Journal of Biosocial Science (2024), 56: 5, 896–919
doi:10.1017/S0021932024000282

RESEARCH ARTICLE

Geographic inequities in neonatal survival in Nigeria: a cross-sectional evidence from spatial and artificial neural network analyses

Daniel A. Adeyinka[1,2,3] and Nazeem Muhajarine[1,2]

[1]Department of Community Health and Epidemiology, College of Medicine, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, [2]Saskatchewan Population Health and Evaluation Research Unit, Saskatoon, Saskatchewan, Canada and [3]Department of Public Health, Federal Ministry of Health, Abuja, Nigeria
Corresponding author: Daniel A. Adeyinka; Email: daniel.adeyinka@usask.ca

(Received 26 January 2023; revised 10 June 2024; accepted 13 June 2024; first published online 19 September 2024)

Abstract
This study was conducted to provide empirical evidence of geographical variations of neonatal mortality and its associated social determinants with a view to improving neonatal survival at the subnational level in Nigeria. With a combination of spatial analysis and artificial intelligence techniques, this study analysed data from the 2016/2017 Nigeria Multiple Indicator Cluster Survey. The analysis focused on the neonatal period of a weighted national representative population of 30,924 live births delivered five years before the survey commencement. Global Moran's I index and local indicator of spatial autocorrelation cluster maps were used to determine hot and cold spots. A multilayer perceptron neural network was used to identify the key determinants of neonatal mortality across the states and geopolitical zones in Nigeria. The overall neonatal mortality rate was 38 deaths per 1000 live births. There is evidence of geographic clustering of neonatal mortality across Nigeria (worse in the North-Central and North-West zones), majorly driven by poor maternal access to mass media (which plays a critical role in promoting positive health behaviours), short birth interval, a higher position in a family birth order, and young maternal age at child's birth. This study highlights the need for a policy shift towards implementing state and region-specific strategies in Nigeria. Gender-responsive, culturally, and regionally appropriate reproductive, maternal, and child health-targeted interventions may address geographical inequity in neonatal survival.

Keywords: Health inequity; social determinants of health; neonatal mortality; sustainable development goals; spatial analysis; multilayer perceptron neural network; Nigeria

Introduction

Despite the progress made in reducing the global under-five mortality rate by 59% from 93 deaths per 1000 live births in 1990 to 38 deaths per 1000 live births in 2019, millions of children continue to die yearly in resource-limited countries (UNICEF, 2021). Among the 5.2 million under-five deaths recorded in 2019, 2.4 million deaths (47%) occurred during the neonatal period (first 28 days of life), making the neonatal period the time of highest mortality risk for children (UNICEF, 2021). With 27 deaths per 1000 live births, neonatal mortality rates (NMR) remain highest in the region of sub-Saharan Africa (UNICEF, 2021). Moreover, the inter-country disparity in neonatal mortality is more profound for Nigeria, as it ranks second after India in the global neonatal mortality burden league table (UNICEF, 2021). In Nigeria, 1 in 28 newborns did not survive the first 28 days of life, resulting in an estimated 270,000 neonatal deaths, which accounted for 11% of the global burden of neonatal deaths in 2019 (UNICEF, 2021). The risk of neonatal death in Nigeria (36 deaths per 1000 live births) is twice the global NMR of 17 deaths per 1000 live births (UNICEF, 2021).

Although recent reviews of health indicators in Nigeria suggest moderate improvement in the survival of under-five children, NMR has stagnated in recent years (Akinyemi, Bamgboye, and Ayeni, 2015; Morakinyo and Fagbamigbe, 2017; Ayoade, 2018). A further concern is the masking of health inequities at the subnational level by aggregating the country's performance at the national level (Simpson's paradox), when tracking the child health-related Sustainable Development Goals (SDG). Understanding the geographical heterogeneity of mortality during the neonatal period – the most crucial period of early child's development (Ezeh *et al.*, 2015; Naline and Viswanathan, 2017), within Nigeria, can provide additional information needed for local-level planning and allocation of resources to areas where they are needed most (underserved population).

Previous studies have addressed social determinants of neonatal mortality (Akinyemi, Bamgboye, and Ayeni, 2015; Kayode *et al.*, 2017; Morakinyo and Fagbamigbe, 2017; Neal, Channon, and Chintsanya, 2018), but more remains to be known about the spatial variations of neonatal mortality in Nigeria. Also, there is a dearth of information on gender differences in NMR across urban–rural areas and geographical regions. According to Akinyemi *et al.* (2015), NMR varied by regions and was highest in the northern region of Nigeria from 1990 to 2013. The regional variations have been traced to the differences in socioeconomic, cultural, and environmental factors (Akinyemi, Bamgboye, and Ayeni, 2015). Drawing on the World Health Organization (WHO) Commission of Social Determinants of Health (SDH), gender and spatial dimensions are important determinants of population health (World Health Organization, 2008).

With respect to the roles of gender (a social and cultural construct) and sex (biological identity) on child survival, epidemiological studies have provided contradictory findings. While some studies have linked worse survival outcomes among male children to biological disadvantages (Boco, 2014; Gebretsadik and Gabreyohannes, 2016; Morakinyo and Fagbamigbe, 2017), others have reported excess of girl-child mortality due to gender discrimination, especially in terms of selective termination of female fetuses and newborns, and neglect of nutrition and health care for the girl-child (Costa, da Silva, and Victora, 2017). Also, evidence suggests that the population residing in socioeconomically disadvantaged areas such as rural residence experience worse health outcomes because of high levels of poverty, inaccessibility to quality health care, and inadequate social infrastructure (McMichael, 2000; Morakinyo and Fagbamigbe, 2017). In contrast, some studies have noted urban area disadvantage for under-five mortality due to air pollution, overpopulation, and waste disposal crisis (Van de Poel, O'Donnell, and Van Doorslaer, 2007; Antai and Moradi, 2010; Kimani-Murage *et al.*, 2014).

It is fundamental that policymakers should address the gender bias and rural–urban disparity in child survival and social determinants of neonatal mortality across the states and regions in Nigeria. In this study, the primary objective was to determine the patterns and determinants of geographical clustering of neonatal mortality in the state and geopolitical zones in Nigeria. The secondary objective was to assess gender inequity in neonatal mortality between urban and rural communities across the zones in Nigeria.

Methods

Study area

Nigeria, the most populated country in sub-Saharan Africa, is located in West Africa. It comprises six geopolitical zones (i.e. North-West [NW], North-East [NE], North-Central [NC], South-West [SW], South-East [SE], and South-South [SS]), which are further divided into 36 states and Federal Capital Territory (FCT) (Figure 1). There are more than 250 ethnic groups, which are divided into

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

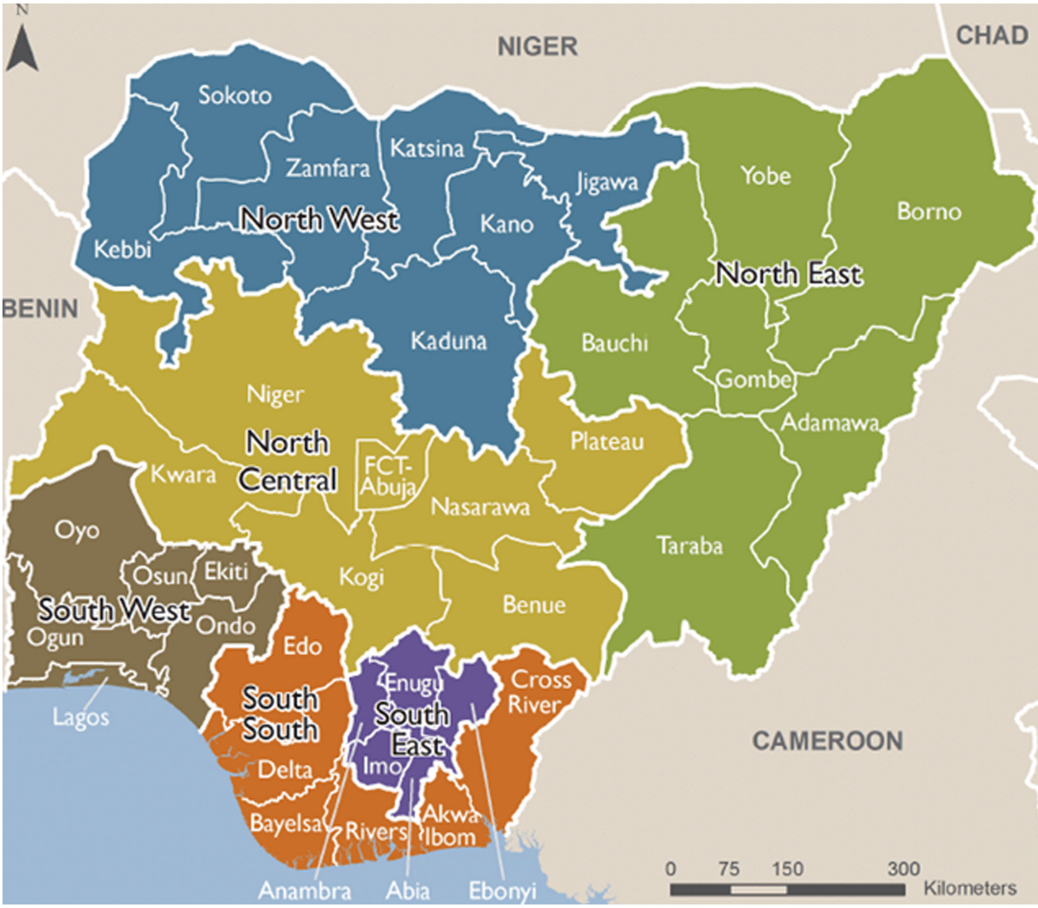


Figure 1. States and Zones in Nigeria (National Bureau of Statistics, 2013).

three major ethnic groups. Predominantly, there are Yoruba in the SW, Igbo in the SE, and Hausa in the Northern Nigeria.

Study design and data sources

This is a cross-sectional study that utilised full birth history, along with maternal and household data files, obtained from the 2016/2017 Nigeria Multiple Indicator Cluster Survey (MICS) (UNICEF MICS, 2018). The MICS is a national population-based survey conducted by trained interviewers in Nigeria, with support from UNICEF Headquarters, New York, to provide estimates of maternal and child health indices for the country (UNICEF and NBS, 2017). A detailed explanation of the methodology used for MICS has been described in the full report (UNICEF and NBS, 2017). With a complex, multi-stage stratified cluster sampling technique, data were collected from 36,176 women aged 15–49 years between September 2016 and January 2017 in the 36 states and FCT of Nigeria (UNICEF and NBS, 2017). The 37 states (including FCT) in the six geopolitical zones corresponded to the sampling strata. The strata were then sorted into rural and urban areas. Overall, 33,901 households from 2239 enumeration areas, otherwise referred to as primary sampling units (PSU), were covered during fieldwork. The PSU, which was used as a proxy for the community, was defined as an administrative/enumeration area with homogeneous population characteristics. Of the 36,176 women selected for interview, the

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

response rate was 95% (34,376 women). To minimise recall bias and accurately estimate neonatal mortality, this study considered children born alive within the last five years preceding the survey commencement (i.e. September 2011–September 2016) and defined neonatal death as a death that occurred within 28 days of birth. The cohort was selected to ensure that the analysis exclusively included neonates delivered in recent years. After removing the data of children whose survival outcomes, dates of birth, and deaths were not documented, an analysis was conducted on 29,786 neonates (corresponding to a weighted sample of 30,924 neonates) delivered to 18,497 women.

Theoretical background

This study utilised the Mosley–Chen framework (Mosley and Chen, 1984), programmatic experience of the authors, and evidence from the literature to identify the relevant social determinants of neonatal deaths in Nigeria. The framework underscores that childhood mortality in resource-limited countries results from the complex interrelationships of multiple biological and social factors at the child, maternal, household, and community levels. In this study, the hypothesis is that substantial variations in neonatal mortality exist across rural/urban communities, states, and geopolitical zones of Nigeria. Also, the geographical and gender inequities in neonatal survival are expected to vary based on the impact of other social determinants of health on the child–mother dyads. In this study, the gender roles depicted by boys and girls are used to show how people are viewed and expected to act based on societal norms, not solely due to biology (i.e. males and females) but also because of environmental factors and upbringing.

Variables

Dependent variable

The outcome variable – neonatal survival status – was generated from information on child survival outcome, age at death, and current age of living children and divided into two categories: alive (coded as 0) and dead (coded as 1).

Independent variables

The selected independent variables were informed by the Mosley–Chen framework, programmatic experience of authors, evidence from literature, and availability of variables in the MICS dataset. The variables were layered across child, maternal, household, and community levels (see Table 1 for details). From the variables collected in the MICS dataset, the housing condition index was generated by applying a principal components analysis (PCA) to reduce variables on the quality of the roof, exterior wall, and floor; overall, Kaiser–Meyer–Olkin measure of adequacy was 0.7, and p-value (Bartlett's test of sphericity) <0.001. The first component was selected based on an eigenvalue of 2.03, explaining 67.7% of the total variance. With the median value as the cut-off point, the housing condition index variable was coded as adequate and inadequate. Also, maternal media exposure, access to drinking water, sanitation, and indoor pollution were generated. Exposure to media was defined as the frequency that mothers were exposed to at least a source of mass media – newspaper/magazine, radio, and television (1: almost every day [high exposure]; 2: at least once a week [moderate exposure]; 3: less than once a week [low exposure]; 4: not at all). Household sanitation, sources of drinking water, and cooking fuel (proxy for indoor pollution) were re-categorised into improved and unimproved, as defined by the WHO/United Nations Children's Fund (UNICEF) Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (WHO, UNICEF, and JMP, 2018). Furthermore, community-contextual variables were derived from maternal-level variables (community level of maternal education) and household-level variables (community infrastructural development) (see Table 1 for details).

Table 1. Sociodemographic Characteristics of Study Participants, 2016/2017 MICS, Nigeria

Variable	Sample size n (%)	Alive n (%)	Dead n (%)	*p*-value	Description
Child-level factors					
Child's gender (N = 30924)				0.0004	Boys = 0, girls = 1
Boys	15704 (50.8)	15024 (50.5)	679 (57.9)		
Girls	15220 (49.2)	14726 (49.5)	494 (42.1)		
Gestation type (N = 30922)				<0.001	Singleton = 0, multiple = 1
Single	29694 (96.0)	28691 (96.4)	1003 (85.5)		
Multiple	1228 (4.0)	1058 (3.6)	171 (14.5)		
Birth order (N = 30924)				<0.001	First birth = 0, 2-3 = 1, 4-6 = 2, ≥7 = 3
First	5426 (17.5)	5170 (17.4)	257 (21.9)		
2-3	10342 (33.4)	10055 (33.8)	287 (24.5)		
4-6	9962 (32.2)	9653 (32.4)	309 (26.3)		
≥7	5194 (16.8)	4873 (16.4)	321 (27.3)		
Previous birth interval (N = 30924)				<0.001	<2 years = 0, first birth = 1, ≥2 years = 2
<2 years	6591 (21.3)	6178 (20.8)	413 (35.2)		
First birth	5492 (17.8)	5222 (17.6)	270 (23.0)		
≥2 years	18842 (60.9)	18350 (61.7)	491 (41.8)		
Maternal age at birth (N = 30924)				<0.001	<20 years = 0, 20-34 years = 1, ≥35 years = 2
<20 years	4315 (14.0)	4074 (13.7)	241 (20.5)		
20–34 years	21311 (68.9)	20602 (69.3)	709 (60.4)		
≥35 years	5298 (17.1)	5074 (17.1)	224 (19.1)		
Maternal-level factors					
Maternal education (N = 30924)				0.016	None/primary = 0, secondary/technical = 1, post-secondary = 2
None/primary	20590 (66.6)	19749 (66.4)	842 (71.7)		
Secondary	7969 (25.8)	7716 (25.9)	253 (21.5)		
Post-secondary	2365 (7.7)	2286 (7.7)	79 (6.7)		
Maternal wealth index (N = 30924)				0.053	Poor = 0, middle = 1, rich = 2
Poor	13905 (45.0)	13353 (44.9)	552 (47.1)		
Middle	6058 (19.6)	5798 (19.5)	260 (22.1)		
Rich	10962 (35.4)	10600 (35.6)	362 (30.8)		

(*Continued*)

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

Table 1. (*Continued*)

Variable	Sample size n (%)	Alive n (%)	Dead n (%)	*p*-value	Description
Maternal media exposure (N = 30921)				0.135	Accessibility to newspaper/magazine or listening to the radio or watching television (high = 0, medium = 1, low = 2, none = 3)
High	10032 (32.4)	9665 (32.5)	367 (31.3)		
Medium	4966 (16.1)	4808 (16.2)	158 (13.5)		
Low	3542 (11.5)	3410 (11.5)	131 (11.2)		
None	12381 (40.0)	11864 (39.9)	517 (44.1)		
Parity (N = 30924)				<0.001	<3 = 0, 3-4 = 1, ≥5 = 2
<3	7841 (25.4)	7578 (25.5)	262 (22.4)		
3-4	10115 (32.7)	9798 (32.9)	317 (27.0)		
≥5	12969 (41.9)	12375 (41.6)	594 (50.7)		
Access to ANC[a] (N = 20761)				0.02	None = 0, skilled = 1, unskilled = 2
None	6724 (32.4)	6457 (32.4)	267 (33.2)		
Skilled	12589 (60.6)	12132 (60.8)	457 (56.8)		
Unskilled	1449 (7.0)	1369 (6.9)	80 (9.9)		
Freq of ANC visits[a] (N = 20761)				0.457	None = 0, 1–7 = 1, ≥8 = 2
None	6724 (32.4)	6457 (32.4)	267 (33.2)		
1–7	10404 (50.1)	10023 (50.2)	381 (47.4)		
≥8	3633 (17.5)	3477 (17.4)	155 (19.3)		
Skilled birth attendants during delivery[a] (N = 20772)				0.705	None = 0, skilled birth attendants = 1, unskilled/friend = 2
None	2646 (12.7)	2533 (12.7)	113 (14.0)		
Skilled	8065 (38.8)	7755 (38.8)	310 (38.4)		
Unskilled	10061 (48.4)	9676 (48.5)	385 (47.7)		
Place of delivery[a] (N = 20769)				0.965	Home = 0, health facility = 1
Home	13350 (64.3)	12834 (64.3)	516 (64.2)		
Health facilities	7418 (35.7)	7131 (35.7)	288 (35.8)		
Marital status (N = 30898)				0.6621	Currently in union = 0, formerly in union = 1, never in union = 2
Currently in union	29714 (96.2)	28594 (96.2)	1120 (95.7)		
Formerly in union	802 (2.6)	770 (2.6)	32 (2.8)		
Never in union	382 (1.2)	364 (1.2)	18 (1.6)		
Contraceptive use (N = 26778)				0.05	Yes = 0, no = 1
Yes	1943 (7.3)	1888 (7.3)	55 (5.4)		
No	24834 (92.7)	23862 (92.7)	973 (94.6)		

(*Continued*)

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

Table 1. (*Continued*)

Variable	Sample size n (%)	Alive n (%)	Dead n (%)	*p*-value	Description
Alcohol intake (N = 30772)				0.269	Yes = 0, no = 1
Yes	3645 (11.8)	3521 (11.9)	124 (10.6)		
No	27127 (88.2)	26082 (88.1)	1045 (89.4)		
Smoking experience (N = 30863)				0.081	Yes = 0, no = 1
Yes	212 (0.7)	198 (0.7)	13 (1.2)		
No	30651 (99.3)	29498 (99.3)	1153 (98.8)		
Household-level factors					
Sex of household head (N = 30924)				0.279	Male = 0, female = 1
Male	29581 (95.7)	28450 (95.6)	1132 (96.4)		
Female	1343 (4.3)	1301 (4.4)	42 (3.6)		
Household head education (N = 30846)				0.0035	None/primary = 0, secondary/technical = 1, post-secondary = 2
None/primary	18097 (58.7)	17336 (58.4)	760 (65.1)		
Secondary	8308 (26.9)	8041 (27.1)	267 (22.9)		
Post-secondary	4441 (14.4)	4300 (14.5)	140 (12.0)		
Ethnic group (N = 30924)				0.081	Hausa = 0, Igbo = 1, Yoruba = 2, others = 3
Hausa	17465 (56.5)	16751 (56.3)	714 (60.8)		
Igbo	2404 (7.8)	2335 (7.9)	69 (5.9)		
Yoruba	2922 (9.5)	2818 (9.5)	104 (8.8)		
Others	8134 (26.3)	7847 (26.4)	287 (24.4)		
Housing condition (N = 30924)				0.644	Inadequate = 0, adequate = 1
Inadequate	13162 (42.6)	12651 (42.5)	511 (43.5)		
Adequate	17762 (57.4)	17099 (57.5)	663 (56.5)		
Polygamy (N = 30924)				0.369	Yes = 0, no = 1
Yes	10873 (35.2)	10441 (35.1)	432 (36.9)		
No	20051 (64.8)	19310 (64.9)	741 (63.1)		
Household access to drinking water (N = 30924)				0.002	Unimproved source = 0, improved source = 1
Unimproved	10811 (35.0)	10331 (34.7)	480 (40.9)		
Improved	20113 (65.0)	19419 (65.3)	694 (59.1)		
Household sanitation (N = 30923)				0.549	Unimproved = 0, improved = 1
Unimproved	15917 (51.5)	15298 (51.4)	619 (52.7)		
Improved	15007 (48.5)	14452 (48.6)	555 (47.3)		

(*Continued*)

Table 1. (*Continued*)

Variable	Sample size n (%)	Alive n (%)	Dead n (%)	*p*-value	Description
Indoor pollution (N = 30924)				0.037	Polluting fuel = 0, clean fuel = 1
Polluting fuel	29088 (94.1)	27965 (94.0)	1123 (95.7)		
Clean fuel	1837 (5.9)	1786 (6.0)	50 (4.3)		
Community-level factors					
Area (N = 30924)				0.2624	Urban = 0, rural = 1
Urban	9308 (30.1)	8985 (30.2)	323 (27.5)		
Rural	21616 (69.9)	20766 (69.8)	850 (72.5)		
Zones (N = 30924)				0.0007	North-Central (NC) = 0, North-East (NE) = 1, North-West (NW) = 2, South-East (SE) = 3, South-South (SS) = 4, South-West (SW) = 5
North-Central (NC)	5079 (16.4)	4863 (16.3)	216 (18.4)		
North-East (NE)	6514 (21.1)	6301 (21.2)	213 (18.1)		
North-West (NW)	12101 (39.1)	11567 (38.9)	534 (45.5)		
South-East (SE)	1599 (5.2)	1557 (5.2)	42 (3.6)		
South-South (SS)	2364 (7.6)	2312 (7.8)	52 (4.4)		
South-West (SW)	3268 (10.6)	3151 (10.6)	117 (9.9)		
Infrastructural development (N = 30924)				0.072	Based on proportion of households with electricity in the community – low = 0, high = 1
Low	16223 (52.5)	15566 (52.3)	657 (56.0)		
High	14701 (47.5)	14185 (47.7)	516 (44.0)		
Comm. maternal education (N = 30924)				0.0008	Based on the proportion of households with women who had at least secondary education in the community – low = 0, medium = 1, high = 2
Low	16436 (53.2)	15709 (52.8)	727 (62.0)		
Medium	5839 (18.9)	5656 (19.0)	183 (15.6)		
High	8649 (28.0)	8386 (28.2)	263 (22.4)		

In union refers to a boarder range of relationships including both married and unmarried partnerships (e.g. cohabitation).
[a]Data available for only women with a live birth in the two years prior to the survey. ANC: antenatal care.

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

Statistical analyses

This study employed artificial intelligence technique – backpropagation feedforward multilayer perceptron (MLP) neural network and geospatial analyses. Descriptive statistics were initially generated for all variables using Stata^{TM} version 15.1 software (College Station, Texas) (*Stata version 15.1*, 2017). The bivariate associations between the outcome variable (neonatal deaths) and independent variables were assessed with the Chi-square test. The significance level was set at two-tailed $\alpha = 5\%$. The complex survey design commands in Stata^{TM} software and sampling weights were applied to account for the hierarchical sampling and unequal selection probabilities of samples. Early NMR (risk of death from birth to 6 days of life) and late NMR (risk of death from 7 days to 27 days after birth) were also computed. Furthermore, strip plots were used to visualise the state distributions of early and late mortality rates based on their zones. The gender inequity gaps in NMR, disaggregated by urban–rural residence across the six geographical zones, were visualised with equiplots.

Geospatial analysis

Initially, the spatial dependencies of NMR were assessed across the states in Nigeria by using geometric centroids and a spatial arc distance of 407 km in a Nigeria shapefile that was obtained from the United Nations Office (United Nations Office for the Coordination of Humanitarian Affairs, 2017). A distance-based weight matrix was generated to ensure that all the states were interconnected – a condition for spatial analysis (Anselin, 2005). The symmetry of connectivity histogram and connectivity map were used to assess the suitability of the spatial weights. The units of spatial analysis were states. As proposed by Anselin (2005), univariate global spatial autocorrelation was performed, and the degree of similarity (i.e. spatial clustering) of NMR across the states was further assessed. A global Moran's I index of a positive value indicates spatial clustering, while a negative value indicates spatial dispersion (Anselin, 2005). Also, univariate local indicator spatial autocorrelation (LISA) cluster and significance maps were generated to identify the states with high NMR as denoted by hot spots, and the states with low NMR (cold spots). The statistically significant hot spots were determined by the grouping of states with high NMRs and vice versa for cold spots.

In the second step, the artificial intelligence technique, specifically the MLP neural network was employed to identify the important predictors of neonatal mortality, stratified by zones. Predictors with $\geq$50% normalised importance were deemed major contributors to NMR. For details of MLP, see 'Artificial neural network', below).

The final step involved determining spatial dependencies between the key predictors identified in step 2 and NMR by generating bivariate LISA cluster maps. To visualise the combined effects of the variables that were spatially autocorrelated with NMR from the bivariate LISA maps (i.e. proportion of mothers who had children with previous birth interval $<$2 years, birth order $>$3, young maternal age at birth [$<$20 years] and no maternal exposure to mass media), PCA was used to reduce these variables to a composite variable referred to as socio-behavioural index. High values of the composite index indicate poor social behaviours (i.e. higher position in a family birth order, births closer together, young maternal age at birth, no maternal access to mass media). With the singular value decomposition (SVD) method and z-score transformation (i.e. mean of zero and variance of one), the first component explained 74.9% of the total variance, and its eigenvalue was 3.0. The most important advantage of SVD is its robustness against outliers (Anselin, 2020). As a result, the combined spatial pattern of the variables that constituted the first principal component of NMR was visualised with a cluster map. The statistical significance of spatial autocorrelations was tested by running 999 Monte Carlo simulations with a p-value$<$0.05. The spatial analysis was implemented in GeoDa software version 1.14 (*GeoDa on Github*, no date).

Artificial neural network

With a view of identifying the key predictors of neonatal mortality at zonal and national levels, backpropagation feedforward MLP neural networks were implemented in the IBM SPSS neural

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

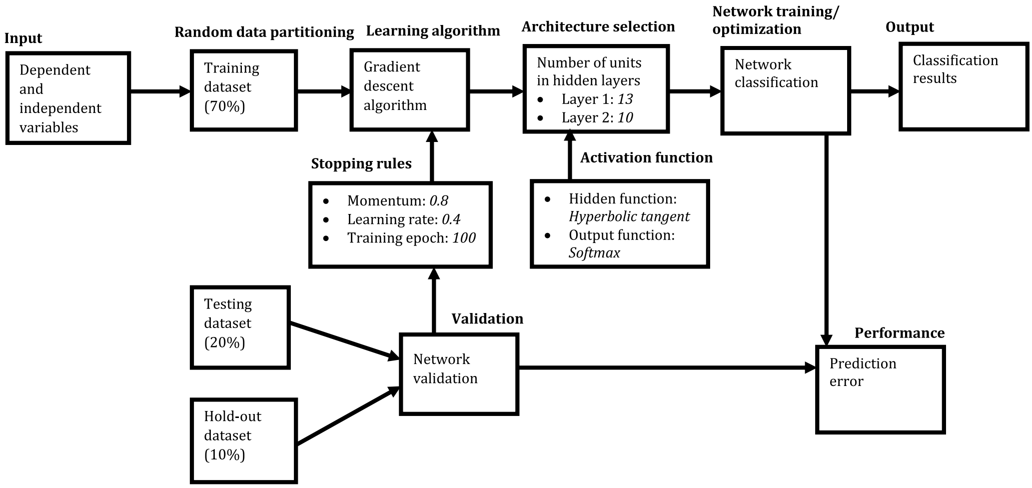


Figure 2. Flow Chart of Multilayer Perceptron Neural Network Modelling.

networks software version 21.0 (IBM, 2012). The unit of analysis for the neural network was at the level of children, stratified by zones. Figure 2 shows the flow chart of data preprocessing for the MLP neural network (see Appendix for details). With the dataset randomly partitioned into training (70%), testing (20%), and holdout (10%) sets, the MLP learning algorithm (gradient descent algorithm) used the training set to learn the inherent pattern of the dataset. The testing and holdout sets were used for model validation. The MLP neural networks were validated based on values of the error function (cross-entropy), area under receiver operating characteristic curve (AUROC), and accuracy rate from holdout samples (IBM Corporation, 2012). The missing data were represented by a specific number (99) and labelled as missing before running the analyses. This approach was undertaken to ensure that all available information was considered. The missing categories were not reported in the results section to avoid ambiguity.

Ethical considerations

Ethical clearances were obtained earlier by the UNICEF MICS team from the National Health Research Ethics Committee, Nigeria, before the survey commencement. In addition, this present study was exempted from ethical review by the University of Saskatchewan Behavioural Ethics Committee (ID no. 904) as datasets were de-identified of the respondents' personal information. The participants' anonymity and confidentiality are assured.

Results

Table 1 shows the sociodemographic characteristics of the study participants. Of the weighted sample of 30,924 live births included in the study, 50.8% were boys, 96.0% were single births, and 60.9% were children who had preceding birth interval $\geq$2 years.

The NMR was 37.9 deaths per 1000 live births. Most of the neonatal deaths (85.9%) occurred within the first 7 days of life, translating to 32.3 deaths per 1000 live births (early NMR), and declined to 5.7 deaths per 1000 live births during the late neonatal period (7–27 days). Although not statistically significant, the NMR was slightly higher in rural areas (39.3 deaths per 1000 live births) than in urban areas (34.7 deaths per 1000 live births); $p = 0.262$. Higher NMR was observed for boys (43.2 deaths per 1000 live births), compared to girls (32.5 deaths per 1000 live births); $p < 0.001$.

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

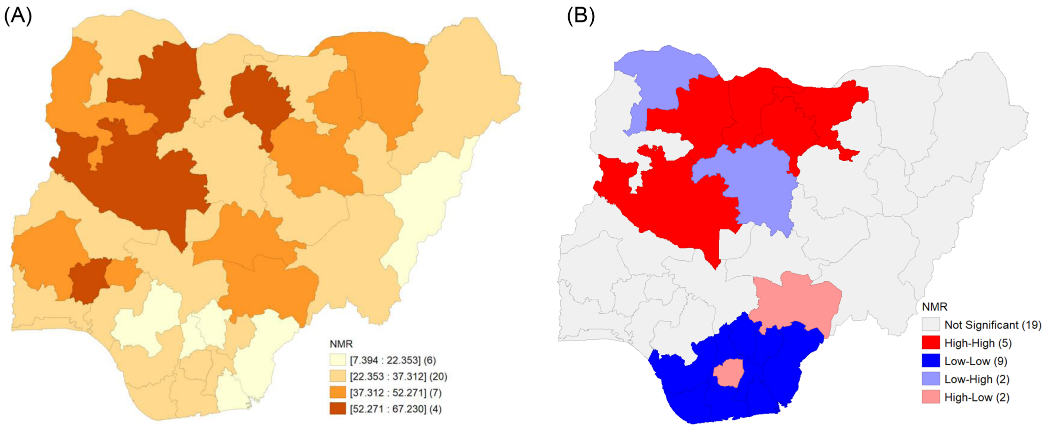


Figure 3. A. Spatial Distribution of NMR, 2016/2017 Nigeria MICS B. Univariate LISA cluster map for NMR, 2016/2017 Nigeria MICS.

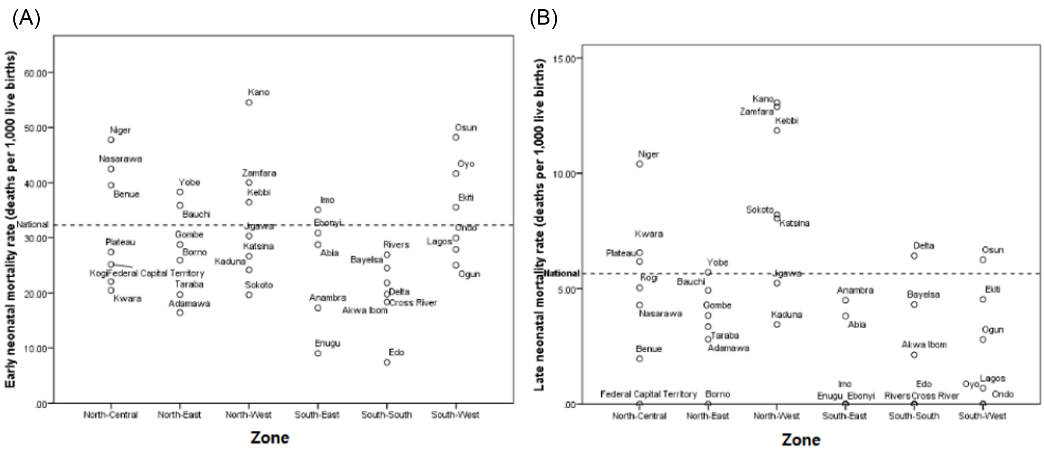


Figure 4. State Level A. Early Neonatal Mortality Rates, 2016/2017 Nigeria MICS B. Late Neonatal Mortality Rates, 2016/2017 Nigeria MICS.

Geographical variations of neonatal mortality rates

Figures 3 and 4 indicate that there were wide variations in NMR across the states and zones in Nigeria. NMR was highest in the NW zone (44.1 deaths per 1000 live births) and lowest in the SS zone (22.1 deaths per 1000 live births). Specifically, Kano State had the highest NMR (67.4 deaths per 1000 live births), followed by Niger State (58.2 deaths per 1000 live births). The lowest NMR was observed in Edo State (7.9 deaths per 1000 live births). The distribution of early and late NMR for states based on their regions is presented in Figure 4a and b, respectively.

As shown in Figure 3b, significant clustering of NMR was observed across the states in Nigeria (global Moran's I index $= 0.1$, $p = 0.02$). The univariate LISA cluster map for NMR further revealed that 13.5% of the states were high-high clusters (hot spots) and located majorly in the NW zone (Jigawa, Katsina, Kano, and Zamfara States) and to a lesser extent in the NC zone (Niger State). The high-high clusters depict the states with statistically significantly higher NMR than the national average. Contrarily, low-low clusters (cold spots) were the states with statistically significantly lower NMR than the national average. The cold spots (24.3%) were concentrated in the SS zone (Akwa Ibom, Bayelsa, Cross River, Delta, and Rivers States), and SE zone (Abia,

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

Anambra, Ebonyi, and Enugu States). However, there were some outliers – high-low and low-high clusters. The high-low clusters were formed by significant clustering of two states (5.4%), where NMRs were high and adjacent to states with low NMRs. The high-low clusters were formed by Benue State (NC zone) and Imo State (SE zone). Two states (5.4%) were identified as low-high clusters in the NW zone (Kaduna and Sokoto States) – states with low NMRs and were neighbours to states with high NMRs. The spatial correlogram that shows the changes in spatial autocorrelation of NMR with distance is shown in Figure A1 in the Appendix. Also, the spatial patterns of early and late NMRs are shown in Figures A2 and A3 in the Appendix).

Magnitude of gender inequity in neonatal mortality rate across urban–rural residence

As shown in Figure 5, mortality rates were highest among boys residing in the rural NW zone (54.2 deaths per 1000 live births) and lowest among boys in the urban SS zone (10.8 deaths per 1000 live births). For girls, the highest NMR was observed in urban NC (39.9 deaths per 1000 live births) and lowest in rural SS (18 deaths per 1000 live births).

Figure 5 shows the absolute inequity (i.e. risk difference) between boys and girls disaggregated by urban–rural residence across the geographical zones. The absolute difference was largest in urban SS and urban SW zones (20 deaths per 1000 live births) and lowest in urban NC (0.4 deaths per 1000 live births). Overall, the gender differences in NMR tended to be larger in the rural North; however, the urban South was observed to have large differences. Except for NW and SW zones, NMR among girls was higher in urban areas. However, NMR among boys was generally higher in rural areas in all zones.

Determinants of neonatal mortality across the zones

From the predictive MLP neural nets, there were zone-specific determinants of neonatal mortality in Nigeria (Table 2). Overall, based on the normalised importance values, multiple births (100%), previous birth interval (53.9%), and birth order (51.3%) were identified as the major contributors to neonatal mortality in Nigeria. The zonal-level analysis also found similar evidence that these three factors were common contributors across all the zones. Except for the NW zone, maternal age at birth appeared consistently across the zones (Table 2). Also, maternal mass media exposure was observed as a top contributor to neonatal mortality in the southern part of the country (Table 2).

To establish spatial relationships of the most important determinants identified from MLP – that is, multiple births, previous birth interval, birth order, maternal age at birth, and maternal access to mass media – bivariate LISA cluster maps were generated (Figure 6 and Appendix Figure A4). There was no statistically significant global spatial association between multiple births and spatial lag of NMR in Nigeria (Moran's I index = -0.1, $p = 0.05$). The local spatial association between multiple births and NMR is presented in Appendix Figure A4. However, births closer together (less than two years gap) and increasing birth order (>3) were significantly associated with the spatial clustering of NMR: Moran's I index = 0.1, $p = 0.01$ and Moran's I index = 0.2, $p = 0.003$, respectively. Also, Moran's I index for NMR and deliveries by adolescent mothers indicates significant clustering (I = 0.21, $p = 0.001$) and no maternal exposure to mass media (I = 0.1, $p = 0.008$).

Figure 6a suggests that there were 5(13.5%) states that formed high-high clusters, implying the clustering of states with high NMR and high percentage of children who were born less than two years apart. The high-high clusters were in the NE zone (Bauchi and Yobe States) and NW zone (Jigawa, Kano, and Katsina States). Also, SE zone (Abia and Anambra States), SS zone (Bayelsa, Delta, and Edo States), NC zone (Kogi and Kwara States), and SW zone (Lagos, Ogun, and Ondo States) clearly indicate clustering of states with significantly low NMRs and low percentage of children who were born less than two years apart (low-low clusters). Figure 6b–d displays bivariate

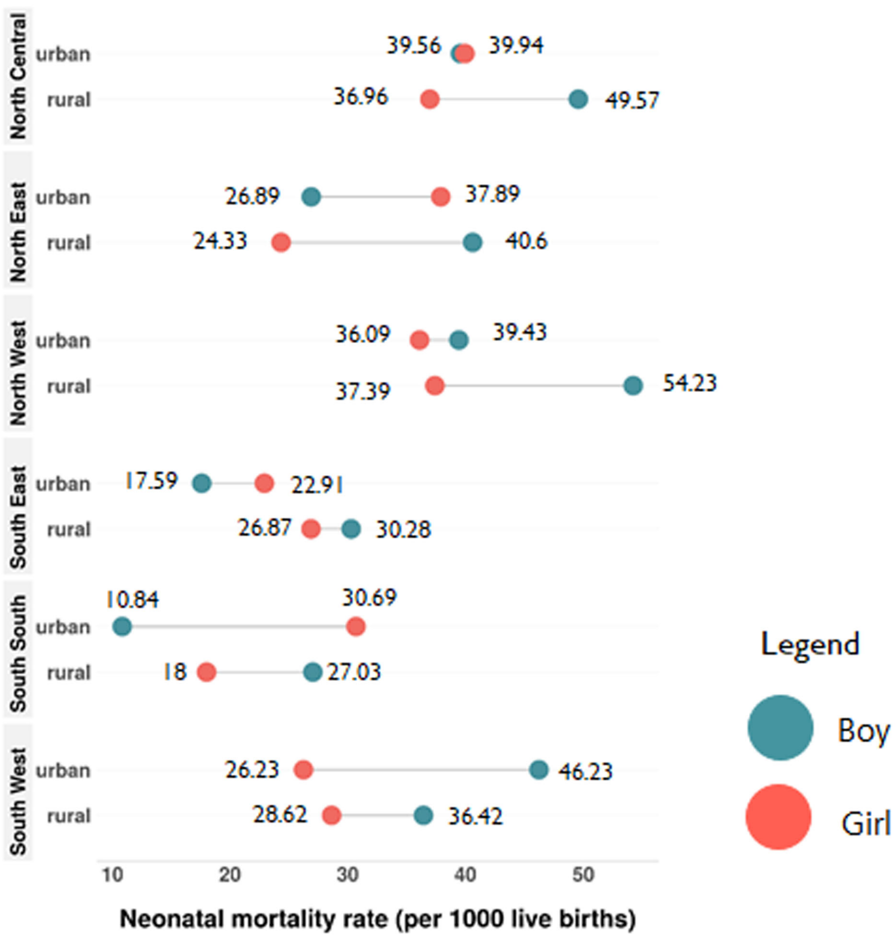


Figure 5. Absolute Gender Inequity in Neonatal Mortality Rate Across the Urban–Rural Residence of Geographical Regions, 2016/2017 Nigeria MICS.

LISA cluster maps for the association between NMR and increasing birth order (>3), deliveries by adolescent mothers, and no maternal exposure to mass media.

The multivariate cluster map also shows evidence of significant positive spatial autocorrelation ($I = 0.2$, $p = 0.002$) between increasing birth order, births closer together, young maternal age at birth, no maternal access to mass media, and NMR in Nigeria (Figure 7). The multivariate map shows that high NMR was spatially correlated with the high values of the derived socio-behavioural index (hot spots) in NE (Bauchi and Yobe), NW (Jigawa, Kano, Katsina, Kebbi, and Zamfara), and NC (Plateau). The SE (Abia, Anambra, Ebonyi, Enugu), SS (Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Rivers), NC (Kogi, Kwara), and SW (Lagos, Ogun, Ondo) were identified as the cold spots – low NMR was spatially correlated with low socio-behavioural index. The high-low clusters were found in NC (Benue), SW (Ekiti, Osun, Oyo), and SE (Imo). The high-low clusters were the states with significant spatial correlation between high NMR and low socio-behavioural index. However, the low-high clusters indicated states with significantly low NMR and high socio-behavioural index. The low-high clusters were formed by NE (Adamawa, Borno, Gombe) and NW (Kaduna and Sokoto).

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

Table 2. Zonal Comparison of NMR, Progress Towards SDG Targets, Top Contributors to Neonatal Mortality and Model Performance

Zone	Neonatal mortality rate (deaths per 1000 live births	[a]Deficit in SDG 3 target (%)	[b]Normalised importance (≥50%) (from MLP neural network)	[c]Model accuracy (%)	AUROC
North-Central	42.5	71.8	Previous birth interval (100%), multiple births (92.9%), birth order (90.3%), household head education (78.9%), sanitation (73.0%), ANC access (72.8%), skilled birth attendance (69.6%), maternal age at birth (65.7%), household ethnicity (65.3%), maternal education (61.2%), maternal poverty (58.0%), housing condition (58.0%), community level of maternal education (55.4%), parity (53.8%), community development (51.9%), frequency of ANC visits (50.4%)	96.2	0.771
North-East	32.7	63.3	Birth order (100%), frequency of ANC visits (71.2%), sanitation (70.8%), multiple births (68.5%), place of delivery (66.5%), birth interval (56.3%), maternal age at birth (54.0%)	97.2	0.694
North-West	44.1	72.8	Multiple births (100%), birth order (59.9%), birth interval (56.7%)	94.3	0.719
South-East	26.3	57.4	Multiple births (100%), maternal mass media exposure (92.2%), maternal educational level, frequency of ANC visits (60.6%), contraceptive use (59.6%), birth order (51.4%), maternal age at birth (50.2%)	99.0	0.945
South-South	22.1	45.7	Polygamy (100%), sex of household head (74.4%), parity (73.2%), ANC access (70.9%), maternal poverty (70.7%), community level of maternal education (63.0%), ethnicity of household head (61.6%), previous birth interval (60%), alcohol intake (59.6%), birth order (55.9%), maternal mass media exposure (53.5%), household head education (53.4%), multiple births (50.1%)	97.5	0.737
South-West	35.7	66.4	Maternal mass media (100%), birth order (97.4%), skilled birth attendance (84.9%), maternal education (82%), community level of maternal education (73.8%), maternal age at birth (68.7%), alcohol intake (66.3%), household head education (61%), multiple births (60.2%), house condition (57.6%), household ethnicity (55.4%), frequency of ANC visits (52.8%), parity (51.7%), contraceptive use (51.6%), previous birth interval (50.1%)	93.3	0.795
National	38.0	68.4	Multiple births (100%), previous birth interval (53.9%), birth order (51.3%)	96.0	0.705

[a]Current deficit in SDG 3 target (%): difference, in percentage, the SDG target, and the estimated rate for NMR as of 2016/2017.
[b]Normalised importance: equivalent to regression coefficient. This is the neural network classification of independent variables based on their strength of association with the outcome variable.
[c]Model accuracy: the predictive performance of the trained neural network on previously unseen datasets (i.e. validation data sets).

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

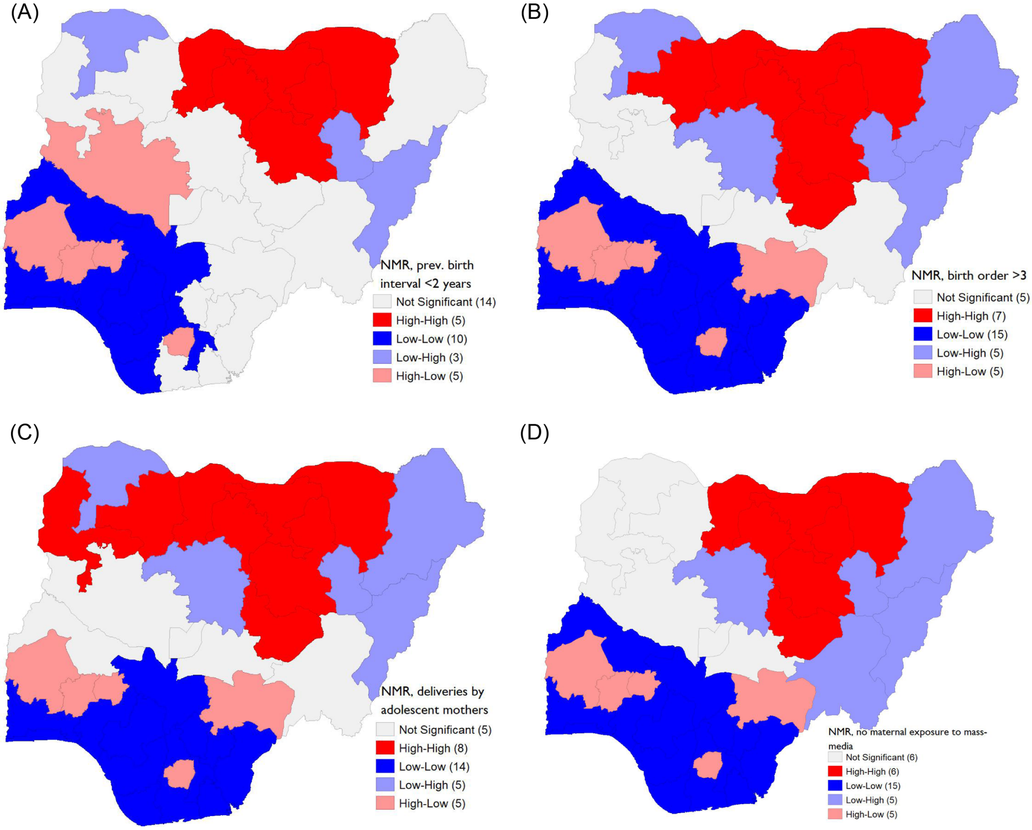


Figure 6. Bivariate LISA Cluster Maps A. NMR and Previous Birth Interval <2 Years B. NMR and Birth Order >3. C. NMR and Deliveries by Adolescent Mothers D. NMR and No Maternal Exposure to Mass Media.

Model assessment

The neural network models produced AUROC ranging from 0.69 to 0.95 (Table 2). The AUROC for the overall (national) model was 0.71, translating to an accuracy rate of 96.0%. With similar cross-entropy errors and accuracy rates across the training, testing, and holdout samples, there is evidence to suggest that the neural networks were not overtrained.

Discussion

In this study, NMR was 37.9 deaths per 1000 live births in Nigeria, and most of the deaths (85%) occurred within the first week of life. This is an indication of a missed opportunity for improving child survival in the early phase of a child's development in Nigeria. Among the zones and states, NC (Benue, Nasarawa, and Niger), NE (Bauchi and Yobe), NW (Kano, Kebbi, and Zamfara), and SW (Ekiti, Osun, and Oyo) were observed to have higher NMRs than the national rate. More importantly, Kano State contributed 15.5% to all neonatal deaths in the country. Also, the findings show that children delivered as part of multiple births, and those with high socio-behavioural index (i.e. delivered later in birth order (>3), born within two years after preceding births, delivered to adolescent mothers, and those without access to mass media) had a higher risk of neonatal death in Nigeria. However, there was no clear evidence of spatial dependence of multiple births on the geographic pattern of NMR. Also, there were interregional disparities in the absolute gender-specific NMR between urban and rural areas. This study clearly shows the need to

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

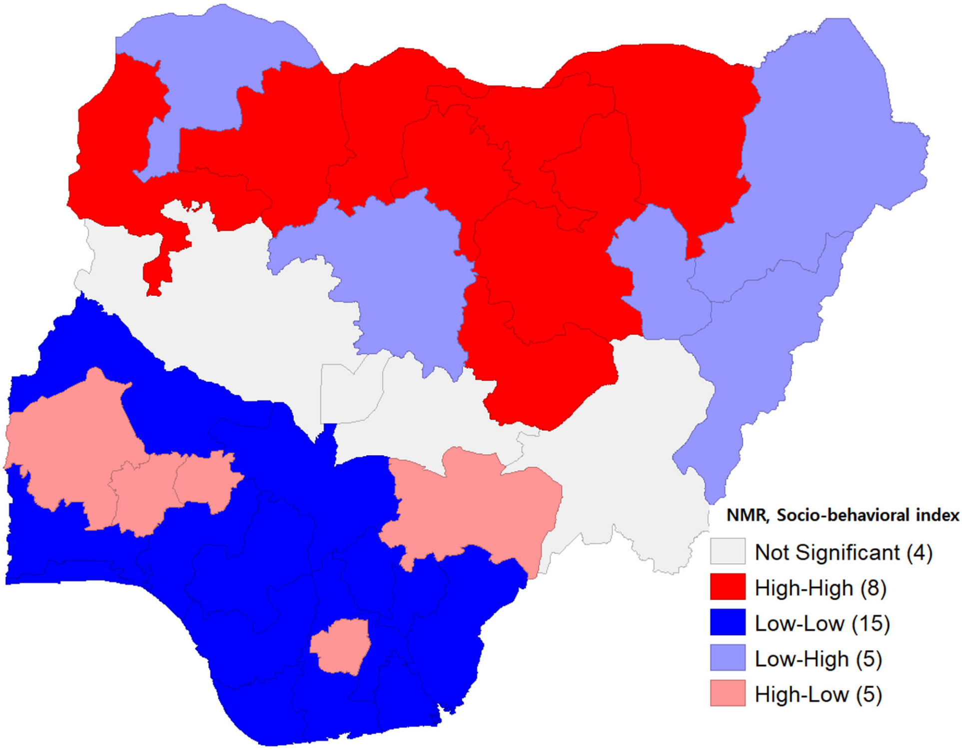


Figure 7. Multivariate (PCA) LISA Cluster Maps of Neonatal Mortality Rate and Socio-Behavioural Index (Previous Birth Interval <2 Years, Birth Order >3, Deliveries by Adolescent Mothers, No Maternal Exposure to Mass Media).
NMR: Neonatal mortality rate; PCA: Principal components analysis.

implement targeted interventions to reduce the gender gap between urban and rural residences across the geographical zones in Nigeria. Gender inequity was worse in the rural areas of northern Nigeria, while it was worse in the urban areas of southern Nigeria. NMR was disproportionately higher among girls in urban areas (except NW and SW zones). Conversely, boys had higher mortality risks in the rural areas for all the zones. The zones with the most equitable NMR were the urban NC region (0.4), followed by urban NW (3.3) and rural SE (3.4).

The geospatial analyses suggest that there was a huge disparity in neonatal mortality within Nigeria. The states in the NW and NC zones had higher NMR and clustered to form hot spots of neonatal mortality. However, a distinct pattern of lower NMR was observed towards the southern part (i.e. SS and SE) – cold spots. The finding that NW and NC had higher NMR is consistent with the pattern reported in the 2016/2017 Nigeria MICS report (UNICEF MICS, 2018). Previous surveys conducted before the Boko Haram insurgency started in Nigeria (i.e. 2009) showed that NMR was worst in the NE zone (National Population Commission (NPC) [Nigeria] and ORC, 2004; National Population Commission (NPC) [Nigeria] and ORC Macro, 2010). It is important to reinforce the consequences of conflicts on maternal and child health in the affected region (Omole, Welye, and Abimbola, 2015; Howell *et al.*, 2020). In line with the ongoing insurgencies in the northern region (Brechenmacher, 2019), hot spots formed in the NW and NC zones might be in part due to neglect of the internally displaced people and a decline in the quality of health services in that area (especially for vulnerable women). According to a report by the Displacement Tracking Matrix, NW and NC zones have also been affected by the protracted humanitarian crisis, made worse due to inter-community violence and banditry (Global Data Institute Displacement Tracking Matrix, 2020). The recommendation is for the Government of Nigeria to prioritise

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

maternal and child health services among vulnerable populations and to develop innovations aimed at improving child health outcomes in the northern region.

In the southern part of Nigeria, maternal mass media exposure was observed to be a social determinant of neonatal survival. These findings at least hint that mass media exposure among women contributed to a reduction of NMR in southern Nigeria. This implies that more policies should be shifted towards implementing context-specific strategies in the states and zones. Culturally appropriate reproductive, maternal, and child health messages targeted to women in the hot spots (northern Nigeria) via mass media campaigns are expected to increase maternal demands for quality preventive and curative services for children. In the same manner, the states that reported better exposure to mass media by women were found to have lower percentages of children who were delivered within two years before the previous birth. Notably, previous birth interval and birth order were observed to be consistent across the zones. Although recent evidence indicates that short previous birth interval is a major driver of childhood mortality, the conclusions have been mixed (Zhu *et al.*, 1999; Conde-Agudelo and Belizán, 2000; Kwarteng Acheampong and Eyram Avorgbedor, 2017). However, most studies emphasise 'maternal depletion hypothesis' for the elevated childhood mortality risks arising from short preceding birth intervals (Conde-Agudelo and Belizán, 2000; Davanzo *et al.*, 2008). In line with the idea of strong competition among siblings, this study shows that children born later in birth order were likely to experience neonatal mortality.

The impact of young maternal age at birth on neonatal mortality differed across the zones. In 21.6% of the states, mortalities were markedly elevated among states with a high percentage of neonates delivered by adolescent mothers. These states were located in northern Nigeria – Bauchi, Jigawa, Kano, Katsina, Kebbi, Plateau, Yobe, and Zamfara. Further analysis revealed that in these eight states that formed clusters of high adolescent mothers and high NMR, neonatal deaths were highest (83.9%) among women who were first married or in union during adolescence stage. Contrarily, NMR was low in 37.8% of the states with a low percentage of neonates delivered by adolescent mothers – located in southern Nigeria – Abia, Akwa Ibom, Anambra, Bayelsa, Cross River, Delta, Ebonyi, Edo, Enugu, Kogi, Lagos, Ogun, Ondo, and Rivers. Child marriage is a serious violation of human rights that has been closely linked to maternal and child mortality (UNICEF, 2021). In light of the reported findings of UNICEF (2021), child marriage affects about 650 million girls and women globally. According to UNICEF, child marriage is prevalent (44%) in the NW and NC regions of Nigeria – ranking 11th globally (Girls Not Brides, 2018; UNICEF, 2018a). Evidence suggests that the key drivers of child marriages in Nigeria include inadequate girl-child education, political/economic ties, gender norms, poverty, and violence against girls (Girls Not Brides, 2018). These findings highlight the need for stakeholders to sensitise the communities in Nigeria on the 2003 Child's Rights Act (*Nigeria: Act No. 26 of 2003, Child's Rights Act, 2003*, 2003) which prohibits forced and child marriages.

What is more striking from this study is that the determinants of neonatal mortality were not uniform across the six geographical zones. Across the zones, the most important contributors to NMR were previous birth interval (NC), birth order (NE), multiple births (NW and SE), polygamy family (SS), and maternal exposure to mass media (SW). This finding indicates that both broad and targeted strategies may be necessary to alleviate the NMR in Nigeria. Nigeria requires impactful policy actions to address the social determinants of neonatal mortality because of the gender, urban–rural, state, and zonal differences in the patterns of neonatal mortalities. To achieve this overarching goal will require the engagement of community members, decision and policymakers, and research institutions. More prominently, the states and zones are at different levels of progress towards achieving the SDG targets.

To the best of the authors' knowledge, this is the first known published literature that utilised spatial analysis and artificial neural networks to cast new light on the urban–rural, state, and zonal variations of social determinants of neonatal mortality in Nigeria. This study is in line with the aspirations of SDG 3 (good health and well-being of children), SDG 5 (promote gender equality), SDG 10 (reduce inter[intra]-country inequality), and SDG 17 (increase the availability of high-quality, timely, and reliable data disaggregated by social determinants of health). Despite the strengths, some limitations exist. Owing to the cross-sectional design of this study, causal arguments should not be made. Rather, the findings should be considered within the context of associations. Another major source of limitation is recall bias/poor memory which could be due to self-reporting by women. This is not likely to markedly affect the study findings because data were limited to live births five years prior to the survey commencement.

Overall, this study found a considerable spatial clustering of NMR in Nigeria (majorly driven by young maternal age at birth, short birth interval, low maternal exposure to mass media, and increasing birth order). This study also found that, with the exception of NW and SW zones, NMR was higher for girls than boys in urban areas. However, NMR was higher for boys than girls in rural areas across all zones. This highlights the need for the country to develop and implement state and region-specific child survival initiatives to address the high rates of neonatal mortality, especially in northern Nigeria (i.e. hot-spot zones). Due to the secondary and quantitative nature of this study, it is challenging to offer explanations for the observed patterns. Interpreting the variation in the impact of social determinants of health across different regions in Nigeria requires a nuanced understanding of the local context, such as cultural, economic, and healthcare factors. Further qualitative studies are therefore needed to explain why some states were in clusters of outliers (high-low and low-high) and reasons for varying patterns of gender inequity across the rural and urban areas.

Data availability statement. Data may be found on the UNICEF MICS website (UNICEF MICS 2018).

Acknowledgements. This study was made possible by doctoral support for DAA through the College of Medicine Graduate Award from the University of Saskatchewan, Canada. The content is solely the responsibility of the authors and does not necessarily reflect the official views of the College of Medicine, University of Saskatchewan, Canada.

Author contribution. DAA conceived the study, analysed and interpreted the data, and wrote the first draft of the paper. NM assisted in the design and data interpretation and critically reviewed the manuscript. NM supervised this study. All authors read and approved the final manuscript.

Funding statement. The authors received no specific funding for this work.

Competing interests. No potential conflict of interest was reported by the authors.

References

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

Anselin L (2005) Exploring spatial data with GeoDa^{TM}: A workbook center for spatially integrated social science. Available at: http://sal.uiuc.edu/http://www.csiss.org/ (Accessed: 20 February 2019).

Anselin L (2020) Dimension Reduction Methods (1): Principal Components Analysis (PCA). Available at: https://geodacenter.github.io/workbook/7aa_dimensionreduction/lab7aa.html (Accessed: 3 July 2020).

Antai D and Moradi T (2010) Urban area disadvantage and under-5 mortality in Nigeria: the effect of rapid urbanization. Environmental Health Perspectives 118, 877–883.

Ayoade MA (2018) Spatio-temporal patterns of under 5 mortality in Nigeria, *SSM - Population Health* **6**, 116–124.

Boco AG (2014) *Assessing sex differentials in under-five mortality in sub-Saharan Africa: A cross-national comparative analysis*, *Canadian Studies in Population*.

Brechenmacher S (2019) Stabilizing Northeast Nigeria after Boko Haram, *Carnegie Endowment for International Peace*. Available at: https://carnegieendowment.org/2019/05/03/stabilizing-northeast-nigeria-after-boko-haram-pub-79042 (Accessed: 19 June 2020).

Conde-Agudelo A and Belizán JM (2000) Maternal morbidity and mortality associated with interpregnancy interval: cross sectional study. *British Medical Journal* **321**, 1255–1259.

Costa JC, da Silva ICM and Victora CG (2017) Gender bias in under-five mortality in low/middle-income countries., *BMJ Global Health* **2**, e000350. https://doi.org/10.1136/bmjgh-2017-000350

Davanzo J, Hale L, Razzaque A and Rahman M (2008) The effects of pregnancy spacing on infant and child mortality in Matlab, Bangladesh: how they vary by the type of pregnancy outcome that began the interval. *Population Studies* **62**, 131–154.

Ezeh OK,, Agho KE, Dibley MJ, Hall JJ and Page AN (2015) Risk factors for postneonatal, infant, child and under-5 mortality in Nigeria: a pooled cross-sectional analysis. *BMJ Open* **5**, e006779. https://doi.org/10.1136/bmjopen-2014

Gebretsadik S and Gabreyohannes E (2016) Determinants of under-five mortality in high mortality regions of Ethiopia: an analysis of the 2011 Ethiopia demographic and health survey data. *International Journal of Population Research* **2016**, 1–7. https://doi.org/10.1155/2016/1602761

GeoDa on Github (no date). Available at: https://geodacenter.github.io/download_windows.html (Accessed: 1 December 2018).

Girls Not Brides (2018) Nigeria - Child marriage around the world. Available at: https://www.girlsnotbrides.org/child-marriage/nigeria/ (Accessed: 27 June 2020).

Global Data Institute Displacement Tracking Matrix (2020) *Nigeria — North Central and North West Zones displacement report 4*, *International Organization for Migration*. Available at: https://dtm.iom.int/reports/nigeria-—-north-central-and-north-west-zones-displacement-report-4-august-2020 (Accessed: 27 January 2024).

Howell E, Waidmann T, Birdsall N, Holla N and Jiang K (2020) The impact of civil conflict on infant and child malnutrition, Nigeria, 2013. *Maternal and Child Nutrition* **16**, e123968.

IBM (2012) SPSS Statistics Software Version 21.0. Available at: https://www.ibm.com/products/spss-statistics (Accessed: 9 November 2019).

IBM Corporation (2012) IBM SPSS Neural Networks 21. Available at: http://www.ibm.com/spss. (Accessed: 9 November 2019).

Kayode G, Grobbee D, Amoakoh-Coleman M, Ansah E, Uthman O and Klipstein-Grobusch K (2017) Variation in neonatal mortality and its relation to country characteristics in sub-Saharan Africa. *BMJ Global Health* **2**, A49.1–A49. https://doi.org/10.1136/bmjgh-2016-000260.130

Kimani-Murage EW, Fotso JC, Egondi T, Abuya B, Elungata P, Ziraba AK, Kabiru CW and Madise N (2014) Trends in childhood mortality in Kenya: the urban advantage has seemingly been wiped out. *Health & Place* **29**, 95–103. https://doi.org/10.1016/j.healthplace.2014.06.003

Kwarteng Acheampong G and Eyram Avorgbedor Y (2017) Determinants of under five mortality in Ghana; A logistic regression analysis using evidence from the demographic and health survey (1988–2014). *American Journal of Public Health Research* **5**, 70–78.

McMichael AJ (2000) The urban environment and health in a world of increasing globalization: issues for developing countries. *Bulletin of the World Health Organization* **78**, 1117–1126.

Morakinyo OM and Fagbamigbe AF (2017) Neonatal, infant and under-five mortalities in Nigeria: an examination of trends and drivers (2003–2013). *PLOS One* **12**, e0182990. https://doi.org/10.1371/journal.pone.0182990

Mosley W and Chen L (1984) An analytical framework for the study of child survival in developing countries. *Popul Dev Rev* **10**, 25–45.

Naline G and Viswanathan B (2017) *Predictors of age-specific childhood mortality in India*. 167/2017. Available at: http://www.mse.ac.in/wp-content/uploads/2018/04/Working-167-.pdf (Accessed: 14 October 2019).

National Bureau of Statistics (2013) Nigeria Demographic Health Survey. Available at: https://dhsprogram.com/pubs/pdf/fr293/fr293.pdf.

National Population Commission(NPC)[Nigeria] and ORC (2004) *Nigeria Demographic and Health Survey 2003*. Available at: http://dhsprogram.com/pubs/pdf/FR148/FR148.pdf.

National Population Commission(NPC)[Nigeria] and ORC Macro (2010) *Nigeria Demographic and Health Survey 2008*.

Neal S, Channon AA and Chintsanya J (2018) The impact of young maternal age at birth on neonatal mortality: evidence from 45 low and middle income countries. *PLOS One* **13**, e0195731. https://doi.org/10.1371/journal.pone.0195731

Nigeria: Act No. 26 of 2003, Child's Rights Act, 2003 (2003). National Legislative Bodies/National Authorities. Available at: https://www.refworld.org/docid/5568201f4.html (Accessed: 27 June 2020).

Omole O, Welye H and Abimbola S (2015) Boko Haram insurgency: implications for public health. *The Lancet* **385**, 941.

Van de Poel E, O'Donnell O and Van Doorslaer E (2007) Are urban children really healthier? Evidence from 47 developing countries. *Social Science and Medicine* **65**, 1986–2003.

Stata version 15.1 (2017). Available at: https://www.stata.com/order/ (Accessed: 30 May 2019).

UNICEF (2018a) *Child Marriage in West and Central Africa*.

UNICEF (2018b) Levels and trends in child mortality. Available at: https://data.unicef.org/wp-content/uploads/2018/09/UN-IGME-Child-Mortality-Report-2018.pdf (Accessed: 14 March 2019).

UNICEF (2021) Towards ending child marriage. Available at: https://data.unicef.org/resources/towards-ending-child-marriage/ (Accessed: 28 January 2024).

UNICEF MICS (2018) 'Datasets'. Available at: http://mics.unicef.org/surveys.

UNICEF and NBS (2017) *Multiple Indicator Cluster Survey 2016-17, Survey Findings Report*. Abuja: Nigeria.

United Nations Office for the Coordination of Humanitarian Affairs (2017) Nigeria - Administrative boundaries (levels 0-3) and senatorial districts. Available at: https://data.humdata.org/dataset/nga-administrative-boundaries (Accessed: 9 November 2019).

WHO, UNICEF and JMP (2018) *JMP methodology: update and SDG baselines*. Available at: https://washdata.org/sites/default/files/documents/reports/2018-04/JMP-2017-update-methodology.pdf (Accessed: 12 May 2019).

World Health Organization (2008) *Closing the gap in a generation: Health equity through action on the social determinants of Health*. Available at: https://www.who.int/social_determinants/final_report/csdh_finalreport_2008.pdf (Accessed: 17 February 2019).

Zhu B-P, Rolfs RT, Nangle BE and Horan JM (1999) Effect of the interval between pregnancies on perinatal outcomes. *New England Journal of Medicine* **340**, 589–594.

APPENDIX

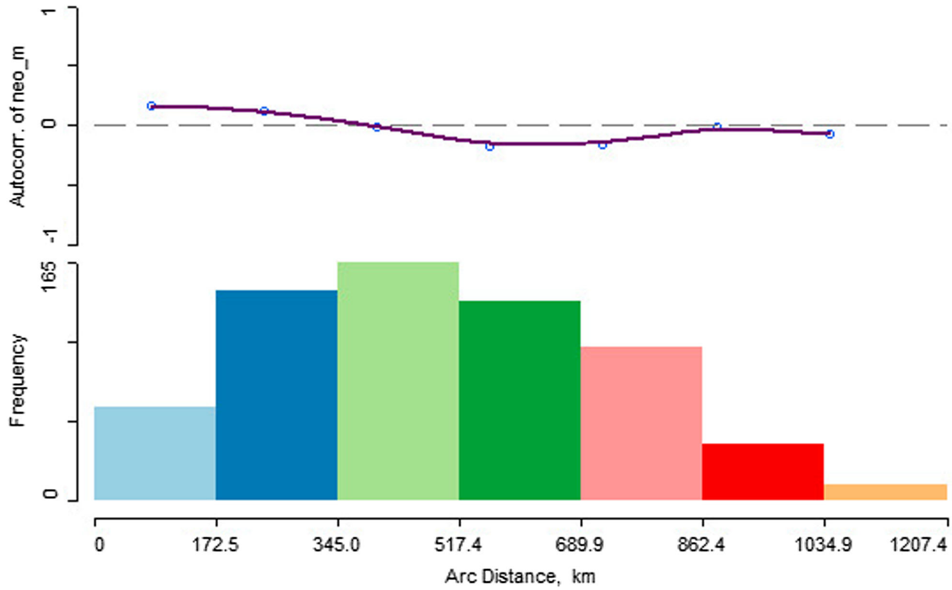
Artificial neural network

With a view of identifying the key predictors of neonatal mortality at regional and national levels, backpropagation feedforward MLP neural networks were implemented in the IBM SPSS neural networks software version 21.0 (IBM, 2012). Much like the human brain, the architecture of MLP is a collection of several artificial neurones that are connected by their weights and assembled into an input layer, at least one hidden layer, and an output layer (IBM Corporation, 2012). The input layer receives the inputs and performs the calculations via the neurones before onward transmission to the hidden layer. The hidden layer is the 'black box' connecting the input and output layers. The output layer receives information from the hidden layer to produce the final results (IBM Corporation, 2012). In addition to the linear activation function of MLP, it can also account for the nonlinear relationship between the inputs and outputs, hence producing more accurate results, compared to the traditional statistical methods (IBM Corporation, 2012).

Data preprocessing

With the dataset randomly partitioned into training (70%), testing (20%), and holdout (10%) sets, the MLP learning algorithm (gradient descent algorithm) used the training set to learn the inherent pattern of the dataset. The testing and holdout sets were used for model validation. The model-building process in this study used two hidden layers. The input layer factors were the independent variables (stratified by zones). The output layer consisted of one factor – neonatal survival status (dependent variable). After eliminating the bias units, the input layer had 74 units, while the output layer had 2 units. The number of units in the hidden layers was automatically computed. The number of units in the hidden layer 1 and hidden layer 2 were 13 and 10, respectively. The initial process generated a weighted sum and bias of input and hidden layers. The weighted sum and bias were activated through the hyperbolic tangent (tanh) activation function and softmax activation function (IBM Corporation, 2012). The computational efficiency of the models was optimised at a learning rate (η) of 0.4 and momentum (μ) of 0.8. The gradient descent allows for weight correction (i.e. tuning) through the backpropagation of errors across the networks using an iterative process (IBM Corporation, 2012). The number of epochs ($\boldsymbol{\rho}$) that allowed convergence of input data was 100. Each epoch involved complete iteration over a batch of training set to adjust the weights and minimise errors of the network with an error rate (δ) of 0.00001.

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press



Autocorr.	0.163	0.122	-0.017	-0.180	-0.169	-0.011	-0.076
Min	0	172.480	344.960	517.441	689.921	862.401	1034.881
Max	172.480	344.960	517.441	689.921	862.401	1034.881	1207.361
# Pairs	64	145	165	137	106	39	10

min: 0, max: 1207.361, total # pairs: 666, Autocorr. = 0 at 409.810 in range: [344.960, 517.441]

Figure A1. Spatial Correlogram of Neonatal Mortality Rate, 2016/2017 Nigeria MICS
The spatial autocorrelation of NMR dropped to 0.12 between 172.5 and 345 km. Beyond 345 km, NMRs were spatially dispersed, ranging from -0.18 to -0.01. The spatial autocorrelation was zero at 409.8km (i.e. absence of systematic spatial variation in NMR).

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

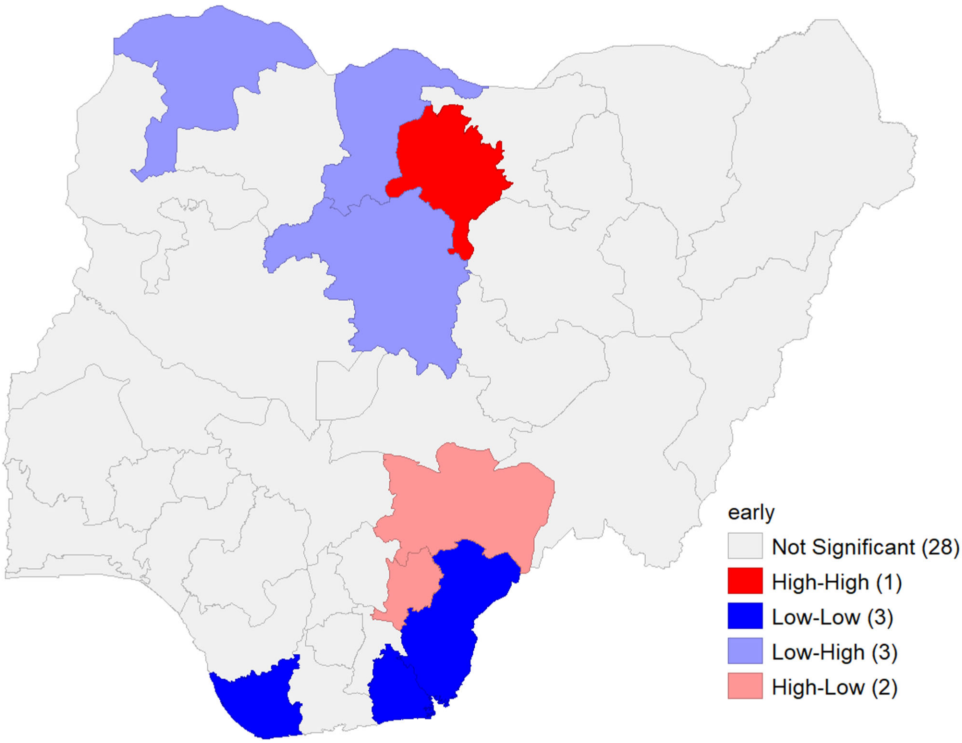


Figure A2. Univariate Local Indicator Spatial Autocorrelation (LISA) Cluster Map of Early Neonatal Mortality Rate, 2016/2017 Nigeria MICS.
Global Moran's I index = 0.02, *p*-value = 0.173
There was no significant spatial dependence of early NMR

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

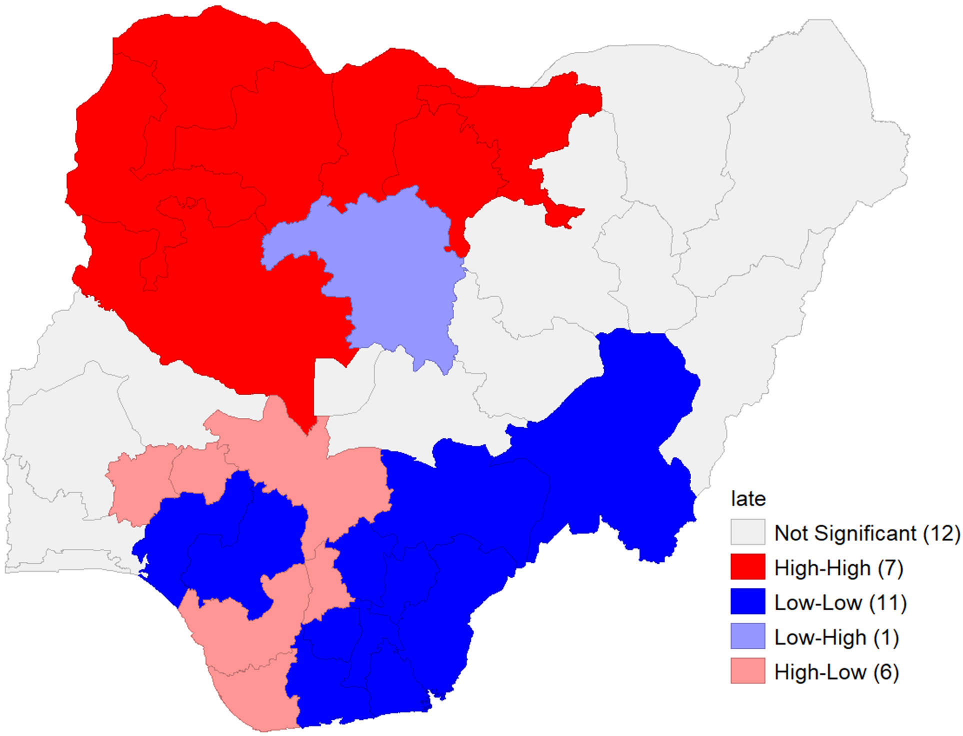


Figure A3. Univariate Local Indicator Spatial Autocorrelation (LISA) Cluster Map of Late Neonatal Mortality Rate, 2016/2017 Nigeria MICS.
Global Moran's I index = 0.3, *p*-value = 0.001
A statistically significant moderate global spatial clustering of late NMR was observed

https://doi.org/10.1017/S0021932024000282 Published online by Cambridge University Press

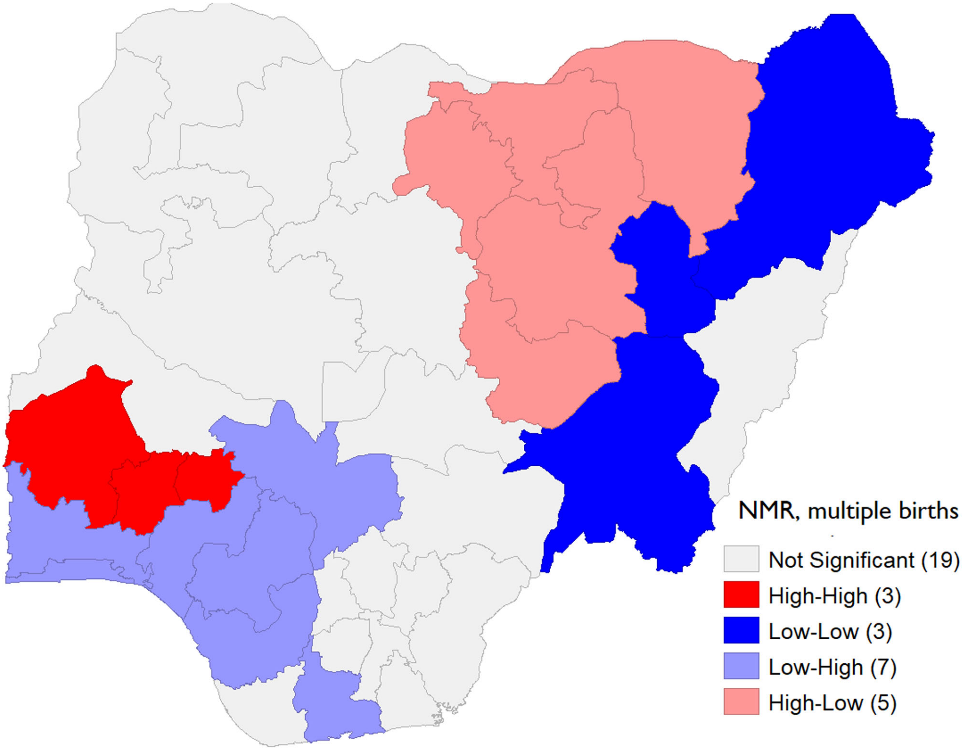


Figure A4. Bivariate Local Indicator Spatial Autocorrelation (LISA) Cluster Cap of Neonatal Mortality Rate and Multiple Births, 2016/2017 Nigeria MICS.
Global Moran's I index = -0.1, *p*-value = 0.05

Cite this article: Adeyinka DA and Muhajarine N (2024). Geographic inequities in neonatal survival in Nigeria: a cross-sectional evidence from spatial and artificial neural network analyses. *Journal of Biosocial Science* **56**, 896–919. https://doi.org/10.1017/S0021932024000282