and 17% of medicines/supplies and indirect facility-level costs as above health-facility costs. These are the same assumptions the previous study used.²

2.2.3 Expected and base service coverage (ce_{ijst} , cb_{ijs})

In this study, the target coverage for each essential service in 2030 was set at 95%. We treat the grid-level service coverage estimates in 2018 as the baseline service coverage based on the previous study. In this study, we assumed that the service coverage in 2018 was maintained at the same level through 2023 and that service coverage will linearly increase from 2024 to 2030 to achieve 95% coverage. We assume that the impact of COVID-19 pandemic on the selected service coverage was not significant. According to Nigeria MICS 2021,⁹ coverage of the selected essential health service slightly increased, compared to the DHS in 2018.

2.2.4 Outreach service cost (oe_{ijst} , ob_{ijst})

Outreach service cost for vaccination services is estimated using the following formula:

$$O_{ijst} = te_{ijst} \times \{(dis_{ijs} \times (c_j + s)) \times 2 + (ad + car)\}$$

$$te_{ijst} = (P_{ijst} \times co_{ijst} \times per_{ijs} \times dose_s) / N$$

O_{ijst} indicates the cost of outreach service for the s^{th} health service in the i^{th} grid location of the j^{th} state in year t . te_{ijst} denotes the number of outreach service to be conducted in the i^{th} grid location of the j^{th} state in year t . P_{ijst} represents the target population of the s^{th} health service in the i^{th} grid location of the j^{th} state in year t . co_{ijst} denotes the service coverage of the s^{th} health service in the i^{th} grid location of the j^{th} state in year t . per_{ijs} denotes the percentage of the s^{th} health service provided by outreach. $dose_s$ indicates the number of doses required for target population (i.e., 3 for pentavalent and 2 for measles vaccines). N represents the average number of vaccination doses per outreach. We set 41 in urban areas and 9 in rural areas as the average number of doses administered per outreach session.¹⁰ dis_{ijs} indicates travel time (minutes) from the i^{th} grid location to the most accessible health facility assuming access to motorized transportation. C_j indicates the transportation cost of motorized transportation per minute by living location (urban or rural) and state. s , ad , and car denote the salary of a nurse per minute, administrative cost and rental car cost, respectively.

According to the previous study in Nigeria,¹¹ adding 1 km to distance to the nearest health facility reduces the likelihood of receiving DPT3 and measles vaccination by 8.8 and 8.2%. Since the travel time by walking was calculated assuming a walking speed of 5 km per hour in all road conditions,¹² We assumed that 8.5% of additional vaccinations would need to be provided by outreach services if walking travel time from the grid location to the most accessible health facility increases by 12 minutes. Also, we assumed 0% of vaccinations was provided by outreach in the grid locations with less than 12 minutes of walking travel time to the nearest health facility.

Travel time (minutes) from the i^{th} grid location to the most accessible health facility using motorized transportation was extracted from the global map developed by the previous study.⁶ We used the Nigeria General Household Survey (NGHS) Wave 3 in 2016 and Wave 4 in 2018 to estimate transportation cost per minute by living location (urban or rural) and state. These surveys collected travel time and transportation costs of motorized transportation from a community center to important structures such as health facilities, schools, and markets in 447 communities. The transportation cost in NGHS was measured in Naira. The exchange rate in this study is 460 Naira

per USD (Central Bank of Nigeria as of April 15, 2023). In addition, to conduct outreach services, health workers need to spend some time coordinating with community members and arrange rental cars. Due to the limited data of coordination time and cost of hiring rental care in each region, we assumed 30 min and 30,000 Naira (i.e., 65 USD) per time in this study based on our experience. We define an urban area as having a minimum total population of 20,000 population based on Global Urban Rural Catchment Areas (URCA). All other areas are classified as rural.

To understand variation in transportation costs and travel time, we estimated negative binomial regressions for each outcome. (The negative binomial is appropriate as transportation costs were count data measured in either Naira or minutes, both measured as integers). We treated travel time as an offset with a fixed logarithmic relationship to these counts and included survey year, living location and state as independent variables. Using the model, we estimated mean transportation cost by living location and state in 2020, assuming the inflation rate from 2016 to 2018 held through 2020. The estimated transportation cost per minute and to the nearest health facility are shown in Supplement file 4.

2.3 Number of avoidable deaths (D_{ijst})

The simplified formula of calculating the number of avoidable deaths (D_{ijst}) by increasing s^{th} essential health services coverage to 95% is as follows:

$$D_{ijst} = \{(P_{ijst} \times M_s) \times \{(ce_{ijst} - cb_{ijst}) \times rrr_s\}\} / (1 - (rrr_s * cb_{ijst}))$$

D_{ijst} indicates the number of avoidable deaths for the s^{th} health service in the i^{th} grid location of the j^{th} state in year t . P_{ijst} represents the target population for the s^{th} health service in the i^{th} grid location of the j^{th} state in year t . ce_{ijst} and cb_{ijst} represent the expected coverage of the s^{th} health service in the i^{th} grid location of the j^{th} state in year t and baseline coverage in 2023, respectively. M_s denotes the mortality rate for the s^{th} health service. rrr_s denotes relative risk reduction (RRR) for the s^{th} health service.

The mortality rate and RRR for the selected essential health service are summarized in Table 3. We used neonatal and under five mortality by geopolitical zone based on the MICS 2021.⁹ Relative risk reduction (RRR) of ANC is 39%.¹³ The percentage of avoidable mortality and relative risk reduction (RRR) of facility-based delivery is 24% and 25-86% respectively based on the Delphi estimates of mortality effects.¹⁴ Finally, the percentage of all-cause deaths avoided by pentavalent and measles vaccination were calculated using the ratio of specific causes of death to all-cause mortality based on the Global Burden of Disease 2019.¹⁵ RRR of pentavalent and measles vaccinations are based on previous studies.^{16,17}

3. Results

3.1 Incremental cost to achieve 95% population coverage by 2030.

Figure 1 shows the total cost to achieve 95% coverage of essential health services by type of cost. The total cost of achieving the target coverage in 2030 was 94 million USD for ANC, 285 million USD for skilled delivery, 499 million USD for BEmOC, 584 million USD for CEmOC, 71 million USD for pentavalent and 58 million USD for measles vaccinations. More than half of total costs for

ANC, skilled delivery, BEmOC and CEmOC comprise human resource costs (78.2% for ANC, 72.2% for skilled delivery, 68.6% for BEmOC, and 67.3% for CEmOC). On the other hand, for vaccination services, outreach is the primary cost driver (75.6.1% for pentavalent and 61.7% for measles vaccination).

High-resolution maps of the mean annual incremental cost per capita by health service are shown in Figure 2. The maps highlight the grid locations and LGAs that require the largest additional investment in order to achieve universal coverage. The mean incremental annual cost per capita were 3.1 USD for ANC, 10.8 USD for skilled delivery, 19.0 USD for BEmOC, 22.2 USD for CEmOC, 5.2 USD for pentavalent vaccination, and 5.7 USD for measles vaccination. The interquartile range (IQR) of the incremental cost per capita varied by health service: 2.2 – 4.1 USD for ANC, 8.0 – 14.1 USD for skilled delivery, 13.9 – 24.6 USD for BEmOC, 16.3 – 28.9 USD for CEmOC, 2.5 – 7.0 USD for pentavalent vaccination, and 2.9 – 7.6 USD for measles vaccinations. Except in cities, incremental costs in the northern parts of Nigeria were higher than in the south. As shown in Supplement file 5, most parts of the northern Nigeria needed to increase health coverage by 8% or more every year from 2024 to 2030 to achieve 95% population coverage. Finally, Supplement file 6 presents grid-level cumulative total cost by service.

3.2 Avoidable deaths by increasing essential health service coverage.

The cumulative number of avoidable childhood deaths from increasing essential health service coverage from the baseline to 95% by 2030 is 240,000 for ANC, 43,000 for skilled delivery, 73,000 for BEmOC, 190,000 for CEmOC, 390,000 for Pentavalent vaccination, and 99,000 for measles vaccination. Supplement file 7 shows the number of cumulative avoidable deaths by grid location and service. Figure 3 shows the LGA-level cumulative avoidable deaths and relative reduction from increasing coverage of maternal services (ANC and BEmOC) and vaccinations (Pentavalent and measles vaccines) to 95% coverage from 2024 to 2030. 31.6% of LGAs had more than 500 additional deaths averted over 7 years by increasing maternal service, while 45.6% of LGAs saved more than 500 childhood lives over 7 years by increasing vaccination service. Due to low service coverage (as shown in Supplement 5) the northern part of Nigeria had a higher relative reduction compared to the southern part of Nigeria. LGAs with larger population were more likely to result in more avoidable deaths but smaller relative reductions since the service coverage in these LGAs were higher than other LGAs.

3.3 Incremental cost-effective ratio (ICER)

Figure 4 shows the ICER of increasing either maternal coverage or vaccination coverage, as well as the ICER of increasing both. The figure also provides a ranking of LGAs by ICER. The highest ICER of maternal, vaccination and both services were 12,786 USD, 3719 USD and 4284 USD, respectively. For maternal service ICER, rural LGAs in the south east geopolitical zone had higher ICERs. Grid locations with close to health facility (i.e., within 12 minutes by walking), assuming no need for outreach service, had lower ICERs than other areas on average. Most LGAs in the North Central Region had lower rank based on maternal service ICER and vaccination service ICER. Supplement 8 reports maternal, vaccine, and total ICER and ranks for each LGA.

Discussion

This study estimated the incremental costs and mortality consequences of increasing maternal and vaccination services at the grid- and LGA-levels in Nigeria. ICER was also calculated to confirm the cost-effectiveness of these services in all LGAs. This study utilized the latest grid-level data on target populations, mortality, service coverage, and time to health facility. We also used the OneHealth tool to calculate unit cost for each target population and took into account outreach cost for delivering vaccination service, indirect facility-level costs and above-health facility costs.

Our estimates of service-specific incremental costs by LGA will help project managers and government officials estimate the gap between current budgets and budgets required to hit 95% coverage targets by 2030, a key step in develop strategies to fill in these gap. We also show these strategies must focus on labor. 65.9% of the total cost of achieving 95% population coverage of ANC, BEmOC, Pentavalent and measles vaccination were labor costs. While we also added above health-facility costs in our estimation based on the previous study², training new health workers could also require larger budgets. Further investigation is needed to estimate the required number of health workers and training cost to achieve target service coverage.

LGAs with lower service coverage and smaller population size will need to expand their budgets more per capita in order to catch up.. A previous study estimated that incremental annual cost per capita to achieve 80% of coverage of 115 and 218 unique health interventions in 21 essential packages were 43 USD and 92 USD in lower-middle-income countries. In the present study, the incremental annual cost per capita for achieving 95% of population coverage of ANC, BEmOC, pentavalent and measles vaccination was 32 USD. It is challenging to compare these results given differences in target coverage, the number of health interventions included, and methodologies employed between the two studies. However, our study underscores the substantial financial commitment required to achieve UHC. Also, the wide range of IQR of the incremental cost per capita between LGAs highlighted the need for subnational-level cost analysis to inform efficient resource allocation. Given geographic diversity and varying health needs and resources across Nigeria, localized estimates of required costs are fundamental for developing effective UHC strategies.

Outreach cost accounted for a major part of vaccination service cost. Key components in calculating outreach cost include the number of doses administered per session, the travel time to health facility, and the percentage of vaccinations provided by outreach service. Increasing the number of doses administered per session would result in considerable cost savings. This underscores the importance of effective planning and coordination in the delivery of outreach services. Strategies to increase the number of children reached during each session, such as robust community engagement, advance notice, and reliable scheduling, can play an essential role in increasing the number of doses administered per session.

Another strategy to reduce the incremental cost of outreach service is to establish new health facilities or posts. This approach requires not only an initial investment for facility establishment but also maintenance costs. On the other hand, newly established health facilities can provide a wide range of health services beyond vaccination. By making health facilities accessible to the surrounding population, there would be potential savings in outreach. However, it is essential to carefully consider the cost-effectiveness of this approach, considering the size of the population served, their health needs, and the financial and logistical capacity to establish and maintain health facilities.

This study confirmed that both maternal and vaccination services were cost-effective interventions in all LGAs, although there was significant variation in ICER. Locations with high baseline service coverage and low outreach cost, which indicated having more health sources, had lower ICER than other areas. Also, childhood mortality and the percentage of all-cause deaths avoided by pentavalent and measles vaccination in urban areas may be lower than those in rural areas. Since we used the consistent mortality and the percentage of avoidable deaths values across geopolitical zones or the country, estimated avoidable deaths in urban areas may be overestimated, which resulted in lower ICER. Accounting for substantial variations in mortality, the burden of diseases, and health resources would improve the estimation of avoidable deaths and ICER.

Limitations

This study has several limitations. One concern is utilizing the high-resolution maps on service coverage estimated in the previous study. The latest maps were in 2018. Since there was no survey data with GPS coordinates, we could not update the map for this study. If significant improvements have occurred in a specific district or community recently, these maps would not capture those changes. Another limitation is the lack of sufficient grid- and district-level data on mortality and the percentage of all-cause deaths. These values were uniform across the country or geopolitical zones. It would result in underestimate or overestimate avoidable deaths depending on the location. Also, in this study, we assumed that an additional 8.5% of vaccinations are provided by outreach services, as a 12 minutes of walking travel time increase. While this assumption is based on the previous study in Nigeria,¹¹ it assumed a linear association between access to health facility and vaccination service utilization. However, the relationship between accessibility and service utilization may not always be linear. Our model also assumed that 95% population coverage can be reachable with adequate funding. However, it may be unrealistic due to vaccine hesitancy and religious reasons. The cost-effectiveness of vaccination service decreased as reaching to 80 – 90% of vaccination coverage. Furthermore, this study did not account for a synergy effect between health services.

Reference

1. World Health Organisation. Primary Health Care on the Road to Universal Health Coverage 2019 MONITORING REPORT CONFERENCE EDITION. Geneva: World Health Organization, 2019.
2. Watkins DA, Qi J, Kawakatsu Y, Pickersgill SJ, Horton SE, Jamison DT. Resource requirements for essential universal health coverage: a modelling study based on findings from Disease Control Priorities, 3rd edition. *The Lancet Global Health* 2020; **8**(6): e829-e39.
3. Moses MW, Pedroza P, Baral R, et al. Funding and services needed to achieve universal health coverage: applications of global, regional, and national estimates of utilisation of outpatient visits and inpatient admissions from 1990 to 2016, and unit costs from 1995 to 2016. *The Lancet Public Health* 2019; **4**(1): e49-e73.
4. Stenberg K, Hanssen O, Edejer TT-T, et al. Financing transformative health systems towards achievement of the health Sustainable Development Goals: a model for projected resource needs in 67 low-income and middle-income countries. *The Lancet Global Health* 2017; **5**(9): e875-e87.
5. World Health O. Guiding principles for immunization activities during the COVID-19 pandemic: interim guidance, 26 March 2020. CC BY-NC-SA 3.0 IGO. Geneva: World Health Organization, 2020.

6. World Health Organisation, UNICEF, UNFPA. Continuing essential Sexual, Reproductive, Maternal, Neonatal, Child and Adolescent Health services during COVID-19 pandemic. Geneva: World Health Organization, 2020.
7. Plotkin MK, Williams KM, Mbinda A, et al. Keeping essential reproductive, maternal and child health services available during COVID-19 in Kenya, Mozambique, Uganda and Zimbabwe: analysis of early-pandemic policy guidelines. *BMC Public Health* 2022; **22**(1): 577.
8. WorldPop. <https://www.worldpop.org/> (accessed Access Data: 15th August 2021).
9. National Bureau of Statistics (NBS), United Nations Children's Fund (UNICEF). Multiple Indicator Cluster Survey 2021, Survey Findings Report. Abuja, Nigeria: National Bureau of Statistics and United Nations Children's Fund, 2022.
10. Flavia Moi, Christina Banks, Laura Boonstoppel. The cost of routine immunization outreach in the context of COVID-19: estimates from Tanzania and Indonesia THINK WELL, 2020.
11. Sato R. Association between access to a health facility and continuum of vaccination behaviors among Nigerian children. *Human vaccines & immunotherapeutics* 2020; **16**(5): 1215-20.
12. Weiss DJ, Nelson A, Vargas-Ruiz CA, et al. Global maps of travel time to healthcare facilities. *Nature Medicine* 2020; **26**(12): 1835-8.
13. Tekelab T, Chojenta C, Smith R, Loxton D. The impact of antenatal care on neonatal mortality in sub-Saharan Africa: A systematic review and meta-analysis. *PloS one* 2019; **14**(9): e0222566.
14. Lee AC, Cousens S, Darmstadt GL, et al. Care during labor and birth for the prevention of intrapartum-related neonatal deaths: a systematic review and Delphi estimation of mortality effect. *BMC Public Health* 2011; **11 Suppl 3**(Suppl 3): S10.
15. Global burden of 369 diseases and injuries in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet* 2020; **396**(10258): 1204-22.
16. Bairwa M, Paliana M, Rajput M, et al. Pentavalent vaccine: a major breakthrough in India's Universal Immunization Program. *Human vaccines & immunotherapeutics* 2012; **8**(9): 1314-6.
17. Fulton TR, Phadke VK, Orenstein WA, Hinman AR, Johnson WD, Omer SB. Protective Effect of Contemporary Pertussis Vaccines: A Systematic Review and Meta-analysis. *Clin Infect Dis* 2016; **62**(9): 1100-10.

Figure 1. Total and incremental cost to achieve 95% population coverage by 2030

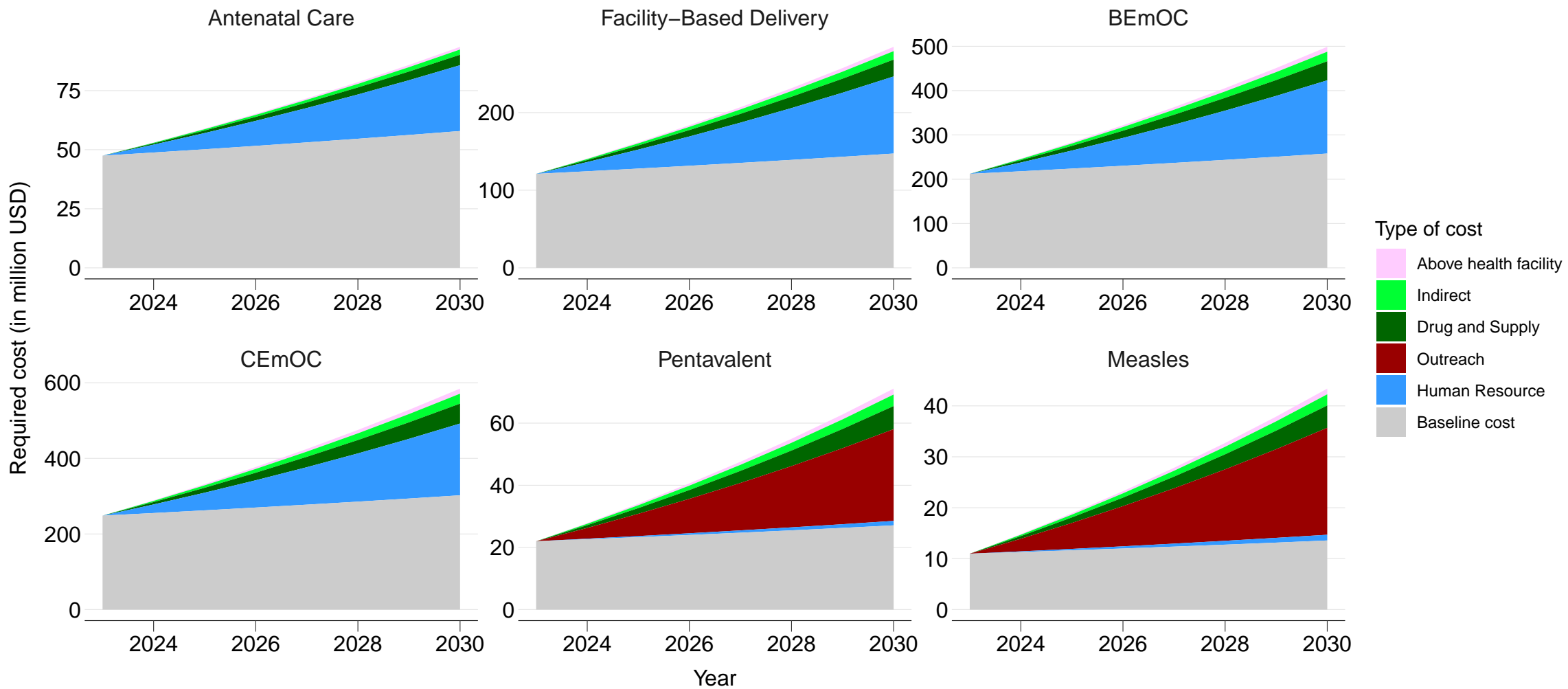


Figure 2. Annual incremental cost per capita (in USD) by essential health service

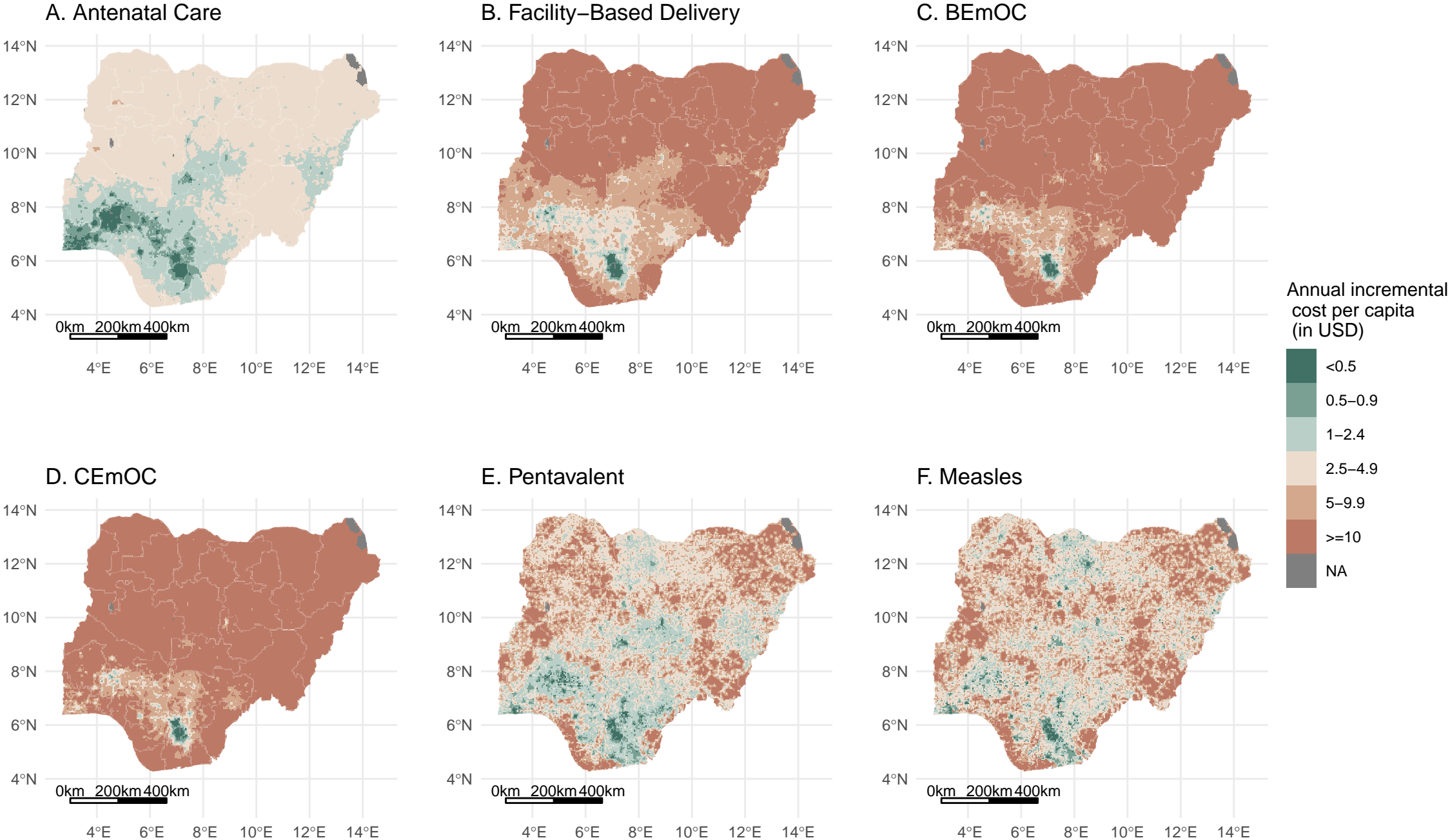


Figure 3 Avoidable deaths and relative reduction by maternal and vaccination services

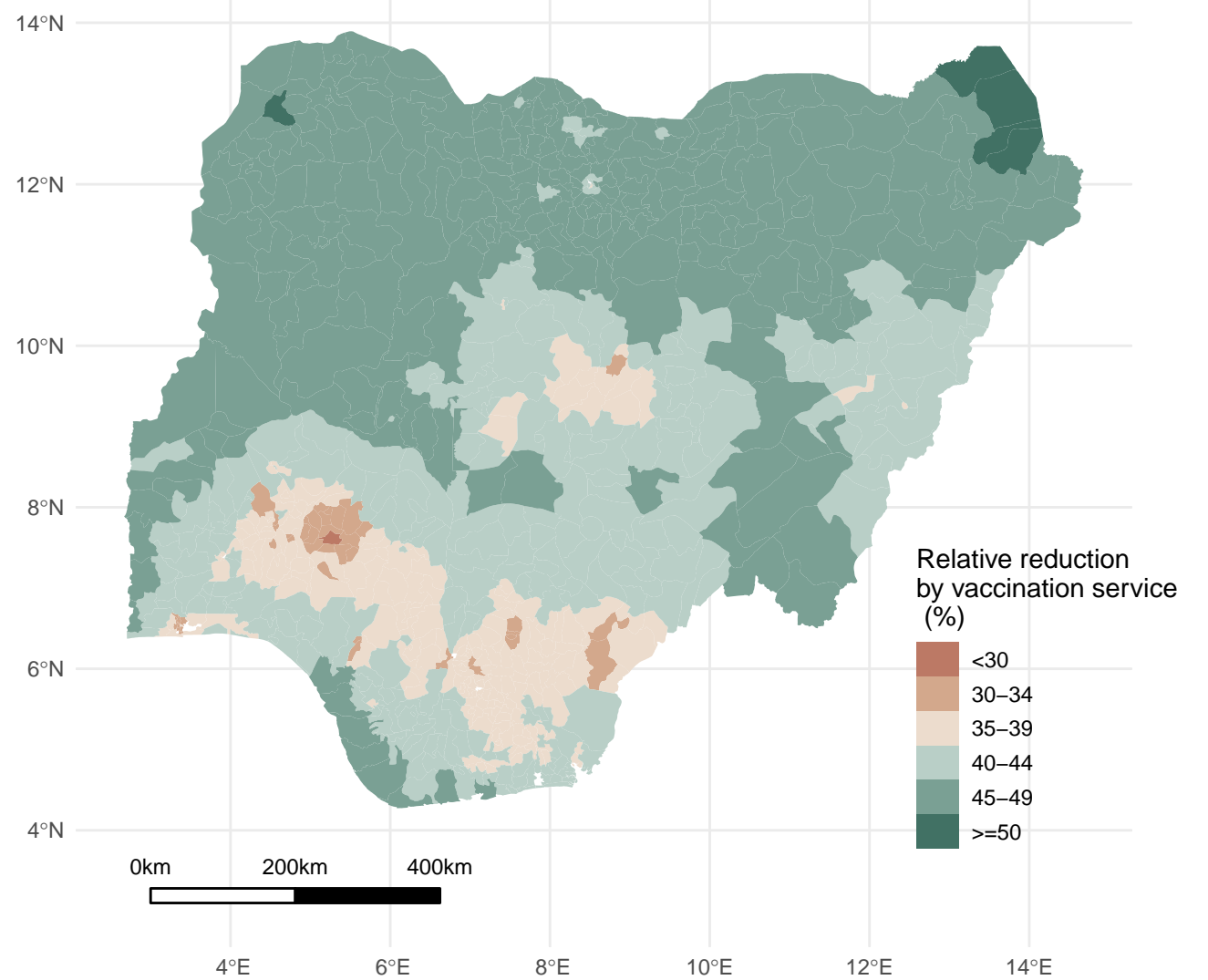
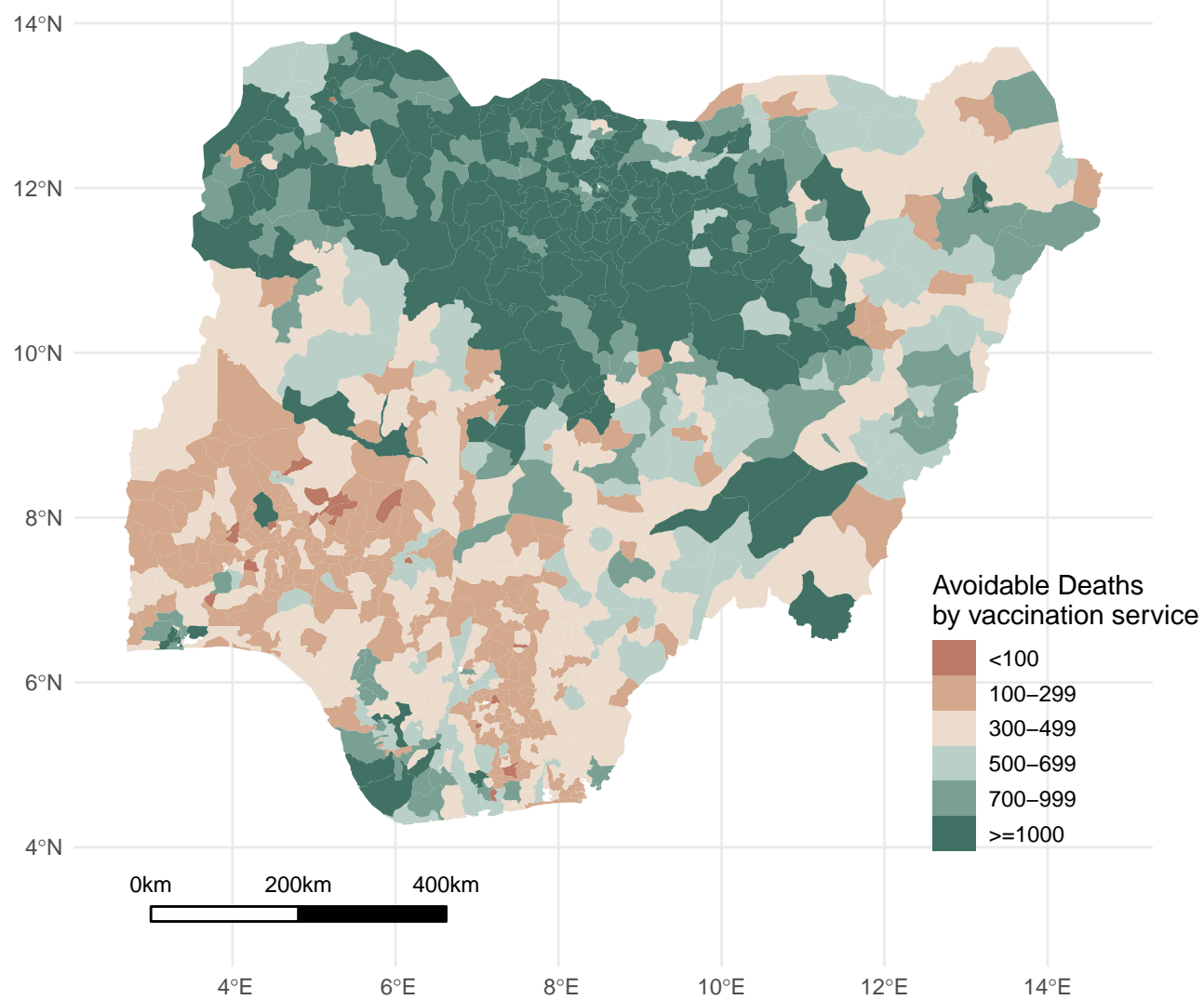
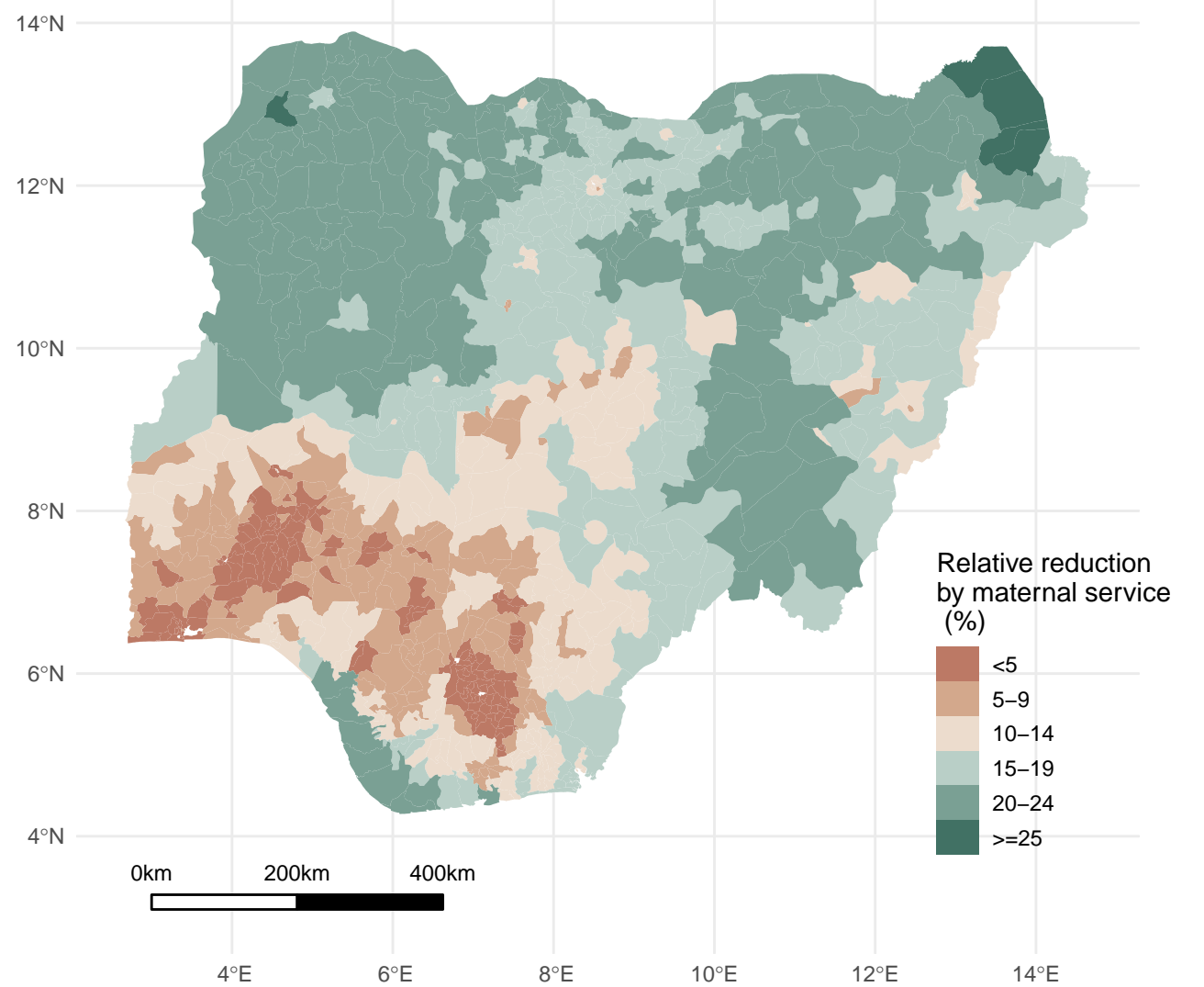
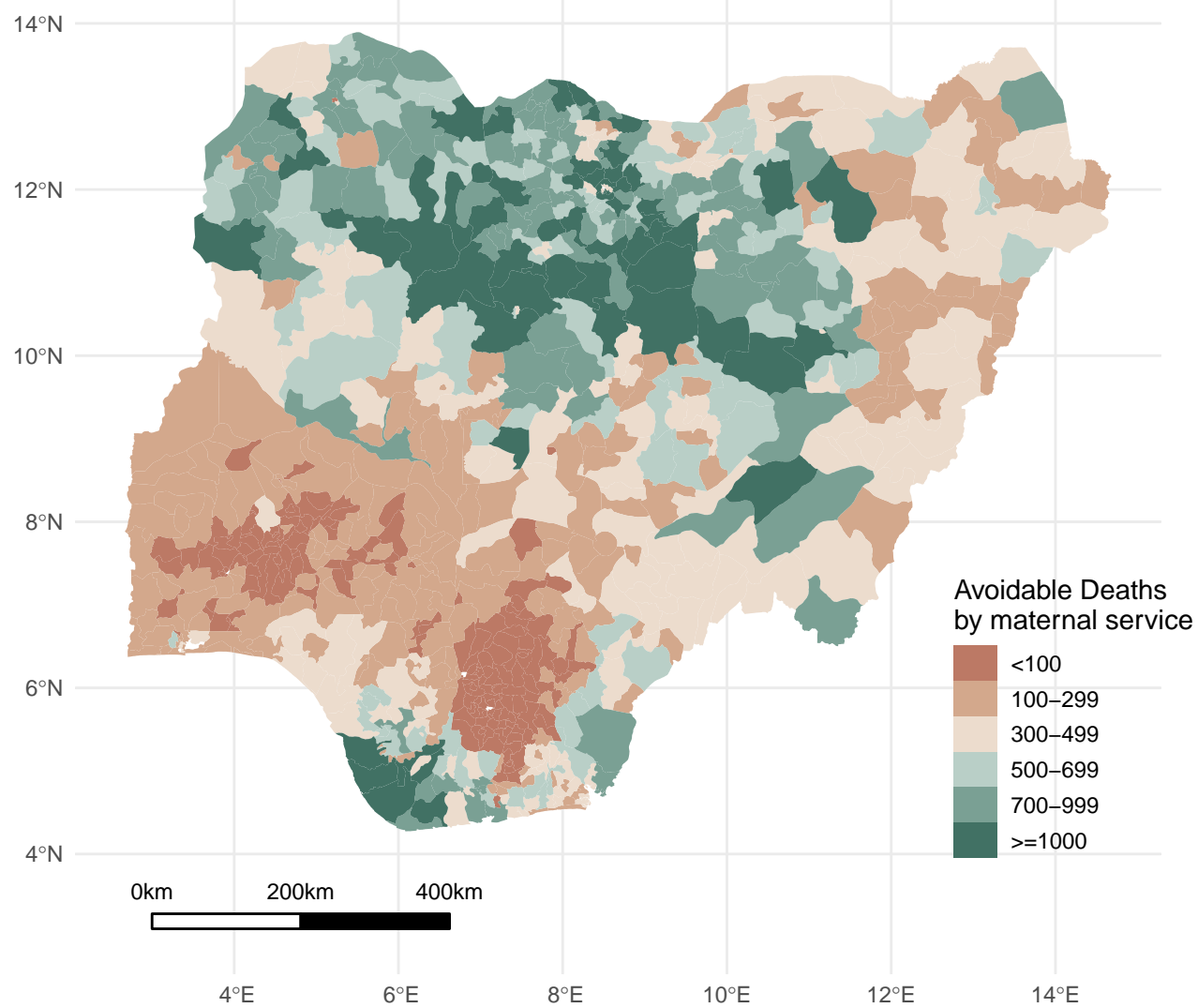
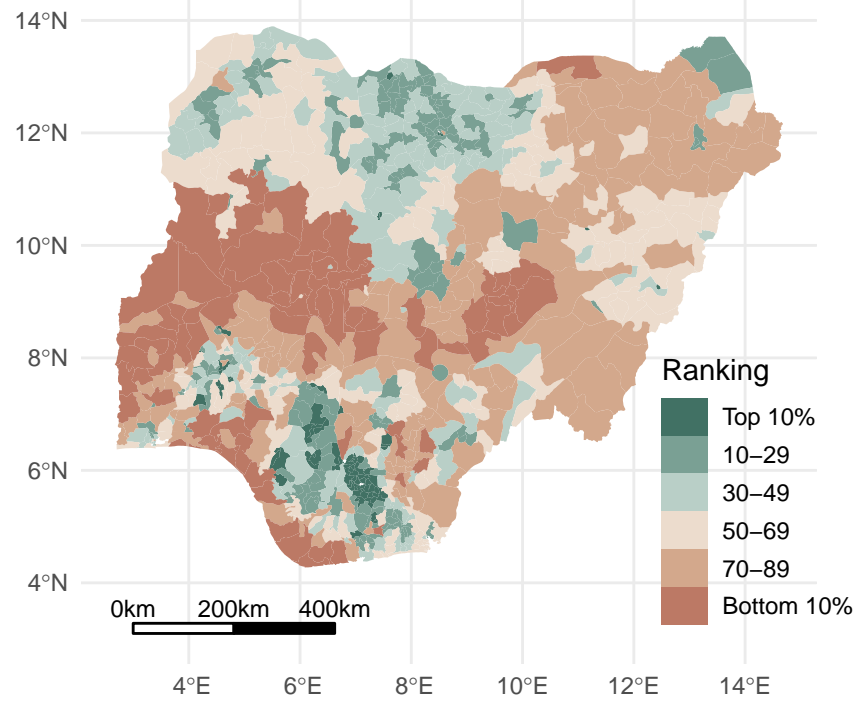
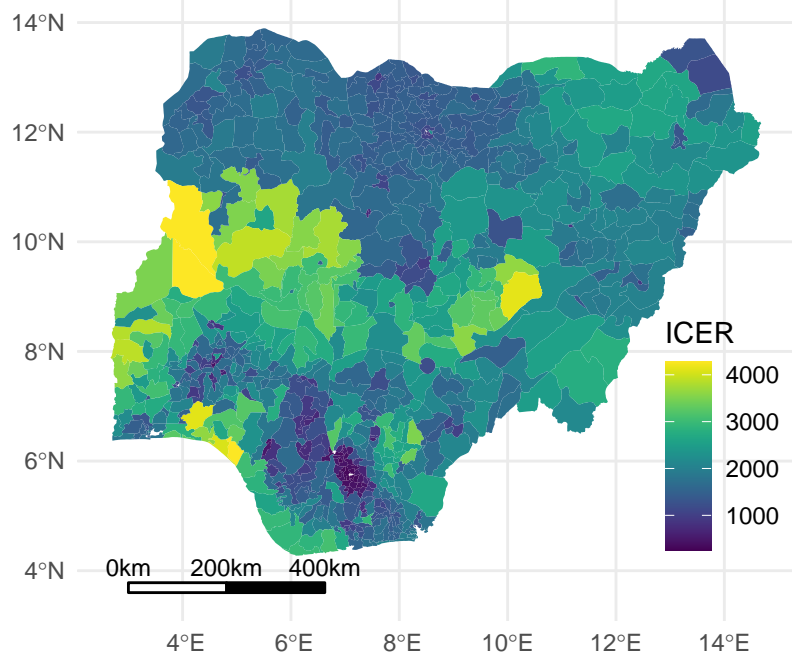
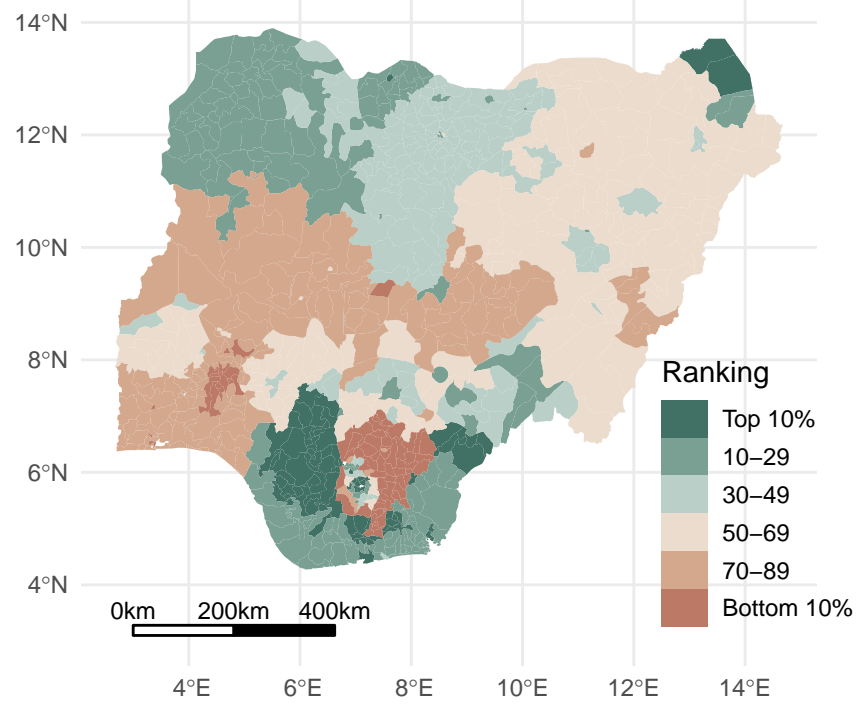
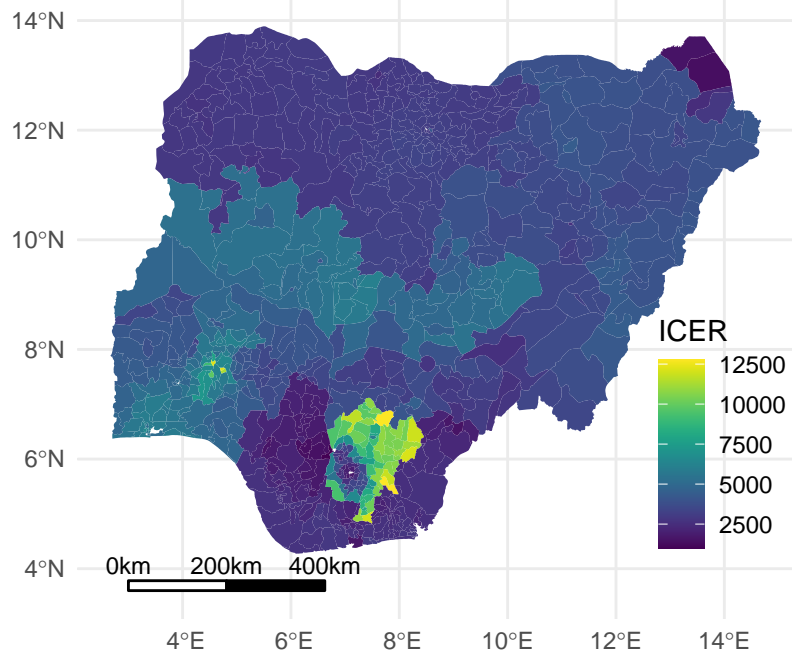


Figure 4. LGA-level cumulative avoidable deaths and relative reduction

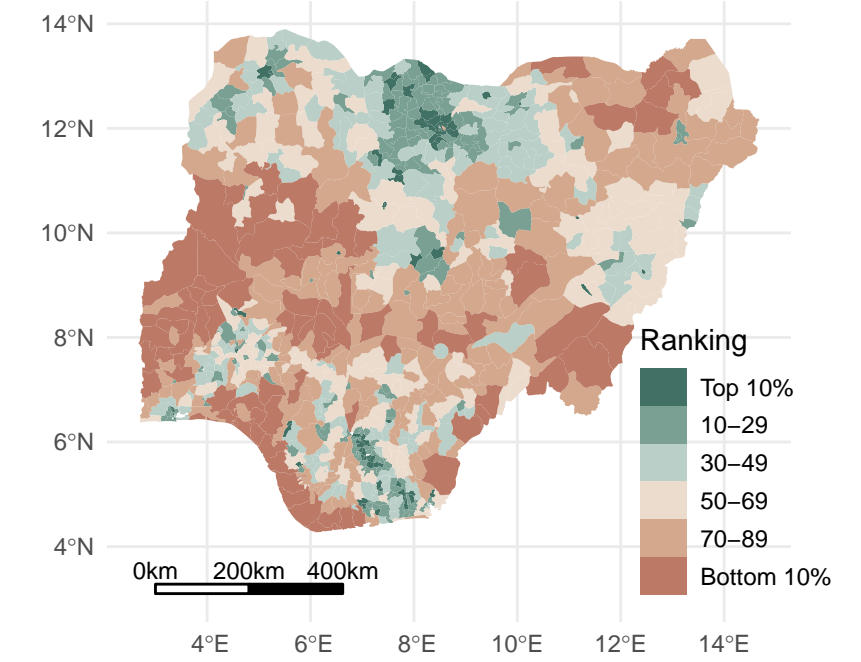
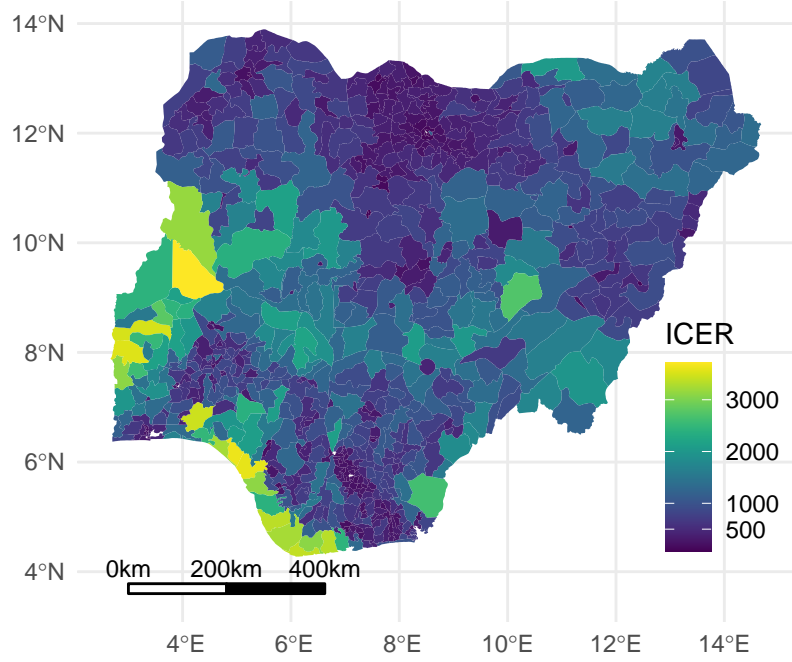
Maternal and Vaccination service



Maternal service



Vaccination service



Conclusion

This dissertation aimed to address the priority setting for achieving Universal Health Coverage (UHC) in Nigeria through a spatial and temporal analysis and cost-benefit analysis. The findings and implications of this research shed light on the challenges and opportunities for improving healthcare accessibility and service coverage in Nigeria.

The Aim 1 study identified individual and contextual factors consistently associated with the utilization of multiple essential maternal and child health services in Nigeria. Higher maternal education and households' wealth were significantly associated with utilization of all types of essential MCH services. On the other hand, households with more children under five years of age and in poor communities were significantly less likely to utilize essential MCH services. Except for childhood immunizations, greater access to transportation was positively associated with utilization. Households with longer travel times to the most accessible health facility were less likely to utilize all types of essential MCH services, except modern contraceptive use and treatment of childhood fever and/or cough. These results allow policymakers to identify the consistent barriers to essential maternal and child health services, and characteristics of underserved populations. It would enable them to develop targeted interventions and policies to improve service coverage.

The Aim 2 study estimated the grid-level coverage of selected essential maternal and child health services in Nigeria using generalized additive models and Gradient Boosting techniques. By mapping the service coverage across the country, policymakers can identify areas with low service coverage and prioritize resource allocation accordingly. This spatial analysis reveals National and sub-national MCH service coverages mask significant spatial heterogeneity in Nigeria, which may result in poor decision making on geographical prioritization at the LGA level. Also, inequities in MCH service coverages between LGAs varied by state and type of service. High-resolution maps such as the ones developed by this study can guide geographic prioritization and help develop better strategies and implementation plans, allowing limited resources to be targeted to areas with lower coverage of essential MCH services.

Furthermore, the Aim 3 study estimated the incremental costs and potential benefit on avoidable child deaths from increasing essential health service coverage in each community and local government area (LGA), Nigeria. This study confirmed that both maternal and vaccination services were cost-effective interventions in all LGAs, although there were some ranges of ICER. LGAs with low service coverage need to spend more budget per capita to achieve 95% target, since the annual required increase of service coverage in those areas was high. 65.9 % of total cost of achieving 95% population coverage of ANC, BEmOC, Pentavalent and measles vaccination was labor cost. The outreach cost accounted for a major part of vaccination service cost. Increasing the number of doses administered per outreach session would result in considerable cost savings. By quantifying the financial resources needed and the potential reduction in child deaths, policymakers can make informed decisions on resource allocation and prioritize interventions that would have the greatest impact on improving health outcomes. These cost estimates also provide valuable information for mobilizing domestic resources and advocating for increased public spending on health to achieve UHC.

In conclusion, this dissertation emphasizes the importance of multi-dimensional priority setting in achieving Universal Health Coverage in Nigeria. By identifying the factors influencing health

service utilization, assessing regional disparities, estimating required costs, and quantifying potential impacts, policymakers can make evidence-based decisions to maximize the efficiency and effectiveness of healthcare interventions. The findings and recommendations of this research contribute to the broader global agenda of achieving UHC and improving health outcomes for all populations, particularly in low- and middle-income countries.