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Subnational estimates of factors associated with under-five mortality in Kenya: a spatio-temporal analysis, 1993–2014

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ABSTRACT

Background To improve child survival, it is necessary to describe and understand the spatial and temporal variation of factors associated with child survival beyond national aggregates, anchored at decentralised health planning units. Therefore, we aimed to provide subnational estimates of factors associated with child survival while elucidating areas of progress, stagnation and decline in Kenya.

Methods Twenty household surveys and three population censuses conducted since 1989 were assembled and spatially aligned to 47 subnational Kenyan county boundaries. Bayesian spatio-temporal Gaussian process regression models accounting for inadequate sample size and spatio-temporal relatedness were fitted for 43 factors at county level between 1993 and 2014.

Results Nationally, the coverage and prevalence were highly variable with 38 factors recording an improvement. The absolute percentage change (1993–2014) was heterogeneous ranging between 1% and 898%. At the county level, the estimates varied across space and over time with a majority showing improvements after 2008 which was preceded by a period of deterioration (late-1990 to early-2000). Counties in Northern Kenya were consistently observed to have lower coverage of interventions and remained disadvantaged in 2014 while areas around Central Kenya had and historically have had higher coverage across all intervention domains. Most factors in Western and South-East Kenya recorded moderate intervention coverage although having a high infection prevalence of both HIV and malaria.

Conclusion The heterogeneous estimates necessitates prioritisation of the marginalised counties to achieve health equity and improve child survival uniformly across the country. Efforts are required to narrow the gap between counties across all the drivers of child survival. The generated estimates will facilitate improved benchmarking and establish a baseline for monitoring child development goals at subnational level.

Key questions

What is already known?

- The recent under-five mortality (U5M) decline in Kenya has been uneven across subnational units and over time with widespread inequities. These inequities are likely to be associated with the uneven use of interventions, healthcare utilisation, distribution of resources and disease prevalence. Thus, subnational estimates of factors associated with child survival are required.

What are the new findings?

- Overall, the coverage of interventions increased between 1993 and 2014, however, the estimates were heterogeneous with widespread geospatial inequities at county-level over time.
- High heterogeneity and varied estimates between the factors ranging from low (less than 35%) for improved sanitation to high (over 65%) for childhood immunisations by 2014.
- Across almost all the factors, counties in Northern Kenya were systematically left behind with lower coverage, Central Kenya always had higher coverage while western and south-east counties had moderate coverage and higher HIV and malaria infection prevalence.

What do the new findings imply?

- Prioritised targeting in the marginalised Northern Kenya region during allocation of resources, finances, policy formulation and planning to increase coverage, reduce health inequities and improve child survival. Additional efforts to reduce malaria and HIV infection in western and coastal regions of Kenya are needed.
- Generated estimates will facilitate benchmarking between counties and form a key baseline for monitoring sustainable development goals and local targets at subnational level.
- Need to evaluate the contribution for each factor relative to U5M variation subnationally to aid in granular targeting.
- Need for additional data for monitoring coverage during the devolved health planning era in Kenya.

INTRODUCTION

The planning and allocation of child health interventions to subnational areas with the greatest need is crucial in improving child survival equitably.[1,2] To identify populations that are marginalised from healthcare access and preventive interventions, requires an evaluation of their coverage. This is necessary to achieve universal health coverage on the pathway to equitable improvements of child survival[3] and ensure that no child is left behind and that resources do not go to waste on populations with the least need.[2] This is enshrined within the sustainable development goals (SDGs) principle of *leaving no one behind and reaching the furthest behind, first*.[4,5]

Increased need for improved understanding of gaps in intervention coverage and other factors known to be associated with under-five mortality (U5M) at local health planning units has spurred improvements in the use of geocoded data from household sample surveys[6,7] within advanced statistical modelling techniques.[8–11] As a result, factors associated with U5M have been mapped at fine-scale spatial and temporal resolution across much of sub-Saharan Africa[6,10,12–19] including Kenya.[6,10,16–23] Previous approaches in Kenya have not always been comparable over time, nor have these studies harnessed all the available data to make predictions across the country's subnational units required for decentralised health planning.[6,10,16–23] Many of these studies have considered a few individual factors only, however, mapping all factors is fundamental for benchmarking of health systems performance across subnational units.[12–15]

Here, we leverage data from multiple sources including all available household sample surveys and population census to provide annual estimates of 43 factors known to be associated with changes in U5M at each of the 47 subnational counties used for decentralised health planning in Kenya.[24] The generated estimates are used to express spatial and temporal inequities and elucidate areas of marginalisation for the periods between 1993 and 2014.

METHODS

Country health context

Kenya's healthcare system is pluralistic with both public and private healthcare facilities providing services. The service delivery is hierarchical with six tiers spanning between community level and tertiary facilities.[25] The government has continually enhanced healthcare utilisation by ensuring healthcare services are affordable and accessible since independence through polices on user fee.[3,26–32] Establishment of the Kenya Expanded Programme on Immunization (EPI) in 1980 introduced vaccines for six major killer diseases at the time including tuberculosis, polio, diphtheria, whooping cough, tetanus and measles. Between 2001 and 2014, yellow fever, hepatitis B and haemophilus influenza B type (*Hib*), pneumococcal conjugate, measles second dose and rotavirus vaccinations were added to the EPI schedule.[33]

Government-led campaigns such as the school feeding, *Malezi Bora* (good upbringing), baby-friendly initiatives at the hospital and community levels (Baby-Friendly Community/Hospital Initiative (BFCI and BFHI)) have addressed poor breastfeeding practices and improved nutrition among children.[34–36] Initiatives to fight malaria targeted to children and mothers were intensified from 2000 through expanded, free delivery of insecticide-treated nets (ITNs),[37,38] replacing failing malaria drugs with efficacious therapeutics,[39,40] targeted indoor residual spraying (IRS) and intermittent preventive treatment in pregnancy (IPTp).[22,38] Beginning 2000, there was an expansion of HIV prevention interventions including an increase in facilities offering prevention of mother-to-child transmission (PMTCT) interventions and increased uptake of antiretrovirals (ARVs) drugs.[41–43]

In 1996/1997, the Integrated Management of Childhood Illness was introduced aiming to improve the management of childhood illness such as diarrhoea, pneumonia, malaria, measles and malnutrition. It involves: (i) strengthening health worker skills in managing illnesses, (ii) strengthening health systems (drug availability, supervision, referral and Health Management Information System (HMIS)) and (iii) the improvement of family and community health practices through community involvement and awareness on measures to improve child health.[44] After 2003, the millennium development goals created an impetus to improve child survival and led to a proliferation of reproductive, maternal, newborn, and child health policies, programmes and increased funding in Kenya.[45]

Kenya has made major strides in the promotion of child health through legal frameworks such as the children Act, vision 2030, Big Four agenda and a new constitution.[24,46] Conversely, Kenya has been affected by several major disasters including floods, droughts, epidemics and post-election violence[47–51] which are antagonistic to child survival. Online supplemental file 1 summarises both the health context and major disasters related to child survival in Kenya since independence.

Following the promulgation of a new constitution in 2010 and the 2013 general elections, Kenya transitioned into a devolved system of government with a central government and 47 semi-autonomous county governments.[24] The counties are now used for decentralised health planning[52] and were adopted as the unit of analysis (figure 1). Under this system, the central Ministry of Health is mandated with policy-making and regulatory roles while allocation and managing healthcare resources and service provision is under the county governments.[53,54]

Subnational variations in U5M between 1965 and 2014 in Kenya have previously been described in detail in Macharia *et al*.[1] Briefly, U5M was highly variable in space and time during the period under consideration (1993–2014). In 1993, 15 counties had U5M of ≥100 deaths per 1000 live births and were located in Western Kenya (Homa Bay, Migori, Siaya, Kisumu, Busia, Kakamega, Vihiga, Bungoma and Kisii), parts of coastal Kenya (Kilifi, Tana River, Lamu and Kwale), northern (Turkana,

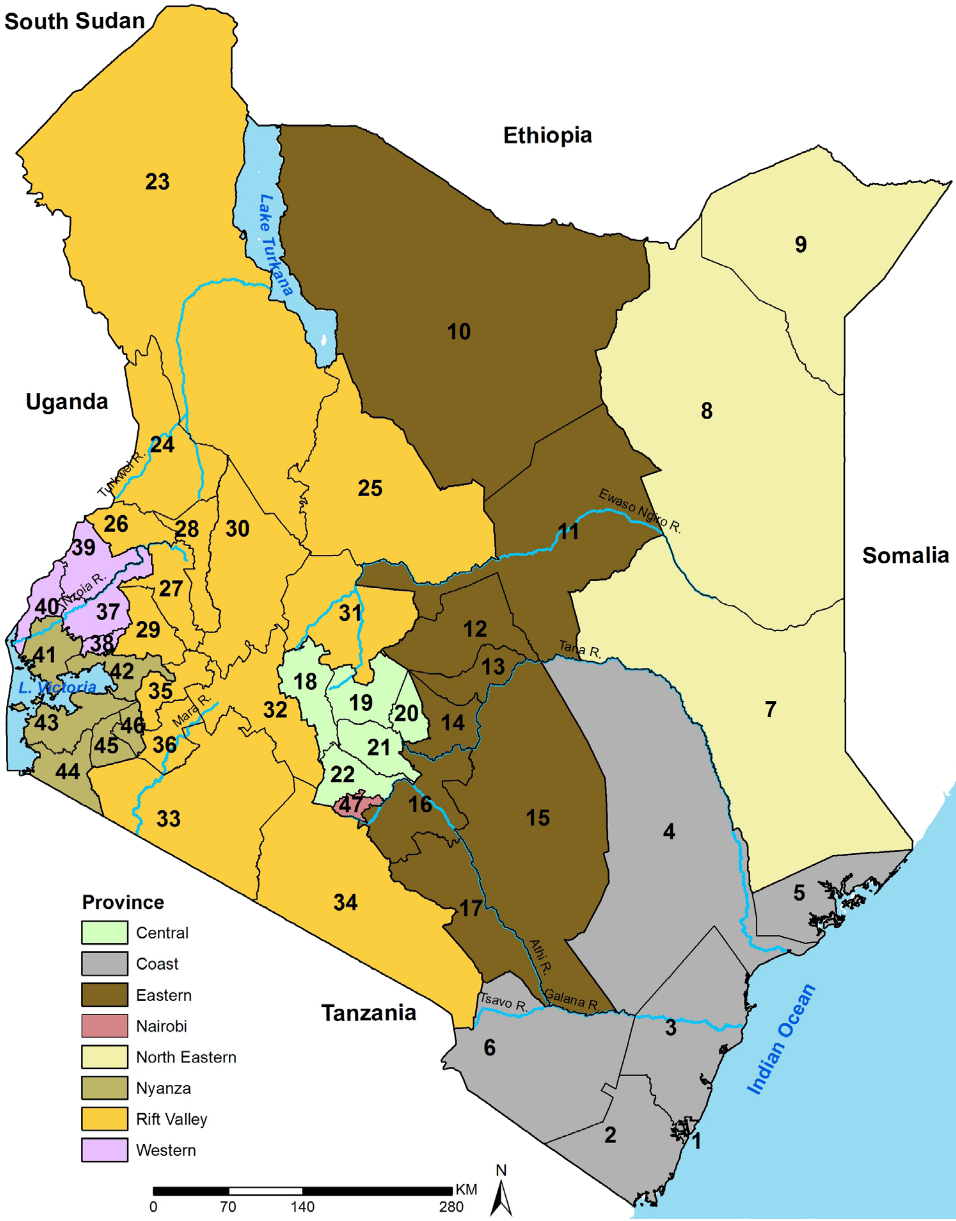

Figure 1 The map of Kenya showing 8 provinces (coloured) and the 47 subnational units (counties) as dark lines, water bodies and major rivers are shown in blue. Source: author. Coast province: Mombasa (1), Kwale (2), Kilifi (3), Tana River (4), Lamu (5), Taita Taveta (6); north eastern province: Garissa (7), Wajir (8), Mandera (9); eastern province: Marsabit (10), Isiolo (11), Meru (12), Tharaka Nithi (13), Embu (14), Kitui (15), Machakos (16), Makueni (17); central province: Nyandarua (18), Nyeri (19), Kirinyaga (20), Murang'a (21), Kiambu (22); Rift Valley province: Turkana (23), West Pokot (24), Samburu (25), Trans Nzoia (26), Uasin Gishu (27), Elgeyo Marakwet (28), Nandi (29), Baringo (30), Laikipia (31), Nakuru (32), Narok (33), Kajiado (34), Kericho (35), Bomet (36); western province: Kakamega (37), Vihiga (38), Bungoma (39), Busia (40); Nyanza province: Siaya (41), Kisumu (42), Homa Bay (43), Migori (44), Kisii (45), Nyamira (46); Nairobi province: Nairobi (47).

Garissa) and eastern (Kitui) regions. Five counties in central region (Kiambu, Embu, Murang'a, Nyeri and Nyandarua) and three in the neighbouring counties (Nakuru, Kajiado and Laikipia) had the highest probability of child survival, ≤50 deaths per 1000 live births in the same year.

During this period (1993–2014), 39 (83%) counties recorded U5M declines ranging between 1.6% in Kiambu and 58.3% in Mandera county. The counties with huge reductions (western and north eastern) had higher U5M in 1993 compared with counties with lower reductions. No county had U5M rates of ≤25 per 1000 live births, the target for 2030 for SDG 3.2 and by 2014, only three counties in western region (Migori, Homa Bay and Siaya) had U5M of ≥100 deaths per 1000 live births.

Data

We accessed information from multiple household sample surveys and population censuses conducted since 1989 available from online data portals. These included the Integrated Public Use Microdata Series,[55] Kenya National Bureau of Statistics,[56] Multiple Indicator

Table 1 Household sample surveys and population censuses undertaken since 1989 used in the analysis comprising six DHS, five MICS, three population censuses, two AIS, three MIS, two WMS and two KIHBS

Survey	Year	Number of counties	Number of households	Clusters/units	Women aged 15–49 years
DHS	1989	38	8173	393	7150
	1993	40	7950	520	7540
	1998	38	8380	536	7881
	2003	47	8561	400	8195
	2008/2009	47	9057	400	8444
	2014	47	36 430	1612	31 079
MICS	2000	42	9045	900	10 537
	2007	3	881	62	881
	2008	8	14 677	650	13 606
	2011	6	6828	300	5908
	2013/2014	3	3744	158	3348
Population Census	1989	47	224 861	36 979	238 027
	1999	47	317 106	61 921	345 647
	2009	47	243 858	96 253	934 904
AIS	2007	47	9691	402	5991
	2012	44	8035	371	7958
MIS	2007	43	6854	200	6111
	2010	47	6538	240	5749
	2015	47	6481	245	5394
WMS	1994	47	10 860	1172	13 385
	1997	41	10 873	1107	2484
KIHBS	2005/2006	47	13 390	1339	16 446
	2015/2016	47	21 773	2387	23 768

Table includes the number of counties covered, clusters and number of women of childbearing (15–49 years).
AIS, AIDS Indicator Survey; DHS, Demographic and Health Surveys; KIHBS, Kenya Integrated Household Budget Survey; MICS, Multiple Indicator Cluster Surveys; MIS, Malaria Indicator Surveys; WMS, Welfare Monitoring Surveys.

Cluster Surveys[57] and Demographic and Health Survey.[58] A survey was included if it contained at least one factor associated with U5M monitored over time, surveyed both in the rural and urban areas and devoid of reported data collection and quality concerns.

The assembled data were spatially misaligned over time due to changes in the number and geographical size of districts (subnational units before counties[1]) between 1989 and 2010 when county boundaries were formally defined.[24] Spatially misaligned historical district boundaries were matched to the current county boundaries (figure 1) as described elsewhere.[1] Table 1 summarises the data sources that were included in the analysis.

Factors associated with U5M

Forty-three factors a priori known to be associated with U5M (table 2 and online supplemental file 2) were identified based on existing frameworks of child survival,[59–61] relevance to Kenya's child health priorities[52] and data availability (table 1). The factors were defined following household sample surveys guidelines.[56–58] The 43 factors were divided into 8 broad thematic areas including environmental, maternal, child, and household factors, infections, healthcare utilisation, child and maternal health interventions. Table 2 outlines the factors and their thematic groups with detailed definitions and the specific data sources outlined in online supplemental file 2.

The comparativeness of various sources of information considered in the current analysis is non-trivial (table 1) given the variations in period, approaches and tools used during data collection. To ensure comparativeness of the various data sources, we implemented several checks. First, we explored and assessed the responses collected per each factor under consideration across all household sample surveys and population censuses (table 1). We then adopted a definition (online supplemental file 2) that ensured identical meaning across all data sources to maintain temporal comparability and allow for tracking of changes over time. Second, using approaches outlined by Ngandu *et al*,[62] we evaluated the effect of recall bias and missing data on estimates when combining Demographic and Health Surveys (DHS) and Multiple Indicator Cluster Surveys (MICS) data. The results were reasonably comparable using unmatched time lags for 3 years (DHS) and

Table 2 The factors associated with child survival and thematic groups as used in the current analysis

Group	ID	Variable
Environmental factors	1	Rural residency
	2	Precipitation
	3*	Enhanced vegetation index (EVI)
Maternal factors	4	Maternal education
	5	Maternal literacy
	6	Female headed households
	7	Short birth spacing
	8	Use of modern contraceptives
	9	High parity
Child factors	10	Underweight
	11	Wasted
	12	Stunted
	13	Breast fed within the first hour of birth
	14	Exclusive breast feeding
	15	Continued breast feeding
	16	Low birth weight (LBW)
Household factors	17	Poor household
	18	Improved sanitation
	19	Access to any form of a toilet
	10	Improved water
	21	Access to wells, borehole and piped water
Infections	22	HIV infection prevalence
	23	Malaria infection prevalence
Healthcare utilisation	24	At least one antenatal care visit (ANC1)
	25	At least four antenatal care visits (ANC4)
	26	Skilled birth attendance (SBA)
	27	Health facility deliveries (HFD)
	28	Diarrhoea treatment-seeking
	29	Fever/cough treatment-seeking
Child health interventions	30	BCG
	31	Three diphtheria–tetanus–pertussis vaccinations (DPT3)
	32	Three doses of polio (Polio3)
	33	Measles
	34	Fully immunised
	35	Oral rehydration salts (ORS use)
	36*	Vitamin A-children
	37*	Insecticide treated bed nets (ITN) use by children
	38*	Recommended antimalarial use
Maternal health interventions	39	Tetanus toxoid injection
	40*	Intermittent preventive treatment in pregnancy (IPTp 1)
	41*	IPTp 2
	42*	Iron supplement
	43*	Vitamin A-mothers

The definitions and respective data sources of factors are shown in online supplemental file 2.
*2003 is the baseline year because the corresponding factors were either not monitored or had not been rolled out.

2 years (MICS) and was adopted for our analyses based on a pragmatic balance between recall data and maintaining a large enough sample for county level estimates. Finally, the use of spatio-temporal methods described in the subnational modelling section allowed for smoothing of data points from the multiple sources.

Subnational modelling

Coverage and/or prevalence for 39 factors were estimated using data defined in table 1 while 4 factors were available either as gridded surfaces or at aggregated geographical units. The four factors included HIV infection prevalence at the provincial level (figure 1) available from Kenya National AIDS Control Council (NACC),[63] a temporal gridded malaria risk surface based on parasite prevalence,[22] and temporal gridded surfaces of enhanced vegetation index (EVI) and precipitation.[64 65] Thirty-five factors were available for the entire analysis period (1993–2014) while eight factors were available from 2003 since they were either rolled out or first monitored from early 2000 (table 2).

Prevalence estimates for each of the 39 factors (table 2) were computed while accounting for sampling design and/or survey weights by survey/census (table 1) at county level. All the household sample surveys (except DHS 2014) were designed to provide precise estimates at national and provincial levels and not powered to provide subnational county-level estimates. To predict across all subnational counties and during non-sampled years and combining raw estimates where more than one survey was conducted in a single year, a Bayesian spatio-temporal Gaussian Process Regression model[66 67] with a heteroscedastic error component defined elsewhere[1] was used (equation 1). In brief, the modelling framework accounts for large sampling variance and heterogeneity between surveys while exploiting spatio-temporal relatedness to increase predictive power (equation 1).

Spatio-temporal model for smoothing factors associated with U5M:

$$\log\left\{\frac{Q_{ikt}}{1-Q_{ikt}}\right\} = \alpha + S_{kt} + Z_{kt} \qquad (1)$$

Q_{ikt} is the weighted proportion for each factor (table 2) for survey i (table 1), county k (n=47; figure 1) and year t (n=22 or 12 years; table 1, online supplemental file 2); α is the intercept, S_{kt} is a spatio-temporal Gaussian process predicted by borrowing strength of information across surveys, counties and years with mean 0 and covariance function $\Sigma = \sigma^2\left[R_S \otimes R_T\right]$. Where $\otimes$ is the Kronecker product, R_S and R_T are the spatial and temporal correlation matrices, respectively. R_S is modelled using a conditionally autoregressive (CAR) process while R_T is an autoregressive process of the first order. Z_{kt} a Gaussian noise modelled with the variance taken to be the product of the log-transformed sample size from a given survey, county and year.[1] Further details of the modelling framework are presented in online supplemental file 3 in Macharia *et al.*[1]

The model for each factor was fitted using Markov chain Monte Carlo (MCMC) algorithm based on 10 000 posterior samples by county and year. The algorithm was iterated for 110 000 times and retained every 10th sample after a burn-in of 10 000 samples. Cross-validation was undertaken to assess the predictive performance of the model through a 10% random hold-out of the observed values. The observed and posterior predictions were used to compute the correlation, mean absolute error and root mean square error. The posterior distribution for each factor was summarised by its mean and 95% CIs for each year and county across the study period.

Analyses and data management were conducted in StataCorp 2014 (Stata Statistical Software: Release V.14) and R statistical software (V.3.4.1) while all the cartographies were done in ArcMap V.10.5 (ESRI, Redlands, CA, USA). While estimates were generated for every year between 1993 and 2014, maps were anchored at stable years with substantial data points corresponding to years when majority of the nation-wide sample surveys were conducted (1993, 1998, 2003, 2008 and 2014).

Patient and public involvement

The study used secondary data only (table 1) that are publicly available through links and sources provided within the manuscript.[55–58]

RESULTS

The data assembled included 20 sample household surveys and 3 population censuses conducted after 1989 covering 870 county-years and 1.7 million women of childbearing age (table 1). The annual predictions spanned either the entire analysis period (1993–2014) for 35 (82%) factors or 12 years (2003–2014) for seven interventions that were introduced or first monitored from the early-2000s.

At the national level, at baseline (1993), child health interventions had high coverage (over 65%). Conversely, rates of healthcare utilisation were moderate (35%–65%) except at least one antenatal care visit (ANC1) which had a high coverage (91%). Both maternal health interventions and household-related factors had either moderate or low coverage (table 3). The coverage of nutritional factors was highly heterogeneous. For example, breastfeeding factors spanned between low (exclusive breast feeding), moderate (breast fed within 1 hour of birth) to high (continued breast feeding) coverage while the prevalence of malnutrition ranged between 7% (acute-malnutrition or wasting) and 40% (chronic-malnutrition or stunting) with underweight (elements of both stunting and wasting) being 19% (table 3). The coverage/prevalence of maternal factors was variable ranging from low (contraceptive use) to high (maternal literacy). The infection prevalence of malaria (24%) and HIV (9%) were high. Table 3 shows the estimate of all factors in 1993 and 2014.

Nationally, all the factors had either an increase in the coverage of intervention or a decline in the infection prevalence between 1993 and 2014 except four factors (female-headed households, continued breast feeding, at least four antenatal care visits (ANC4) and tetanus toxoid injection) which showed minimal change. The percentage change in each of the four factors was less than 10%. The absolute percentage change was heterogeneous ranging from 1% to 898% across the 43 factors (table 3). Eighteen factors (42%) had an absolute percentage change of less than 25% while seven factors (16%) had a change of over 100%. Table 3 shows the percentage changes highlighting those that stagnated (red), had small (light green), moderate (mild green) or sizeable improvements (dark green).

By 2014, most of the factors had coverage of over 35%. For example, breastfeeding indicators, most maternal factors, household factors (except improved sanitation), maternal health interventions (except antimalarials and IPTp) and healthcare utilisation rates, all had moderate to high coverage (table 3).

National estimates mask important subnational county differences in the coverage or prevalence of the factors associated with U5M over time. The subnational estimates for all the factors across the study are presented in online supplemental file 3 while a subset of seven factors across seven themes are presented in figure 2. Further, figure 3 (1993) and figure 4 (2014) show scaled heat plots of all 43 factors and the 47 counties across the study period representing the prevalence and coverage estimates. Overall, across the continuum of all factors, intervention coverage was lower and disease infection prevalence higher in 1993 compared with 2014 (figures 2–4 and online supplemental file 3).

The reduction in infection prevalence and the increase in intervention coverage was characterised by epochs of improvement, deterioration and reversals in gains made. The improvements were observed mainly after 2008 through to 2014 largely as a result of counties in Western Kenya and those neighbouring central parts catching up with the Central Kenya counties while counties in the northern parts of Kenya showed little improvements. Overall, the improvement phase (2008–2014) was preceded by a period of deterioration and stagnation between the late-1990s to early-2000s while the early-1990s was characterised by moderate coverage of most interventions (figures 2–4 and online supplemental file 3).

Despite the increase in intervention coverage and reduction in disease infection prevalence across factors and counties, there were notable exceptions. Instances, where coverage decreased by more than 5% in several counties included; a reduction in access to safe water, ANC4 coverage, use of recommended antimalarial medicine, tetanus toxoid vaccination coverage and an increase in the proportion of poor households. The counties most affected by these reversals were mainly located in Northern Kenya (Garissa, Wajir, Mandera, Marsabit,

Table 3 The national coverage and or prevalence of the factors associated with child survival in 1993 and 2014 and change between the two time points

Thematic group	ID	Factors associated with under-five mortality	Estimate (95% CI)		Change (95% CI)	
			1993	2014	Percentage	Absolute
Environmental factors	1	Rural residency	84.2 (83.5 to 84.9)	58.0 (57.7 to 58.8)	−31.3 (−31.7 to −30.9)	−26.4 (−26.8 to −26.0)
	2	Precipitation	35 455.97 mm	43 866.85 mm	19.2	8410.9
	3	EVI	0.33	0.31	−5.5	0.02
Maternal factors	4	Maternal education less than pry school	57.7 (56.4 to 59.0)	36.38 (35.6 to 37.2)	−36.9 (−37.5 to −36.3)	−21.3 (−21.9 to −20.7)
	5	Maternal literacy	76.7 (75.5 to 77.8)	84.1 (83.5 to 84.7)	9.6 (9.1 to 10.2)	7.4 (6.9 to 7.9)
	6	Female household head	33.6 (32.7 to 34.5)	32.2 (31.7 to 32.7)	−4.2 (−4.6 to −3.8)	−1.4 (−1.8 to −1.0)
	7	Short birth interval	25.2 (24.1 to 26.2)	16.9 (16.4 to 17.5)	−49.1 (−49.4 to −48.8)	−8.3 (−8.6 to −8.0)
	8	Modern contraceptives use	20.8 (20.0 to 21.5	39.5 (38.7 to 40.3)	90.8 (90.5 to 91.1)	18.8 (18.8 to 19.1)
	9	High parity	35.9 (35.0 to 36.8)	25.3 (20.8 to 21.17)	−30.1 (−30.5 to −29.7)	−10.8 (−11.2 to −10.4)
Child factors	10	Underweight	18.9 (18.0 to 19.9)	10.6 (10.2 to 11.1)	−43.9 (−44.3 to −43.5)	−8.3 (−8.7 to −7.9)
	11	Wasted	6.8 (6.2 to 7.4)	4.1 (3.8 to 4.4)	−39.7 (−39.9 to −39.5)	−2.7 (−2.9 to −2.5)
	12	Stunted	40.0 (38.8 to 41.2)	25.8 (25.2 to 26.5)	−35.5 (−36.0 to −35.0)	−14.2 (−14.7 to −13.7)
	13	Breast fed within first hour of birth	55.5 (54.1 to 56.8)	62.8 (61.8 to 64.1)	13.2 (12.3 to 14.1)	7.3 (6.4 to 8.2)
	14	Exclusive breast feeding	17.6 (14.8 to 20.4)	60.9 (57.5 to 64.3)	246.0 (245.1 to 246.9)	43.3 (42.4 to 44.2)
	15	Continued breast feeding	91.6 (90.2 to 92.9)	87.9 (85.2 to 90.1)	−4.0 (−5.7 to −2.3)	−3.7 (−5.4 to −2.0)
	16	Low birth weight	8.7 (7.7 to 9.6)	7.6 (6.9 to 8.2)	−12.6 (−13.1 to −12.1)	−1.1 (−1.6 to −0.6)
Household factors	17	Poor household	38.4 (37.4 to 39.3)	34.7 (34.2 to 35.2)	−9.6 (−10.0 to −9.2)	−3.7 (−4.1 to −3.3)
	18	Improved sanitation	8.4 (8.0 to 8.5)	17.6 (17.2 to 18.0)	109.5 (109.2 to 109.8)	9.2 (8.9 to 9.5)
	19	Improved and intermediate sanitation	83.2 (82.5 to 83.9)	90.1 (89.8 to 90.4)	8.3 (8.0 to 8.6)	6.9 (6.6 to 7.2)
	20	Improved water	29.9 (28.1 to 30.5)	43.6 (43.1 to 44.1)	45.8 (45.4 to 46.2)	13.7 (13.3 to 14.1)
	21	Improved and intermediate water	51.4 (50.5 to 52.4)	63.4 (62.9 to 63.8)	23.3 (22.9 to 23.7)	12.0 (11.6 to 12.4)
Infections	22	HIV	9.16	5.01	−82.8	−4.2
	23	Malaria	23.9 (16.1 to 34.8)	4.7 (3.6 to 8.4)	−80.3	−19.2

Continued

Table 3 Continued

Thematic group	ID	Factors associated with under-five mortality	Estimate (95% CI) 1993	Estimate (95% CI) 2014	Change (95% CI) Percentage	Change (95% CI) Absolute
Healthcare utilisation	24	ANC1	91.4 (90.8 to 92.1)	95.6 (95.3 to 95.9)	4.6 (4.2 to 5.0)	4.2 (3.8 to 4.6)
	25	ANC4	62.4 (61.1 to 63.6)	56.3 (55.4 to 57.2)	−9.8 (−10.6 to −9.2)	−6.1 (−6.8 to −5.4)
	26	Skilled birth attendance	42.1 (42.0 to 44.3)	63.5 (62.8 to 64.3)	50.8 (50.1 to 51.5)	21.4 (20.7 to 22.1)
	27	Health facility births	41.6 (40.3 to 42.9)	63.0 (62.2 to 63.8)	51.4 (50.7 to 52.1)	21.4 (20.7 to 22.1)
	28	Diarrhoea treatment-seeking	39.2 (36.3 to 42.0)	57.8 (56.0 to 59.6)	47.4 (45.9 to 48.9)	18.6 (17.1 to 20.1)
	29	Fever treatment-seeking	46.0 (44.4 to 47.6)	72.8 (71.7 to 73.9	58.3 (57.3 to 59.3)	26.8 (25.8 to 27.8)
Child health interventions	30	BCG	96.2 (95.2 to 97.1)	96.7 (96.1 to 97.2)	0.5 (0.1 to 1.0)	0.5 (0.1 to 1.0)
	31	DPT3	86.7 (85.0 to 88.4)	90.1 (89.1 to 91.1)	3.9 (3.1 to 4.7)	3.4 (2.6 to 4.2)
	32	Polio3	85.5 (83.7 to 87.2)	90.9 (90.0 to 91.8)	6.3 (5.5 to 7.1)	5.4 (4.6 to 6.2)
	33	Measles	83.6 (81.8 to 85.8)	87.1 (86.0 to 88.1)	4.2 (3.3 to 5.1)	3.5 (2.6 to 4.4)
	34	Fully immunised	78.1 (76.0 to 80.2)	78.5 (77.5 to 80.1)	0.5 (−0.6 to 1.6)	0.4 (−0.7 to 1.5)
	35	ORS use	30.8 (28.0 to 33.5)	54.7 (52.8 to 56.5)	77.6 (76.0 to 79.2)	23.9 (22.3 to 25.5)
	36	Vitamin A-children*	34.1 (32.8 to 35.5)	67.8 (57.1 to 68.5)	98.8 (98.3 to 99.3)	33.7 (33.2 to 34.2)
	37	ITN use by children in malarious areas*	6.2 (5.4 to 7.0)	61.9 (61 to 62.8)	898.4 (897.7 to 899.1)	55.7 (55.0 to 56.4)
	38	Antimalarial use in malarious areas*	13.9 (12.0 to 15.9)	33.5 (31.9 to 15.2)	141.0 (139.8 to 142.2)	19.6 (18.4 to 20.8)
Maternal health interventions	39	Tetanus toxoid injection	51.8 (50.2 to 53.3)	51.5 (49.3 to 52.0)	−0.6 (−1.5 to 0.3)	−0.3 (−1.2 to 0.6)
	40	IPTp 1 in malarious areas*	13.3 (11.6 to 15.1)	41.2 (39.9 to 42.4)	210.5 (209.7 to 211.3)	27.9 (27.1 to 28.7)
	41	IPTp 2 in malarious areas*	5.6 (4.4 to 6.8)	25.7 (24.6 to 26.8)	358.9 (358.4 to 359.4)	20.1 (19.6 to 20.6)
	42	Iron supplement*	46.1 (44.5 to 47.6)	69.8 (68.7 to 70.9)	51.4 (50.4 to 52.4)	23.7 (22.7 to 24.7)
	43	Vitamin A-mothers*	14.3 (13.2 to 15.3)	54.5 (53.3 to 55.6)	281.1 (280.4 to 281.8)	40.2 (39.5 to 40.9)

*2003 is the baseline year because the corresponding factors were either not monitored or had not been rolled out. The four indicators without CI were externally sourced.
ANC1, one antenatal care visit; ANC4, four antenatal care visits; DPT3, three diphtheria–tetanus–pertussis vaccinations; EVI, enhanced vegetation index; IPTp, intermittent preventive treatment in pregnancy; ITN, insecticide-treated net; ORS, oral rehydration salts.

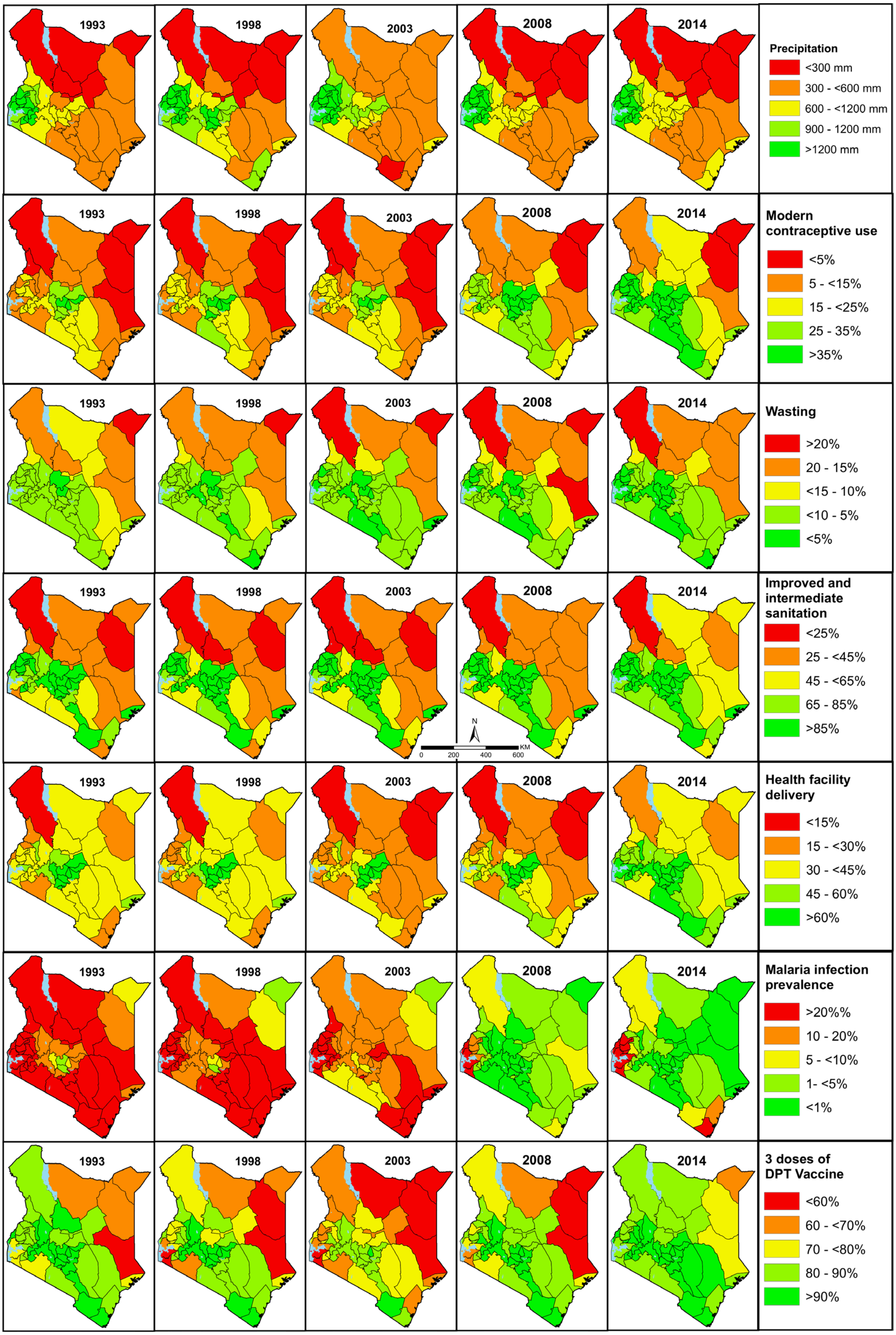

Figure 2 A subset of seven factors associated with child survival including precipitation, use of modern contraceptives, wasting, a combination of intermediate and improved sanitation, health facility delivery, malaria infection prevalence and three doses of diphtheria–tetanus–pertussis (DPT) vaccine. The factors are classified into five classes colour-coded from red (low coverage or high disease prevalence) to green (high coverage or low disease prevalence). The rest of the factors are presented in online supplemental file 3. Source: author.

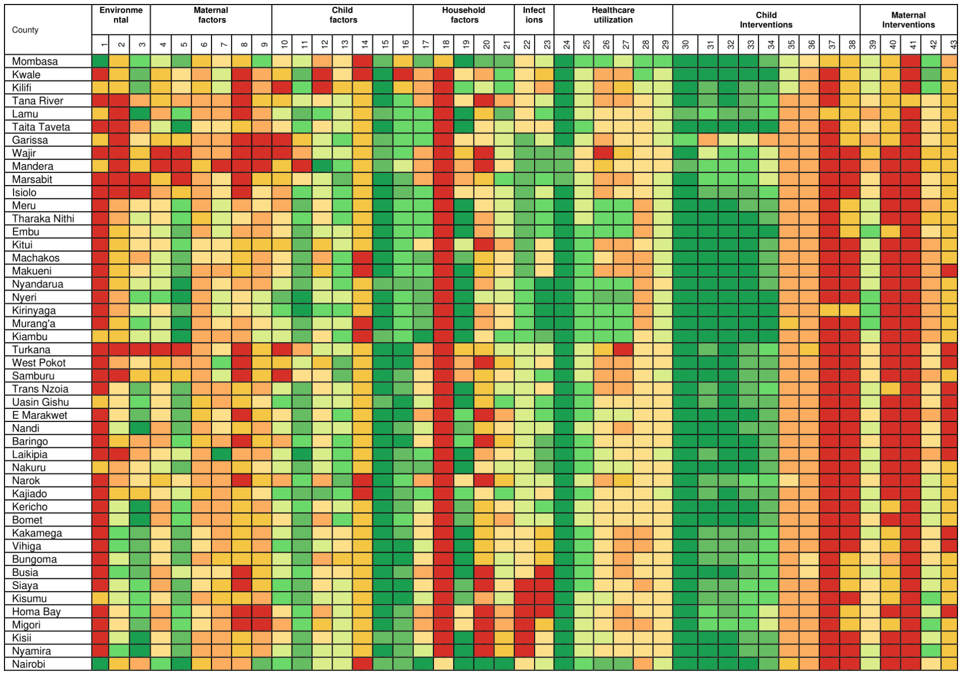

Figure 3 Ranking of factors associated with child survival in 1993 from low intervention coverage or high disease prevalence (red) to high intervention coverage or low disease prevalence (green). The second row are the 43 factors (table 2) while online supplemental file 3 has the actual values. Colour codes can be compared within an indicator across the 47 spatial units in 1993 and 2014 but not between factors. Source: author. An octile ranking was used to divide each factor into eight equal classes from <12.5% to ≥87.5% for interventions whose coverage varied from 0% to 100%. For factors whose coverage was not expected to range between 0% and 100% (such as nutrition status), they were first rescaled to 0%–100% and then divided into octiles.

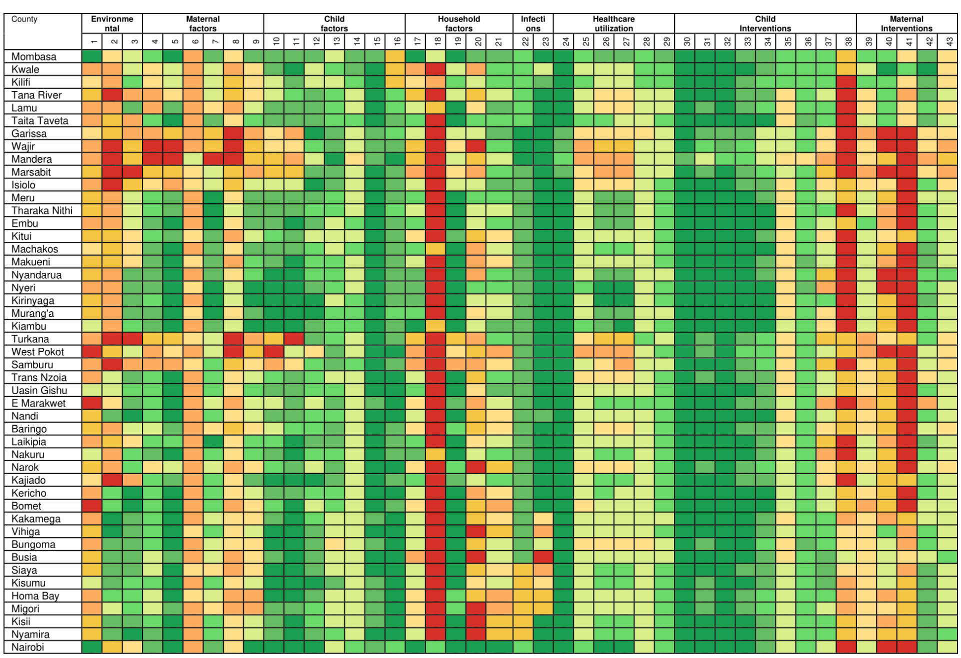

Figure 4 Ranking of factors associated with child survival in 2014 from low intervention coverage or high disease prevalence (red) to high intervention coverage or low disease prevalence (green). The second row are the 43 factors (table 2) while online supplemental file 3 has the actual values. Colour codes can be compared within a factor across the 47 spatial units in 1993 and 2014 but not between factors. Source: author. An octile ranking was used to divide each factor into eight equal classes from <12.5% to ≥87.5% for interventions whose coverage varied from 0% to 100%. For factors whose coverage was not expected to range between 0% and 100% (such as nutrition status), they were first rescaled to 0%–100% and then divided into octiles.

Turkana, West Pokot, Samburu) and partly western region (Trans Nzoia and Vihiga) and along the Indian ocean (Lamu) (figures 2–4 and online supplemental file 3).

The coverage of interventions and prevalence between factors was highly variable across the years. For example, there was a huge difference between the coverage of vaccinations such as three diphtheria–tetanus–pertussis vaccinations (DPT3) (mainly over 60% across counties) compared with access to modern contraceptives (mainly below 40% across all counties). Similarly, the usage of recommended antimalarial medicine and improved sanitation were always less than 20% compared with the coverage of ANC1 which was above 75% in a majority of the counties over the entire period (figures 2–4 and online supplemental file 3).

More prominent was the consistent colocation of disadvantaged counties over time for almost all factors. Counties in Northern Kenya had lower coverage for almost all maternal and child health (MCH) interventions, poor health utilisation rates, lower coverage of household factors and higher disease prevalence during the analysis period (online supplemental file 3). However, HIV and malaria infection prevalence were lower in Northern Kenya. Likewise, there was consistent colocation of counties that performed better (Central Kenya) from 1993 to 2014. In western and south-east counties, the coverage of interventions and disease prevalence were moderate except high infection prevalence of HIV and malaria (figures 2–4 and online supplemental file 3). The validation statistics showed a fair agreement between the observed and predicted estimates for a majority of the factors (82%) with a correlation coefficient above 0.6 (online supplemental file 4).

DISCUSSION

The compilation of a large database of household sample surveys, population census and other opportunistic sources allowed for the evaluation of trends, variations and changes in 43 factors associated with child survival at subnational county-level over two decades in Kenya. The geospatial framework applied harmonises previous approaches[6 10 16–23] that have not always been comparable. The results depict substantial but heterogeneous gains in the provision and scaling up of MCH interventions between 1993 and 2014. The coverage ranged between suboptimal to moderate levels illustrating widespread disparities and inequities in the continuum of child and maternal healthcare. The trends, variations and changes observed, over time, especially between 2008 and 2014, can be linked to important initiatives and programmes in Kenya as summarised in the country health context and online supplemental file 1.

By 2014, two in every three children received child health interventions except for access to recommended antimalarial medicines (table 3). These include all childhood immunisations, oral rehydration salts, ITNs and vitamin A supplements. Childhood immunisations have been offered free of charge and probably why their coverages have been high over time. However, the proportion of fully immunised children stagnated (0.5% overall change) possibly due to those who do not receive timely immunisation or drop out before completing their immunisation schedule.[12 68–70] Demand and supply challenges such as spatial access, health workforce, stockouts, cost of transportation and cold chain could also have hampered vaccination uptake especially in Northern Kenya where coverage was lower.[70–75] Child and maternal survival interventions such as supplements have been delivered through the *Malezi Bora* initiative since 2007, a health facility-based delivery system migrating away from the previous door-to-door approach to reduce implementation cost.[35] This might have also encouraged the uptake of immunisations. However, the coverage of maternal interventions was slightly lower than that of childhood interventions.

ITNs were only limited to the private and special project-based distributions until 2000 when they were partially subsidised through to 2004 followed by high subsidies and delivered via MCH clinics. After 2006, ITNs were available free of charge through routine delivery and mass delivery in 2006, 2008, 2011/2012, 2014 and 2015.[37 38] Increase in coverage of ITNs among children coincides with these efforts (online supplemental file 3, figures 3 and 4). The regions with high malaria prevalence (counties in western, coastal and partly in the Kenyan highlands) have benefited from targeted ITN distribution and historical clinical trials which might explain their higher coverage relative to other regions.[38] The low coverage of recommended antimalarial medicine might be due to frequent changes in first-line treatment of uncomplicated malaria; from chloroquine to the long half-life, single-dose sulfadoxine-pyrimethamine (SP) in 1998 which was later changed to artemisinin-based combination therapy in 2006.[38–40]

The period of greatest decline in malaria risk occurred prior to the scaling of ITNs and coincided with a period of use of infective drugs. The decline could be linked to the widespread availability of SP and its long half-life providing prophylaxis after single-dose administration.[76] On the other hand, increasing HIV infection prevalence in the 1990s (online supplemental file 3) led to the establishment of NACC that put measures that coincided with HIV decline. Since 2000, PMTCT, paediatric HIV programmes, ARVs uptake, testing and behavioural change campaigns have increased steadily.[41–43 45 77–81]

Increase in healthcare utilisation rates can be linked to policies on user fees. The health voucher programme for maternity services (2006–2016), the abolishment of delivery fees (2007), free maternity services (2013) and suspension of user fee (1990).[3 26–32] From 1991, user fees charged for services such as drugs and laboratory services hampered utilisation.[82–85] This led to the removal of user fees at dispensaries and health centres (except a for registration fee) in 2004[3 26] with a health sector services fund introduced in 2010 to compensate for the removal of user fee at dispensaries and health centres.[26] Before the suspension of user fees, antenatal care utilisation declined in all counties with Mandera, Wajir, Marsabit, Garissa, Isiolo, Tana River and Turkana counties witnessing larger declines between 1993 and 2003 (online supplemental file 3). Similar trends were observed for other markers of healthcare utilisation such as institutional deliveries. However, an immediate shift in utilisation trends, declining in the 1990s (eg, institutional deliveries) especially in northern counties (Mandera, Isiolo, Garissa, Wajir, Marsabit, Samburu, Laikipia, Baringo and West Pokot) was witnessed from 2006 after the new policies on user fees (online supplemental file 3).

Long physical distances to point of care affect utilisation rates negatively, however, in Kenya, over time, the number of health facilities has increased reducing the travel time needed to seek care.[73–75] Therefore, it is plausible that the quality and availability of services offered at points of care might be major factors relative to the physical distance in influencing utilisation rates in some parts of Kenya. The stagnation of ANC4 rates and some of the immunisations could be because they require multiple contacts with the health system, inadequate staff or poor adherence to treatment guidelines.[12 21] However, counties in Northern Kenya, have always had poor physical access to healthcare services hence lower utilisation rates. In 2003, only 18% of the total population was within the recommended distance of a health facility (5 km radius) improving marginally to 29% in 2008 compared with national averages of 71% and 89%, respectively.[74] For example, mean travel time of up to 120+ minutes was significantly associated with poor immunisation outcomes only in Northern Kenya (Isiolo and Marsabit).[71]

Low breastfeeding coverage and high malnutrition levels continue to be a public health concern for Kenya with moderate gains witnessed across time.[86–89] The small improvements can partly be associated with breastfeeding initiatives (BFCI and BFHI) both at the hospital and community level,[36] food fortification, micronutrients, nutritional campaigns, school and community level initiatives (online supplemental file 1). However, the number of children receiving the minimum acceptable diet was low and declined over time.[90–93] The piloting and demonstration of BFCI in parts of Siaya (Bondo) and Meru (Igembe North) counties in 2011 showed increased likelihood of participating in ANC, institutional deliveries and initiating breast feeding within an hour of birth[94] and appears to be linked to broad increases in coverage (online supplemental file 3). Following the demonstration, BFCI was included in the National Nutrition Action Plan and prioritised as a *high impact nutrition intervention*.[94]

The use of modern contraceptive increased by over 90%, however, despite this improvement by 2014, only 40% of the women in need of contraception were covered (table 3). Family planning reduces closely spaced births, ill-timed births and high parity and might explain why there was a moderate reduction in short birth interval and high parity[95–97] (online supplemental file 3). There have been several efforts and initiatives to improve the coverage of family planning by addressing drivers of the slow progress.[98–102] For, example, The government committed to increase the budget allocated for family planning services in 2012 which may have led to the achievement of 2020 target (58% coverage) and is now focusing on equitable access subnationally.[103 104] The marked regional heterogeneities in contraceptive use (online supplemental file 3) have been linked with socioeconomic and cultural environment[102] and possibly the regional initiatives addressing areas with lower coverage. For, example, after the launch of *AMUA* project (a social franchise) to provide family planning among under-served communities led to improved contraceptive use in the focus counties of western and coastal parts of Kenya between 2003 and 2008 (online supplemental file 3).[105]

The coverage of both improved sanitation and access to clean water at household level has remained low. The poor coverage has been associated with low education attainment, living in rural areas and poverty.[106] The government of Kenya committed to focus on the poorest, eliminate open defecation by 2030 and to invest 0.5% of its gross domestic product by 2020 to sanitation.[107] However, currently (2019), only a third of the households have access to piped water and 8.2% do not have access to any sanitation facility.[108] Minimal improvement in household wealth (online supplemental file 3) compounded the already dire need for access for safe and clean water and improved sanitation.

Historical (1993–2013) county level data on subnational policy and their implications are scarce for periods before 2013 when the devolved government was incorporated; thus, county level discourse is based on exemplar and limited information. At the county level, the coverage of interventions was disproportionately distributed over time; the coverage ranged between high to acutely low in disadvantaged and marginalised areas. Overall, counties in Central and Western Kenya had a moderate to high intervention coverage while counties in Northern Kenya were marginalised across the entire study period.

Northern Kenya is predominately arid and semi-arid (ASAL) with a low amount of rainfall and vegetation (online supplemental file 3) associated with reduced yields from rain-fed agriculture, persistent food insecurity and lack of green pastures for livestock.[109 110] They have challenges in accessing clean water and improved sanitation, low education attainment and more poor households, consequently, malnutrition is high in this region.[106 110] Healthcare utilisation rates are low due to poor infrastructure and limited geographical access, conflict and insecurity hence low immunisation rates and use of modern contraceptives.[71 73 74 101 111] However, in this region, religion and cultural beliefs might be a stronger determinant of contraception use in comparison to poverty and lack of access.[112–114] In view of historical and economic similarities between regions in Kenya, six economic blocs were formed. Among them is the Frontier Counties Development Council consisting of ASAL counties mainly in Northern Kenya (Lamu, Tana River, Garissa, Wajir, Mandera, Marsabit, Isiolo, Turkana, Samburu and West Pokot) which aims to enhance socioeconomic development and sustainable development through better cooperation through projects such as livestock strengthening.[115] These counties can further harness the assembled data to gain better insights on trends for informed decision making.

Conversely, the counties in Central Kenya with the higher coverage historically have higher agricultural productivity, lower rates of disease, better access to education, clean water and quality sanitation. Spatial access to healthcare is better in most parts of these counties, hence, better healthcare utilisation rates, access to vaccinations and supplementations.[71 74 75 116] The infection prevalence of HIV and malaria have declined across much of the country but remain high in Western Kenya and parts of south-east (online supplemental file 3). This has led to targeted interventions, for example, restricting IPTp to high prevalence areas, the pilot introduction of RTSS vaccine, and focused efforts to increase coverage of ITNs, IRS larval source management[117] and increased attention to HIV preventative interventions[43 118–121] in these two regions.

In this paper, we have not attributed the changing coverage of interventions and infection prevalence variations to disparities in U5M.[1] However, preliminary analysis, show that counties with high U5M (western and coastal region) were characterised with high HIV and malaria prevalence. Central region with low infection prevalence and higher coverage of interventions had lower U5M although smaller upsurges. Northern region with low HIV and malaria prevalence but constrained by low access to interventions, poor healthcare utilisation limited access to clean and safe water and sanitation had moderate U5M. The correlation coefficient between these factors and U5M (online supplemental file 5) were statistically significant for all but three factors. Malaria prevalence and early infant breast feeding had moderate correlation.[122] This underpins the need for a rigorous examination of the impact of these factors on driving trends in U5M across the 47 counties. Such evidence would be important for the health planners and policy makers and for targeted resource allocation.

The estimates generated in this analysis have important implications on existing efforts to improve child survival across Kenya under the decentralised governance structure while *leaving no one behind and reaching the farthest behind, first*. County planners can gain insights on coverage and trends to facilitate prioritisation. For example, by 2014, Mandera's coverage of ANC1, BCG and polio vaccines were ≥70% while improved sanitation and contraceptive use were ≤3% justifying additional funds and prioritisation for the latter factors. These estimates provide opportunities for benchmarking across counties where localised initiatives which have been shown to successfully improve coverage and in reduce disease prevalence.[12–15] The success of *Afya Uzazi* (healthy parenthood) programme in Baringo and Nakuru counties in improving access to quality health services by targeting family planning, pregnancies and deliveries, can be a benchmarking point for neighbouring counties.

At the national level, the government through *The Commission on Revenue Allocation* can leverage on the generated estimates when distributing national-level resources to 47 counties. The commission uses a weighted average of key factors including health indicators and can leverage on these estimates to better disaggregate the differences between counties. Further, counties in Northern Kenya should be targeted and prioritised during resources allocation and policy formulation to increase intervention coverage while more concerted efforts should be directed to western and coastal parts of the country to lower HIV and malaria infection prevalence. Various divisions such immunisation, national malaria control programme, human nutrition and dietetics unit within the national Ministry of Health can use the estimates as baseline to evaluate the impact of interventions that had been rolled out. This evaluation can be extended to include international development partners such as the GAVI the vaccine alliance to evaluate the impact of their funding or justify support for immunisation outreach programme. The findings should also form a key baseline for monitoring SDGs indicators proposed under the Inter-Agency and Expert Group on SDG Indicators[123] and county-specific targets as outlined in each county blue print, the County Integrated Development Plan for the 47 county governments.[124] The estimates form a key input in epidemiological studies of child survival across Kenya and these will be made available through a data visualisation web portal. Finally, the modelling framework can be applied to update the subnational estimates and evaluate progress as new data sources becomes available such as the recently concluded population census in Kenya (2019).[55 108]

We compared our estimates with previous estimates generated from similar and comparable studies that computed the prevalence of wasting, stunting and underweight, access to improved water sources, coverage of DPT3 (for the period 2000–2014)[125–127] and skilled birth attendance (SBA) (for the period 2014)[128] (online supplemental file 6). The estimates were highly correlated and generally with good concordance, identifying and ranking nearly all similar counties with the highest coverage (or lowest disease prevalence) and those with lowest coverage (or highest disease prevalence) (online supplemental file 6). The slight differences observed with reference to SBA are likely due to more data used in the current study within a spatio-temporal model without covariates relative to fewer data sources within a spatial model with covariates used in the comparator.[128]

Limitations

There are several caveats to this analysis. Tracking of coverage estimates beyond 2014 was not possible due to lack of data post-2014 limiting the number of the possible applications. Despite interpolating in space and time, household surveys are limited as they are conducted every three to five years powered for precise estimates at provincial level, thus they are not an alternative to quality data from HMIS. Additionally, factors such as human resources for health which affect child survival were not included due to lack of spatio-temporal data. The introduction and expansion of District Health Information System version 2 (DHIS2)[129 130] as part of the HMIS in Kenya and the development of approaches to deal with limitations of routine data[131–134] will allow incorporation of more variables in future analyses.

Recall and self-report biases were associated with some indicators, especially for longer recall periods, however, this effect was minimised by limiting the recall period to 3 years preceding the survey.[62] There was selection bias for some indicators because the survey included only the experiences of mothers with a live birth 3years preceding a survey leaving out mothers with other birth outcomes or those who might have died during pregnancy or delivery. The coverage estimates are not indicative of the quality of interventions received nor do they measure effective coverage which combines the need for, use and quality of the interventions.[12 135]

There was bias due to the modifiable areal unit problem, where results obtained might have been different if data had been aggregated into differently sized spatial units. A small proportion of clusters near county boundaries may have been misclassified because the displacement of cluster coordinates (due to confidentiality) was not accounted for. However, the use of CAR models to smooth estimates across adjacent counties potentially reduced this effect. Some small-scale heterogeneities were masked especially in high sized counties of Northern Kenya and disaggregation of the results to units lower than the counties (subcounties) would improve relevance at county level, however, the precision would reduce drastically. This provides an impetus for a strengthening DHIS2 and in the meantime powering household surveys to be representative at county level and conducting them more regularly.

While exploring inequities across other domains such as disparities across wealth quintiles, urban/rural stratifications or education attainment is important for policy making, however, the focus our work was to explore and describe inequities across geographic areas (counties) for 43 factors. Majority of the other domains including wealth quintiles, urban/rural differences have previously been explored through the standard DHS reports and by Keats and colleagues[21] in Kenya.

CONCLUSION

By harnessing and combining multiple data sources including household sample surveys and population censuses within a geospatial framework, levels and trends of 43 factors associated with child survival were generated between 1993 and 2014 in Kenya. The variation between factors over time was wide and estimates were highly heterogeneous between counties and over time. The marginalised counties that have been left behind should be given priority to address health inequities. The subnational estimates are useful to county planners in the current decentralised system of governance for evidence-based priority setting, a key baseline for monitoring and tracking of interventions within the defined local and global targets such as the SDGs.

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Contributors PMM undertook the development of the models, analysis and writing of the first draft of the manuscript. NKJ provided support for data assembly, checking, interpretation and data validation. BS, RWS and EO provided scientific and methodological support throughout the project. EO conceived the project, provided overall management and interpretation of results. All authors reviewed the final analysis, have access to the data and approved the final manuscript. All authors read and met ICMJE criteria for authorship.

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Additional file 1: Kenya's health context

Figure 1: The Kenya Health context between 1965 and 2018 showing major initiatives that were put in place in Kenya to improve child survival.

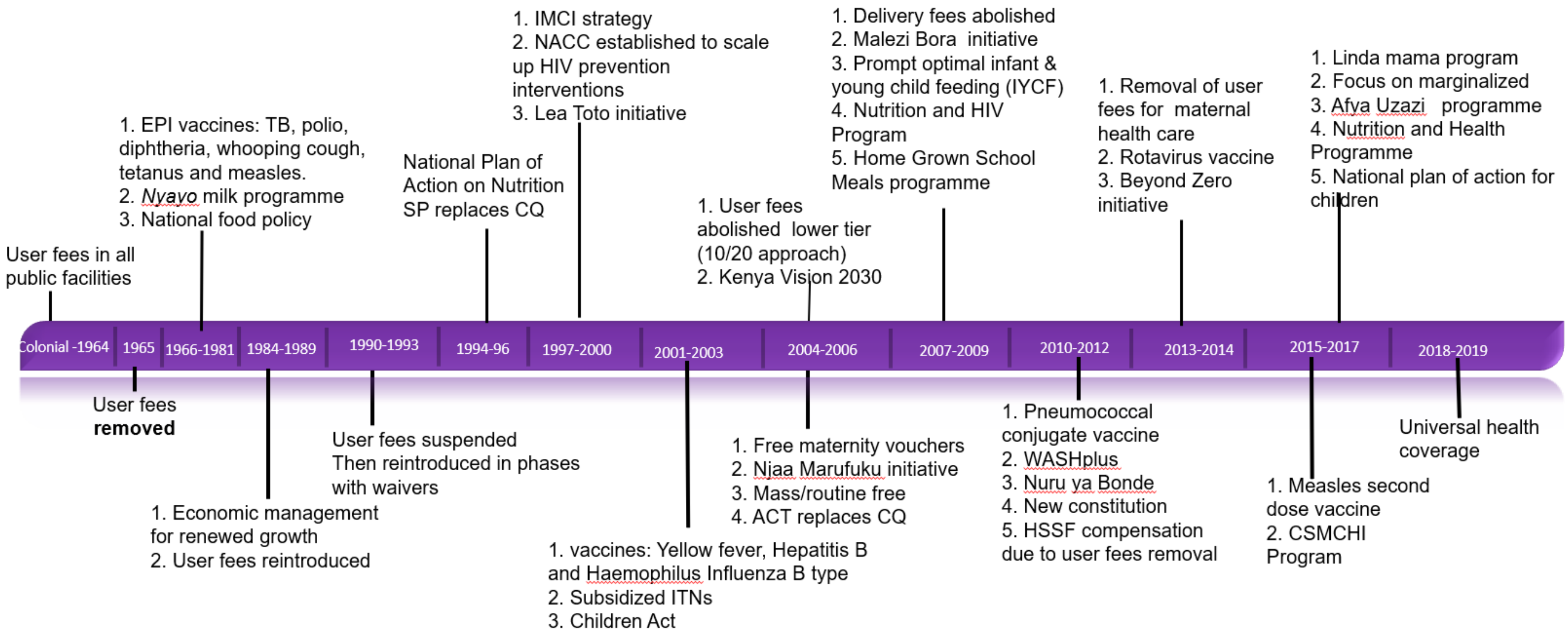
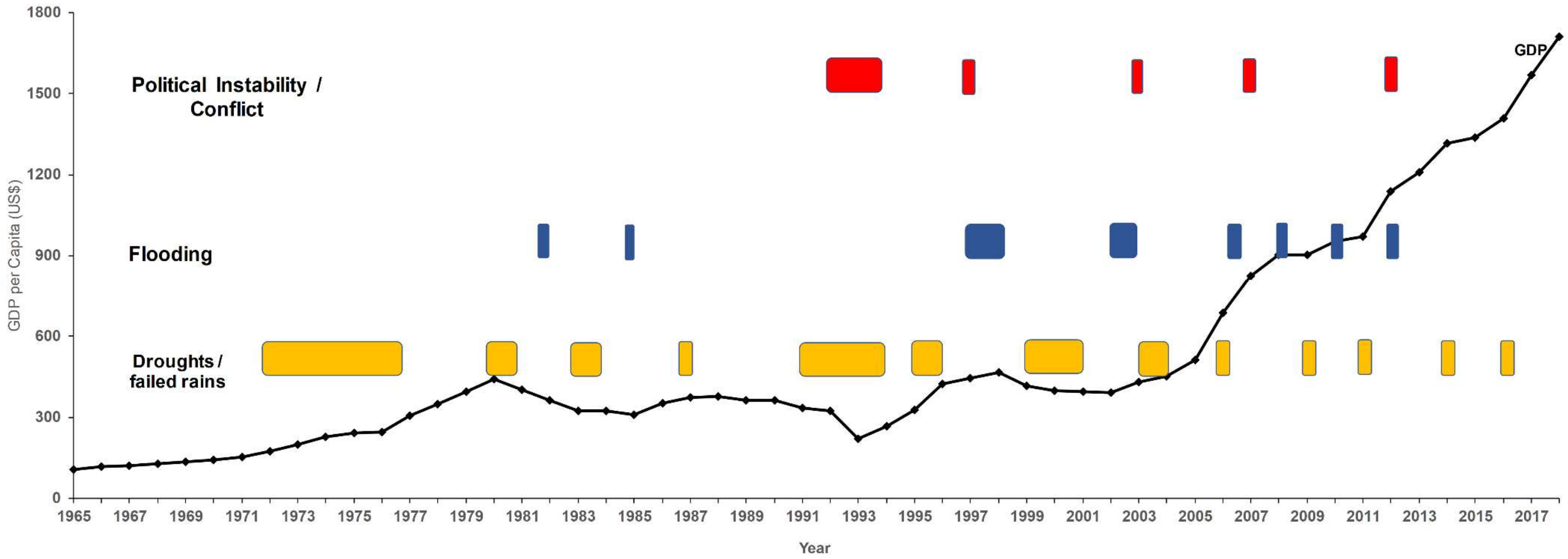


Figure 2: National profile of GDP and major disasters in Kenya including political instability events and conflict (red), flooding (blue) and droughts/failed rains (orange) between 1965 and 2017



Additional File 2:

Factors associated with child survival including their definition and source of data including household sample surveys or population census.

Group	ID	Variable	Definition	Datasets in reference to Table 1	Time
Environmental factors	1	Rural residency	The proportion of households in rural areas	All census, DHS, WMS, MICS, AIS, KIHBS and MIS	Year of Survey
	2	Precipitation	Annual average precipitation by county between 1990 and 2015	Tropical Rainfall Measuring Mission Multi-Satellite and weather station data.	-
	3	Enhanced vegetation index (EVI)	A vegetation index at 250 spatial resolution averaged to the county level	MODIS -Moderate Resolution Imaging Spectroradiometer-	-
Maternal Factors	4	Maternal education	The proportion of mothers (15-49 years) who had less than primary education at the time of the survey	All DHS, MICS, MIS and KIHBS; WMS 1997, AIS 2007; Census 1989,1999	Year of Survey
	5	Maternal literacy	The proportion of mothers (15-49 years) who can read all or parts of a sentence provided at the time of the survey	All DHS, MIS and KIHBS; WMS 1997; MICS 2007, 2008, 2011, 2013	Year of Survey
	6	Female-headed Households	The proportion of households headed by a female at the time of survey	All census, DHS, WMS, MICS, AIS and KIHBS	Year of Survey
	7	Short birth spacing	The proportion of children with a preceding or succeeding birth interval <24 months	All DHS	Previous 5 years
	8	Use of modern contraceptives	The proportion of women aged 15 to 49 years using any form of modern contraceptive at the time of the survey	All DHS; MICS 2007, 2008, 2011, 2013; WMS 1994	Year of survey
	9	High parity	The proportion of women aged, <30 years with 3 or more children or aged >29 years with 5 or more children	All Census, DHS and MICS; MIS 2015, AIS 2007	
Child factors	10	Underweight	The proportion of children whose weight for age was <=-2 standard deviations at the time of the survey	DHS 1993, 1998, 2003, 2014; MICS 2007,2011; All WMS; KIHBS 2015. The estimates were computed based on the WHO 2006 reference for a well-nourished population	
	11	Wasted	The proportion of children whose weight for height was <=-2 standard deviations at the time of the survey		
	12	Stunted	The proportion of children whose height for age was <=-2 standard deviations at the time of the survey		
	13	Breastfed within the first hour of birth	The proportion of last born <5 years who were breastfed within the first hour after birth	DHS 1993, 1998, 2003 2008, 2014; MICS 2007, 2013; KIBHS 2015	Previous 5 years for DHS, WMS and KIHBS Previous 2 years for MICS
	14	Exclusive breastfeeding	The proportion of lastborn living with the mother and breastfed up to six months at the time of the survey	DHS 1993, 1998, 2003, 2008, 2014; MICS 2007, 2008, 2011, 2013; All KIHBS	
	15	Continued breastfeeding	The proportion of children 6-18 months old who were still being breastfed at the time of the survey.	DHS 1993, 1998, 2003, 2008, 2014; All WMS, MICS and KIHBS	
	16	Low Birthweight (LBW)	The proportion of children weighing < 2500g at birth at the time of the survey among those whose weight was taken	DHS 1993, 1998, 2003, 2008, 2014 MICS 2000, 2011, 2008, 2013: All WMS	
Household factors	17	Poor household	The proportion of households classified as poor or poorer by wealth index constructed using principal component analysis	DHS 1993, 1998, 2003, 2008, 2014; Census 1999,2009; All MICS, MIS and AIS	Year of survey
	18	Improved Sanitation	The proportion of households who have access to flush toilet facilities	All Census, DHS, WMS, MICS, AIS, KIHBS and MIS	
	19	Access to any form of a toilet	The proportion of households who have access to any form of a toilet facility (improved and intermediate)		
	10	Improved water	The proportion of households who have access to piped water for drinking		
	21	Access to wells borehole and piped water	The proportion of households who have access to either piped (improved water) or boreholes/wells water for drinking (Intermediate)		
Infections	22	HIV infection prevalence	The proportion of adults aged 15-49 who were HIV positive during the time of the survey	[1]	Year of survey
	23	Malaria infection prevalence	The proportion of children aged 2-10 years with *Plasmodium falciparum* parasite in their blood.	[2]	Year of survey
Healthcare Utilization	24	At least one antenatal care visit (ANC1)	The proportion of women (15-49) who attended at least one ANC visit by a skilled provider (doctor nurse or midwife) during their last pregnancy in the last three years from the survey time	DHS 1993, 1998, 2003, 2008, 2014; MICS 2007, 2008, 2011, 2013; All AIS and MIS	Previous 5 years for all surveys expect MICS (2 year)
	25	At least four antenatal care visits (ANC4)	The proportion of women (15-49) who attended four or more ANC visit during their last pregnancy in the last three years from survey time	DHS 1993, 1998, 2003, 2008, 2014; MICS 2008, 2011, 2013 AIS 2012; MIS 2015	

	26	Skilled birth attendance (SBA)	Proportion of mothers who were attended by a doctor, nurse, midwife or a community health worker during delivery	All DHS, WMS and MICS; AIS 2012; KIBHS 2015	
	27	Health facility deliveries (HFD)	Proportion of mothers who delivered at a health facility	All DHS, WMS; KIBHS and MICS; AIS 2012	
	28	Diarrhoea treatment-seeking	The proportion of children <5 years who had diarrhoea within the past two weeks before the survey whose treatment was sought from a medical facility	All DHS; MICS 2007, 2008, 2011,2013	Year of survey
	29	Fever/cough treatment-seeking	The proportion of children <5 years who had fever/cough within the past two weeks before the survey whose treatment was sought from a health provider	All DHS and MICS; MIS 2015	
Child health interventions	30	Bacille Calmette–Guérin (BCG)	Proportion of children alive at the time of the survey aged 12-23 months who received BCG vaccine	All DHS, WMS and MICS; KIHBS 2015.	Previous 2 years for all surveys (12-24 months old)
	31	Three diphtheria–tetanus–pertussis vaccinations (DPT3)	The proportion of children alive at the time of the survey aged 12-23 months who received up to the third dose of DPT vaccine		
	32	Three doses of Polio (Polio3)	The proportion of children alive at the time of the survey aged 12-23 months who received up to the third dose of Polio vaccine		
	33	Measles	Proportion of children alive at the time of the survey aged 12-23 months who received measles vaccine		
	34	Fully immunized	The proportion of children aged 12-23 months, alive at the time of the survey who received Polio 3, DPT3, BCG and measles vaccines		
	35	Oral rehydration salts (ORS use)	Proportion of children <5 years old who had diarrhoea within the past two weeks before the survey who received ORS treatment	All DHS, MICS and KIHBS	Year of survey
	36	Vitamin A- children	The proportion of children 6-59 months old who received Vitamin A supplement within six months before the survey	DHS 2003, 2008, 2014; All MICS	
	37	Insecticide-treated bed nets (ITN) use by children	The proportion of children <5 years who slept under an ITN in the previous night before the survey	DHS 2003, 2008, 2014, KIHBS 2005; All MIS	
	38	Recommended antimalarial use	Proportion of children <5 old who had fever within the past two weeks before the survey who received the recommended antimalarial drugs among those given any drug for fever	DHS 2003, 2008, 2014; All MIS and MICS	
Maternal health interventions	39	Tetanus toxoid injection	Proportion of women who received the recommended doses (2) of tetanus toxoid injection during their last pregnancy up to three years since data collection.	DHS 1993, 1998, 2003, 2008, 2014	Previous 5 years
	40	Intermittent preventive treatment in pregnancy (IPTp 1)	Percentage of women (15-49 years) with live birth, three years preceding a survey who during the last pregnancy received at least one dose of SP/Fansidar	DHS 2003, 2008, 2014; All MIS	
	41	IPTp 2	Percentage of women (15-49 years) with a live birth in three years preceding the survey who, during the last pregnancy, received two doses of SP/Fansidar at least one of which was received during an ANC visit		
	42	Iron supplement	The proportion of mothers who took iron tablets/syrup during their last pregnancy	DHS 2003, 2008, 2014	
	43	Vitamin A-mothers	Proportion of mothers who received vitamin A supplement within 2 months after delivery		

The determinants with a recall period of five years preceding the survey (See the column for the year of the survey) were limited to three years due to errors and bias associated with a longer recall period [3].

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1 NACC. Kenya HIV prevalence estimates. 2020.https://nacc.or.ke/ (accessed 22 Oct 2020).

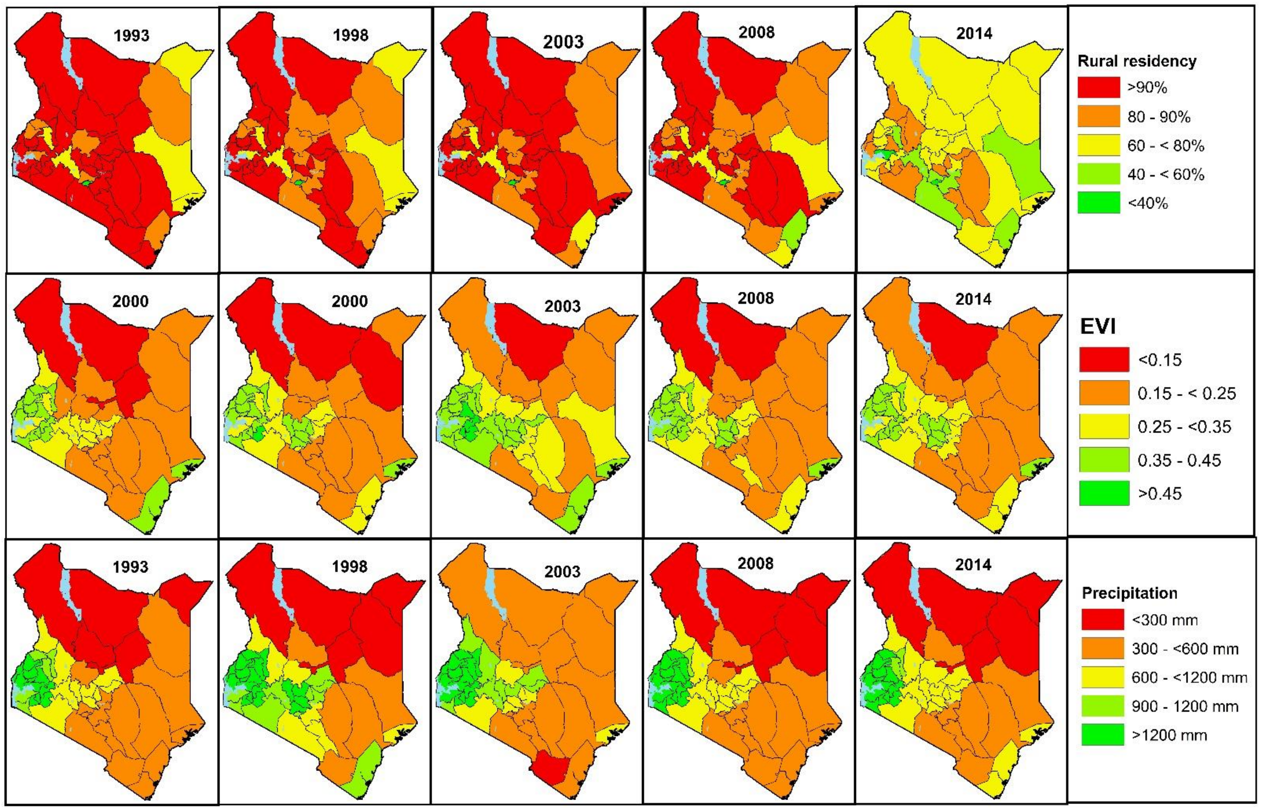
2 Macharia PM, Giorgi E, Noor AM, *et al.* Spatio-temporal analysis of Plasmodium falciparum prevalence to understand the past and chart the future of malaria control in Kenya. *Malar J* 2018;**17**:340. doi:10.1186/s12936-018-2489-9

3 Ngandu NK, Manda S, Besada D, *et al.* Does adjusting for recall in trend analysis affect coverage estimates for maternal and child health indicators? An analysis of DHS and MICS survey data. *Glob Health Action* 2016;**9**:32408. doi:10.3402/GHA.V9.32408

Additional File 3:

County level estimates of the coverage or prevalence of factors associated with under-five mortality in Kenya: 1993-2014

Figure 1: Rural residency, annual total precipitation and annual average EVI* at the county level between 1993 and 2014 in Kenya.



EVI*-enhanced vegetation index

Figure 2: County level trends in maternal education, maternal literacy and the head of a household between 1993 and 2014

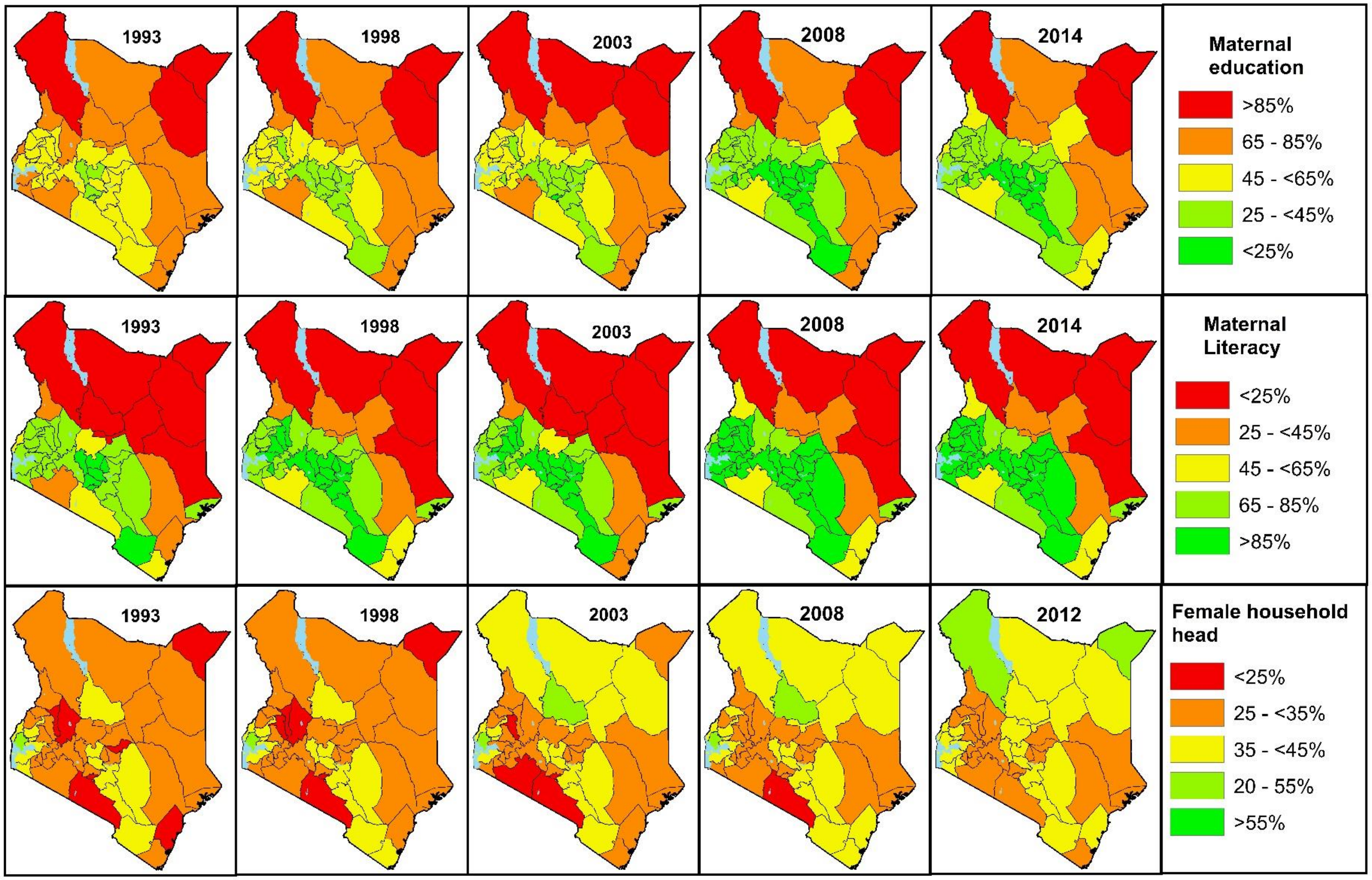


Figure 3: High parity, short birth interval and the use of modern contraceptives at county level between 1993 and 2014 in Kenya.

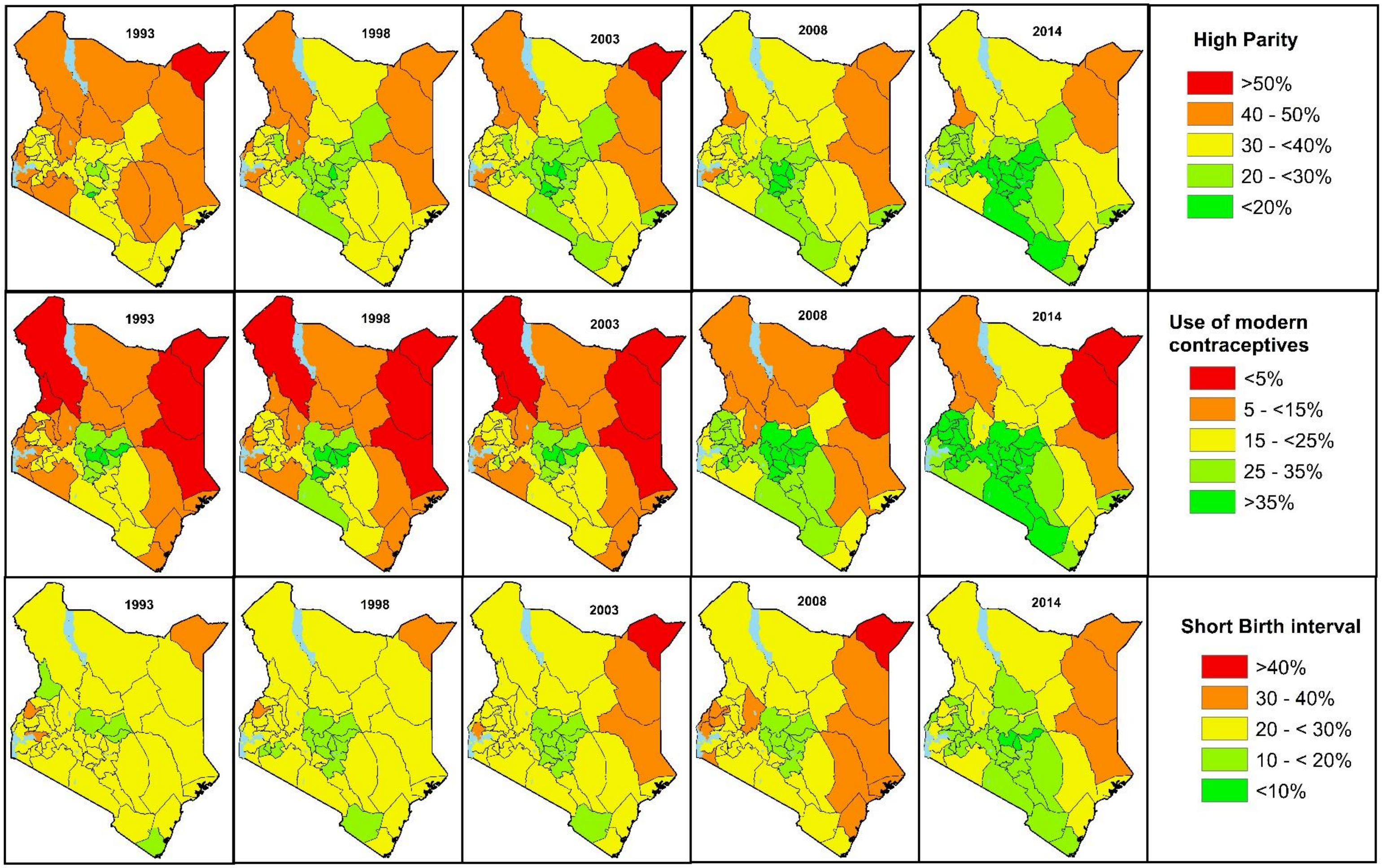


Figure 4: County level prevalence of child growth (stunting, underweight and wasting) between 1993 and 2014 in Kenya.

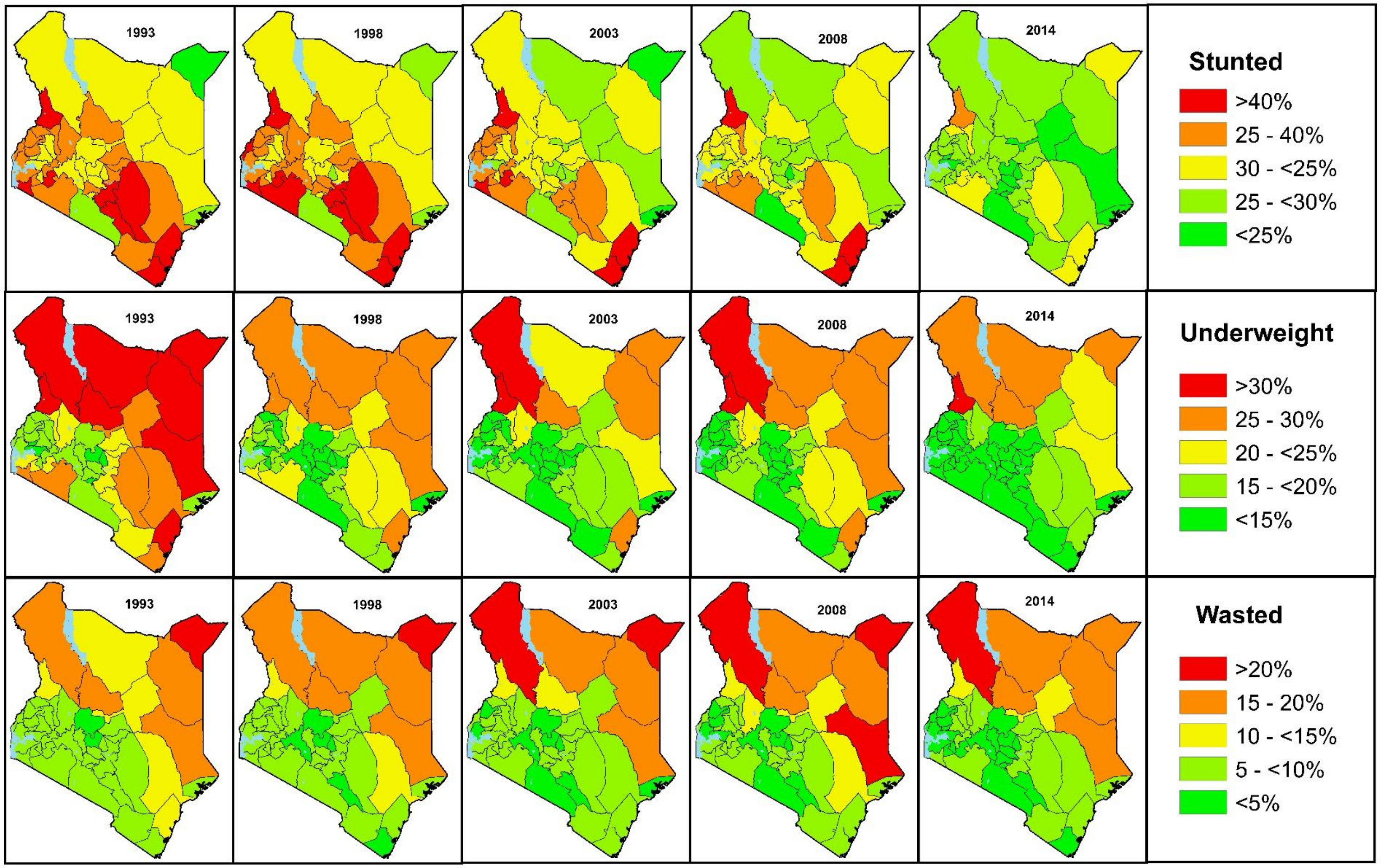


Figure 5: County level coverage of breastfeeding practices and the prevalence of low birth weight in Kenya between 1993 and 2014

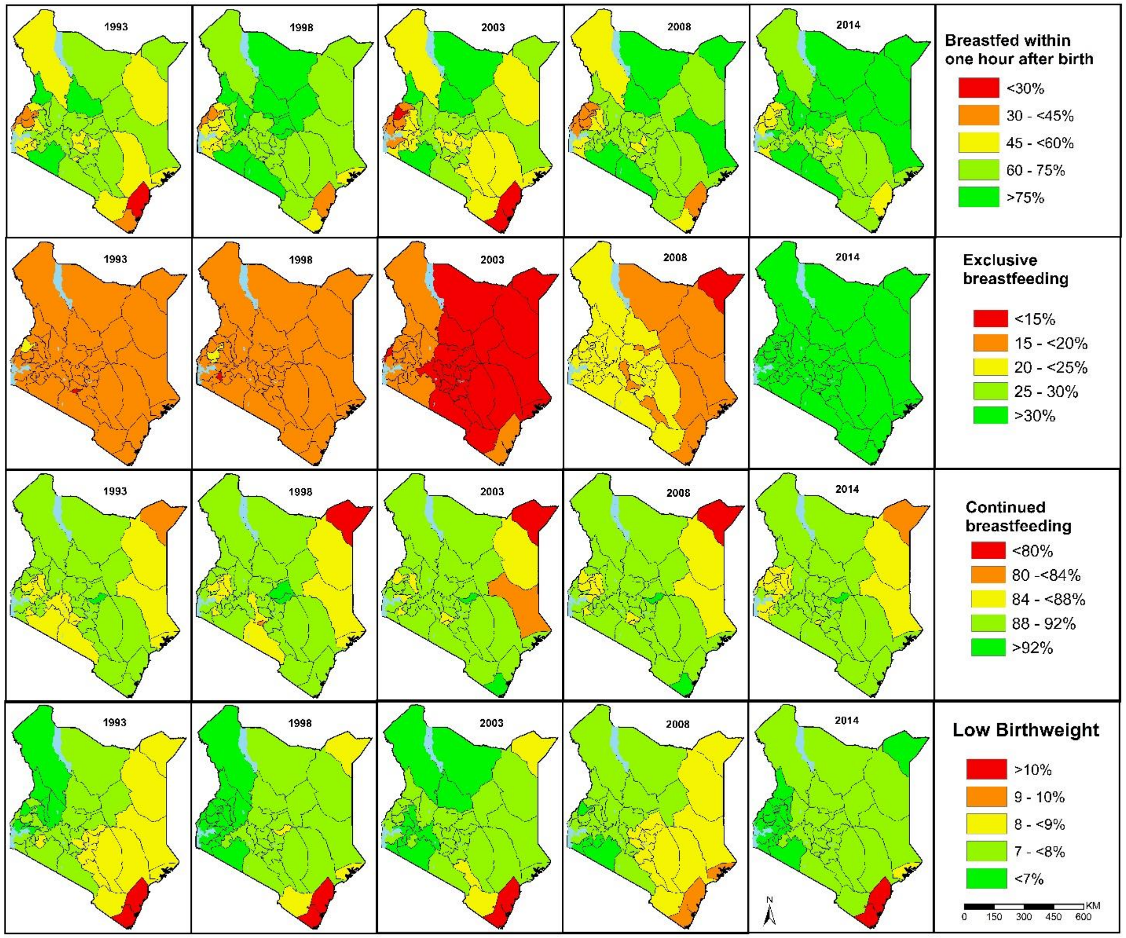


Figure 6: County coverage of access to safe and clean water, sanitation and household wealth in Kenya between 1993 and 2014

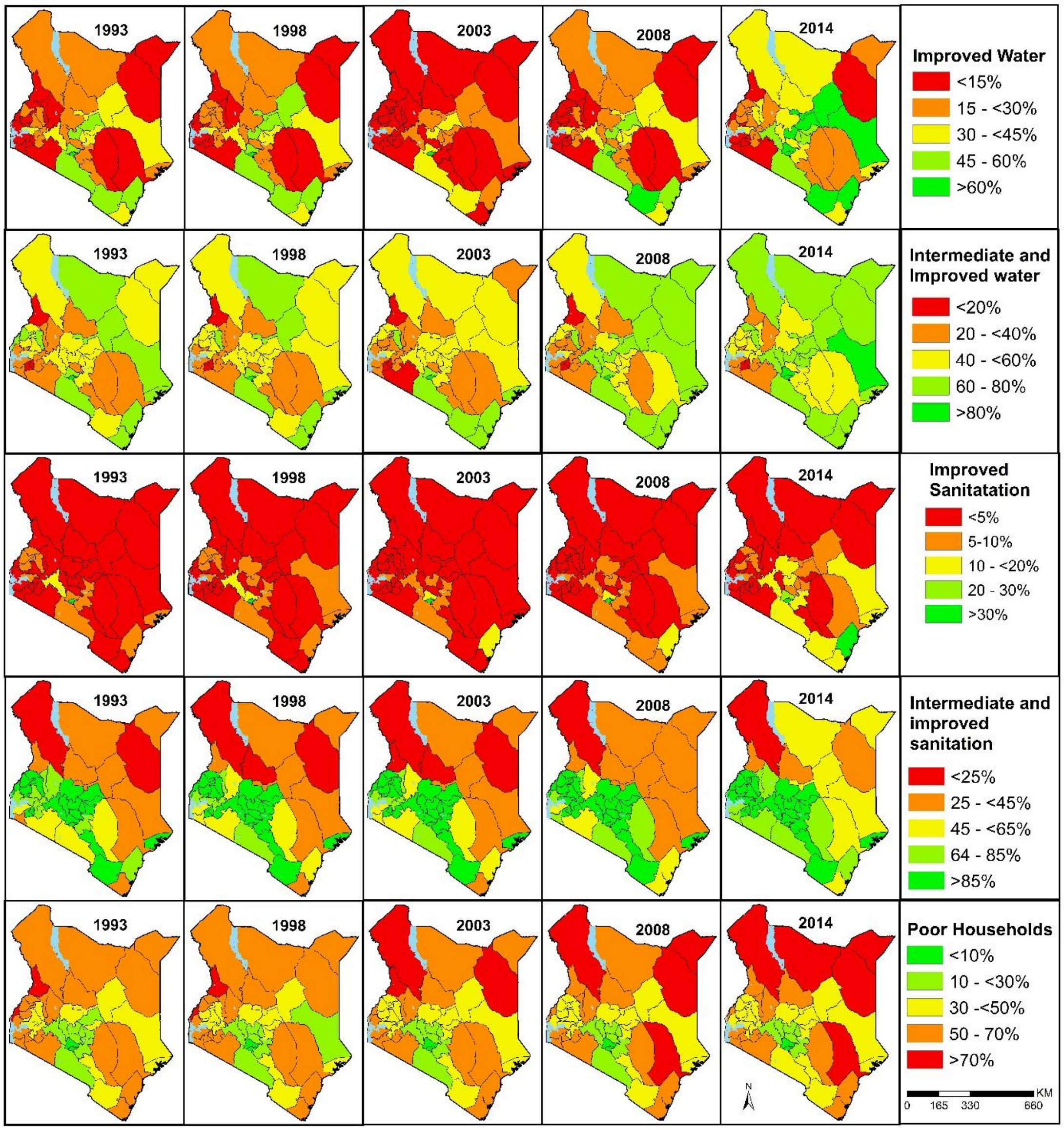
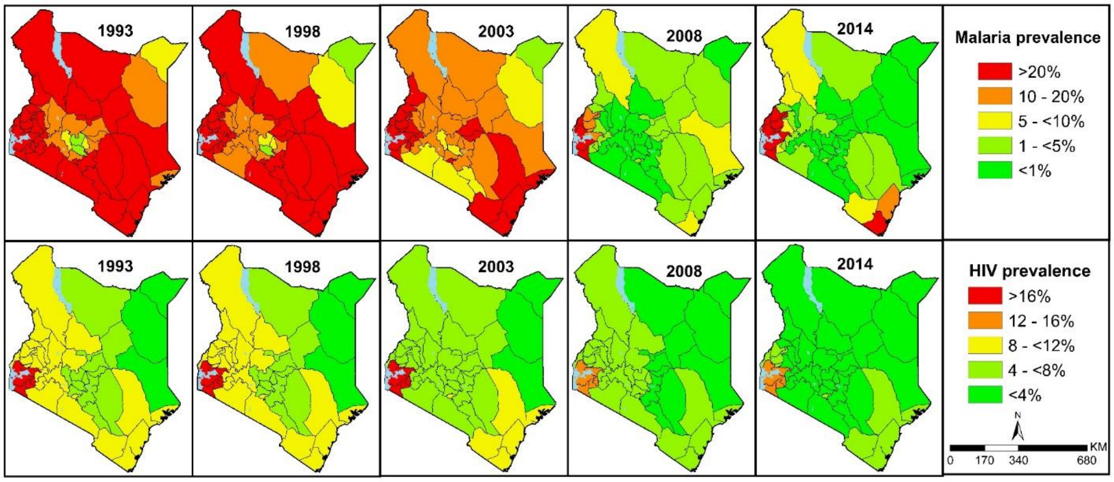


Figure 7: County level prevalence of malaria [1] and provincial level HIV [2] between 1993 and 2014 in Kenya



1 Macharia PM, Giorgi E, Noor AM, *et al.* Spatio-temporal analysis of Plasmodium falciparum prevalence to understand the past and chart the future of malaria control in Kenya. *Malar J* 2018;**17**:340. doi:10.1186/s12936-018-2489-9

2 NACC. Kenya HIV prevalence estimates. 2020.https://nacc.or.ke/ (accessed 22 Oct 2020).

Figure 8: County level coverage of at least one ANC visit (ANC1), four ANC visits (ANC4), skilled birth attendance (SBA), health facility delivery (HFD), treatment-seeking for fever and diarrhoea from 1993 to 2014

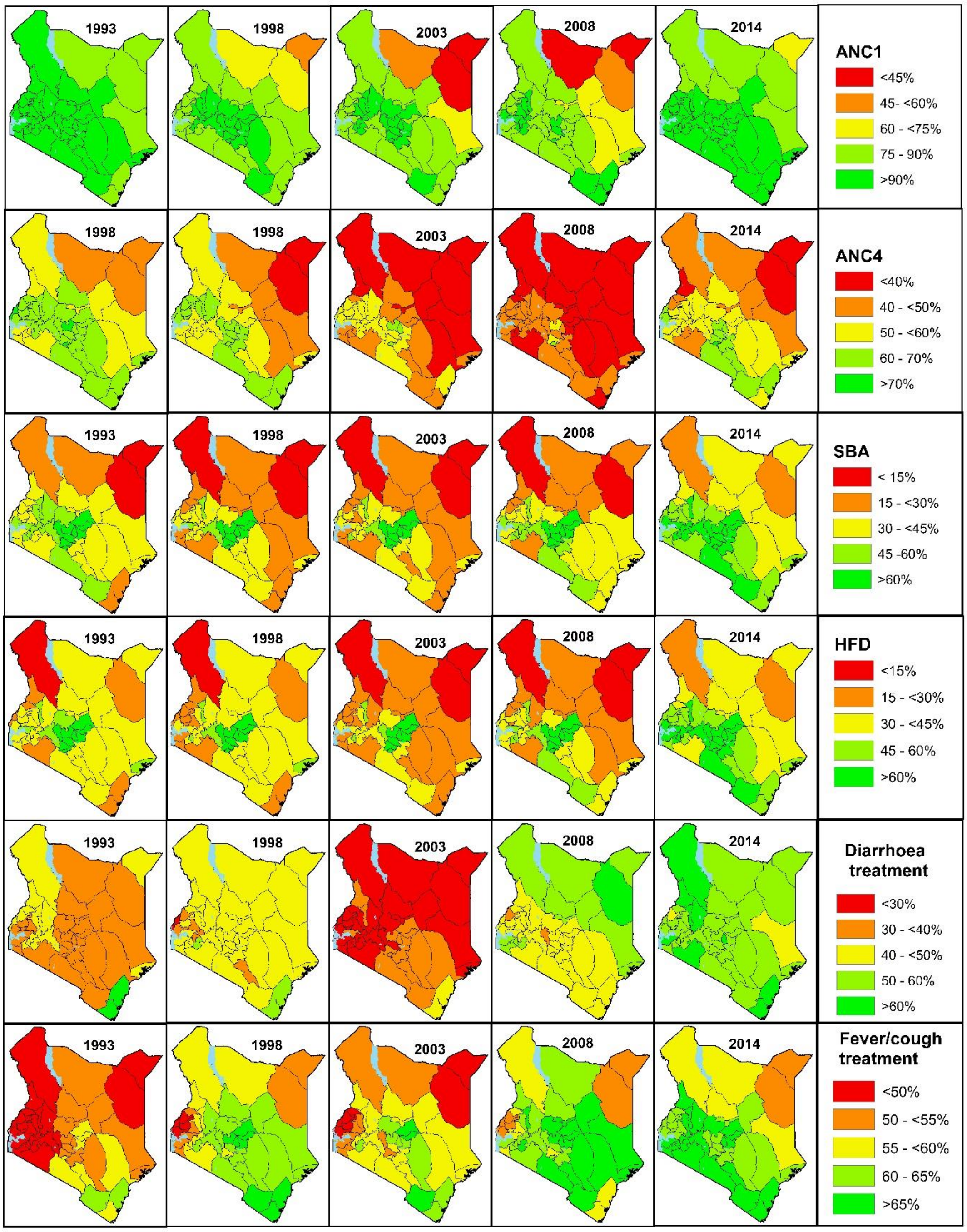


Figure 9: County level immunization coverage for BCG, three doses of DPT, three doses Polio, measles and fully immunized between 1993 and 2014 in Kenya.

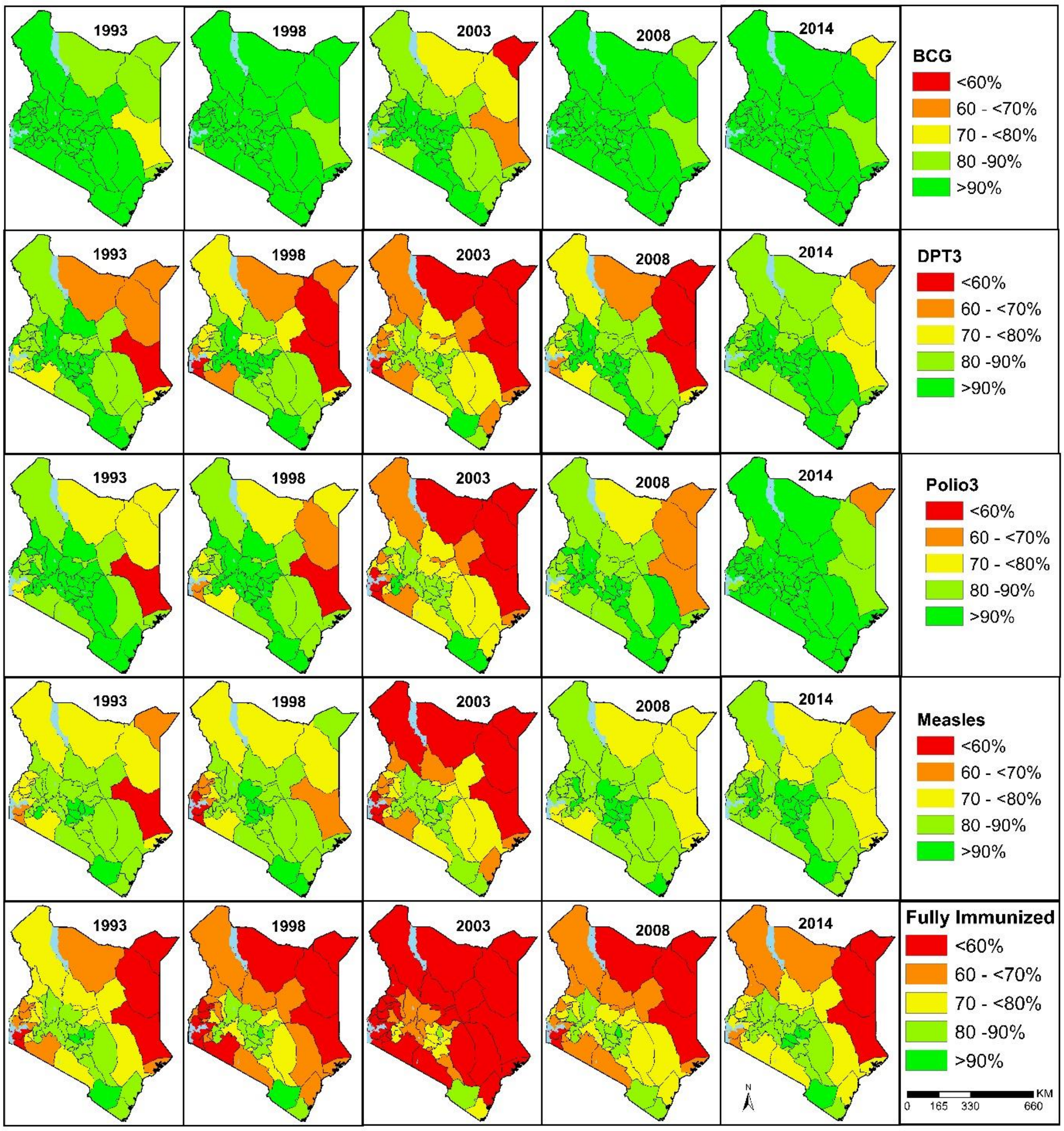


Figure 10: The county level coverage of child health interventions (vitamin A, ITN use, antimalarials and ORS) between 2003 and 2014 in Kenya.

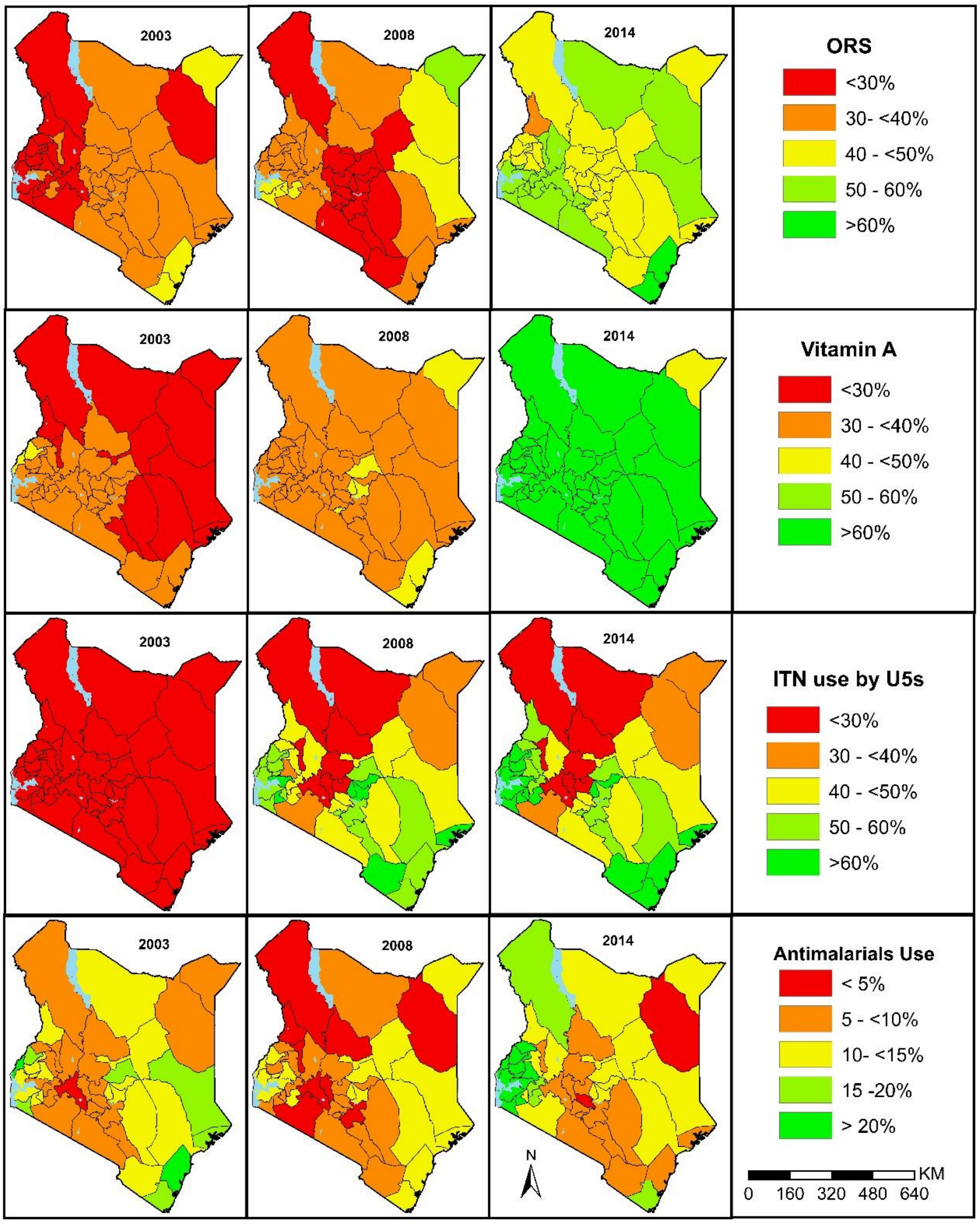
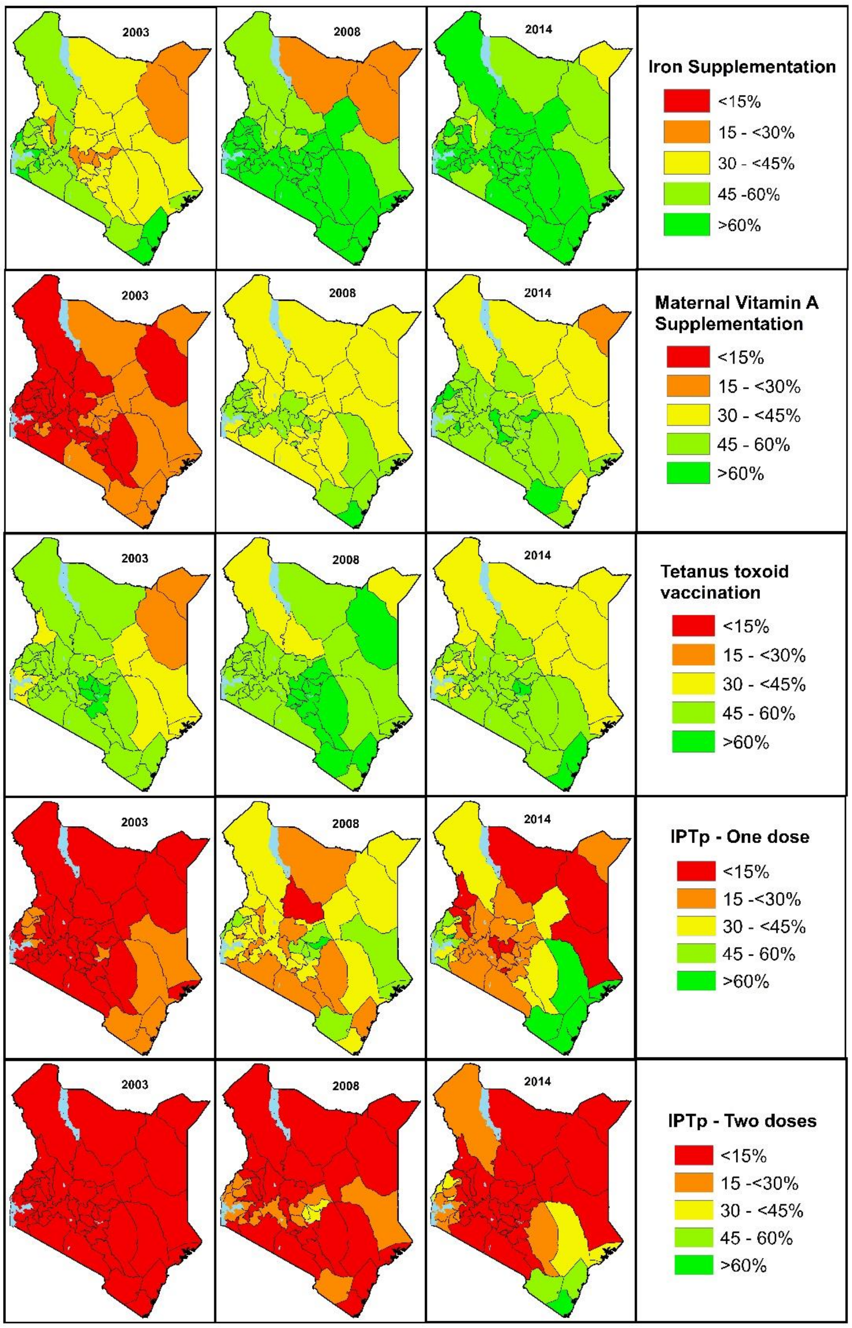


Figure 11: County level coverage of supplements (iron, vitamin A) and Intermittent preventive treatment in pregnancy (one and two doses) between 2003 and 2014 in Kenya.



Additional file 4: Validation statistics

The correlation, mean absolute error (MAE) and root mean square (RMSE) from the cross-validation exercise in the spatio-temporal modelling framework. The blue-coloured cells show high correlation (≥0.7), grey -moderate correlation (≥0.5 but < 0.7) and white low correlation (≥0.4 but <0.5).

	ID	Factor	Correlation	MAE	RMSE
Maternal Factors	1	Less than primary school (maternal)	0.95	6.32	9.05
	2	Maternal literacy	0.69	12.2	16.6
	3	Female household head	0.56	6.04	9.05
	4	Short Birth interval	0.65	5.32	7.06
	5	Modern contraceptives use	0.66	5.94	12.12
	6	High parity	0.74	5.8	8.9
Child factors	7	Underweight	0.72	5.51	6.90
	8	Wasted	0.67	2.88	4.05
	9	Stunted	0.55	6.4	8.9
	10	Breastfed within 1st hour of birth	0.70	10.41	12.63
	11	Exclusive breastfeeding	0.99	3.78	5.17
	12	Continued breastfeeding	0.87	4.02	4.91
	13	Low Birthweight	0.42	3.91	4.82
Household factors	14	Poor household	0.61	14.21	20.18
	15	Improved Sanitation	0.89	3.41	6.41
	16	Improved and intermediate sanitation	0.87	7.6	12.6
	17	Improved water	0.85	8.88	13.27
	18	Improved and intermediate water	0.76	12.0	16.3
Healthcare Utilization	19	ANC1	0.64	8.46	13.76
	20	ANC4	0.64	8.66	11.79
	21	Skilled birth attendance	0.76	9.76	12.56
	22	Health facility births	0.90	7.10	10.02
	23	Diarrhoea treatment-seeking	0.61	9.48	12.39
	24	Fever treatment-seeking	0.52	12.13	15.29
Child health interventions	25	BCG	0.65	6.60	12.11
	26	DPT3	0.75	6.36	8.64
	27	Polio3	0.82	8.88	11.13
	28	Measles	0.66	8.76	13.12
	29	Fully immunized	0.64	10.29	13.61
	30	ORS use	0.44	12.38	15.81
	31	Vitamin A- children	0.89	9.80	11.54
	32	Child ITN use	0.82	10.81	14.42
	33	recommended antimalarials	0.55	10.60	14.02
Maternal health interventions	34	Two doses of tetanus toxoid	0.67	10.61	13.02
	35	IPTp1	0.62	13.29	15.88
	36	IPTp2	0.51	10.80	16.56
	37	Iron supplement mothers	0.79	10.41	11.87
	38	Vitamin A mothers	0.83	9.44	11.59

Additional file 5: Corelation coefficients

The correlation coefficients between under five mortality and each of the 43 factors associated with child survival in Kenya. Corresponding p values are presented, brown (not statistically significant) green (statistically significant)

Theme	ID	Factor	Correlation	P value
Environmental factors	1	Vegetation index	0.15	< 0.0001
	2	Precipitation	0.25	< 0.0001
	3	Rural residence	0.03	0.4032
Maternal Factors	4	Less than primary school (maternal)	0.30	< 0.0001
	5	Maternal literacy	-0.18	< 0.0001
	6	Female household head	0.09	0.0047
	7	Short Birth interval	0.42	< 0.0001
	8	Modern contraceptives use	-0.31	0.0299
	9	High parity	0.40	< 0.0001
Child factors	10	Underweight	0.11	0.0005
	11	Wasted	0.08	0.0093
	12	Stunted	0.25	< 0.0001
	13	Breastfed within 1st hour of birth	-0.60	< 0.0001
	14	Exclusive breastfeeding	0.1	0.0013
	15	Continued breastfeeding	-0.1	0.009
	16	Low Birthweight	-0.02	0.6020
Household factors	17	Poor household	0.32	< 0.0001
	18	Improved Sanitation	-0.07	0.0316
	19	Improved and intermediate sanitation	-0.19	< 0.0001
	20	Improved water	-0.27	< 0.0001
	21	Improved and intermediate water	-0.14	0.0006
Infections	22	HIV	0.40	< 0.0001
	23	Malaria	0.65	< 0.0001
Healthcare Utilization	24	ANC1	-0.20	<0.0001
	25	ANC4	0.13	<0.0001
	26	Skilled birth attendance	-0.28	<0.0001
	27	Health facility births	-0.27	< 0.0001
	28	Diarrhoea treatment-seeking	-0.12	0.0001
	29	Fever treatment-seeking	-0.40	< 0.0001
Child health interventions	30	BCG	-0.30	< 0.0001
	31	DPT3	-0.28	< 0.0001
	32	Polio3	-0.21	< 0.0001
	33	Measles	-0.35	< 0.0001
	34	Fully immunized	-0.25	< 0.0001
	35	ORS use	0.06	0.0657
	36	Vitamin A- children	-0.27	< 0.0001
	37	Child ITN use	-0.18	< 0.0001
	38	recommended antimalarials	0.48	< 0.0001
Maternal health interventions	39	Two doses of tetanus toxoid	-0.23	0.0074
	40	IPTp1	0.16	0.0001
	41	IPTp2	0.21	< 0.0001
	42	Iron supplement mothers	-0.16	< 0.0001
	43	Vitamin A mothers	-0.23	< 0.0001

Additional file 5: Comparison between estimates generated in the current work and from other sources

Corelation

Table 1: Corelation coefficients between estimates generated from the current study and estimates from [1–4]

ID	Determinant	Source	Temporal range	Correlation	P value
1	Underweight	[1–3] IHME	2000-2014	0.8575	<0.0001
2	Wasting			0.7728	<0.0001
3	Stunting			0.7475	<0.0001
4	Three doses of DPT			0.8001	<0.0001
5	Improved water			0.7403	<0.0001
6	Skilled birth attendance	[4] Worldpop	2014	0.6547	<0.0001

IHME- institute of Health Measure Evaluation, MAP-Malaria Atlas Project

Ranking of determinants

The high coverage or low prevalence counties were the best performing in 2014 based on estimates from the current study and the comparator with blue coded counties simultaneously identified from the two sets of data. Likewise, for the counties lagging behind (Low coverage or high prevalence counties), analogous interpretation applies.

Table 2: Ranking of estimates generated from the current study and other sources (Table 1 above)

Determinant	**High coverage or low prevalence counties**		**Low coverage or high prevalence counties**		**Overall match**
Match	Current study	Table 1	Current study	Table 1	Matched-pairs
Underweight	Nairobi Nyeri Kirinyaga Murang'a Siaya Kisumu Vihiga Kiambu Homa Bay Nyandarua	Nairobi Nyeri Kirinyaga Murang'a Siaya Kisumu Vihiga Kiambu Homa Bay Kisii	West Pokot Turkana Mandera Marsabit Samburu Wajir Baringo Isiolo Tana River Garissa	West Pokot Turkana Mandera Marsabit Samburu Wajir Baringo Isiolo Tana River E-Marakwet	18/20=90%
Wasting	Siaya Vihiga Kirinyaga Nyeri Kakamega Kisii Kisumu Nakuru Kajiado Bungoma	Siaya Vihiga Kirinyaga Nyeri Kakamega Kisii Nyamira Nairobi Murang'a Kiambu	Turkana Garissa Mandera Samburu Wajir Marsabit West Pokot Isiolo Baringo Tana River	Turkana Garissa Mandera Samburu Wajir Marsabit West Pokot Isiolo Baringo Tana River	16/20=80%
Stunting	Nairobi Nyeri Kirinyaga Garissa Mombasa Murang'a Isiolo Kisumu Vihiga Kajiado	Nairobi Nyeri Kirinyaga Garissa Mombasa Murang'a Isiolo Siaya Laikipia Kiambu	West Pokot Kilifi Mandera Kitui Kwale Bomet Trans Nzoia E-Marakwet Narok Baringo	West Pokot Kilifi Mandera Kitui Kwale Bomet Trans Nzoia E-Marakwet Narok Tana River	16/20=80%
Improved (piped) water	Nairobi Mombasa Taita Taveta Nyeri Meru Kiambu Kilifi Isiolo Garissa Kajiado	Nairobi Mombasa Taita Taveta Nyeri Meru Kiambu Kilifi Nakuru Kirinyaga Kwale	Migori Kisii Nyamira Vihiga Busia Homa Bay Wajir Narok West Pokot Tana River	Migori Kisii Nyamira Vihiga Busia Homa Bay Trans Nzoia Nandi Kakamega Siaya	13/20=65%

Three doses of DPT	Kirinyaga Kiambu Bomet Embu Machakos Nandi Kericho Makueni Taita Taveta E-Marakwet	Kirinyaga Kiambu Bomet Embu Machakos Nandi Uasin Gishu Nyamira Vihiga Nyeri	Mandera Wajir West Pokot Garissa Marsabit Migori Turkana Lamu Homa Bay Bungoma	Mandera Wajir West Pokot Garissa Marsabit Migori Turkana Lamu Kajiado Narok	15/20=75%
Skilled birth attendance	Nairobi Murang'a Mombasa Kirinyaga Kiambu Embu Tharaka Nithi Meru Nyandarua Nyeri	Nairobi Murang'a Mombasa Kirinyaga Kiambu Nyamira Kisii Kakamega Busia Vihiga	Wajir Turkana Marsabit Tana River Isiolo Samburu Garissa Mandera West Pokot Trans Nzoia	Wajir Turkana Marsabit Tana River Isiolo Samburu Garissa Lamu Kitui Taita Taveta	12/20=60%

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