Epidemiology and control profile of malaria in

Kenya

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Preface

Over the last 15 years the Government and international donors under the Roll Back Malaria Partnership have invested billions of shillings in reducing the burden of malaria in Kenya. In particular, significant funding and technical support has been received from the GFATM, PMI, DFID, WHO and other partners. Across the country, tens of million insecticide treated nets (ITNs) and artemisinin combination therapy (ACT) have been distributed to protect the population and to treat those sick with malaria, respectively. In epidemic prone and a few selected high burden counties, millions of households have also been covered with indoor residual spraying (IRS). To build on these achievements, the National Malaria Strategy (NMS) 2009-2017 has even more ambitious goals to fulfil the fundamental vision of a malaria free Kenya.

To achieve these goals, effective planning and allocation of resources is paramount. This requires high quality evidence on the epidemiology of malaria, the distribution of population under different transmission settings and their access to various interventions. This evidence must be at geographic units where relevant policy implementation decisions are made. Under the new devolved system established by the 2010 Kenya constitution, the delivery of health care to the population, including implementation of malaria prevention and treatment, has become the role of the County government, with budgetary and regulatory support from the National Ministry of Health. To support evidence-based decision making, the Kenya government, with support from partners developed a detailed County malaria epidemiology and control profiles in 2013. This effort was the first across sub-Saharan Africa to link resource allocation with such detailed sub-national evidence in the epidemiology of malaria and has since been adopted by several countries in the continent.

In the intervening years, new data on the malaria burden have become available and large scale efforts at the scale up of malaria have been undertaken. Furthermore, updated profiles are also required to mark the end of the Millennium Development Goals and develop baseline data for the Sustainable Development Goals (SDGs). It is for these reasons that the NMCP, with financial support from DFID has commissioned the Kenya Medical Research Institute/Wellcome Trust Research Programme and the London School of Hygiene & Tropical Medicine of the United Kingdom, under the LINK Project, to undertake a detailed review of the epidemiology and control of malaria in Kenya. Updated data on malaria epidemiology and vector control and new evidence on case management and prevention of malaria in pregnant women has been included.

The Ministry of Health is confident that the County epidemiology and control profiles developed here will provide the basis for more efficient decision-making for malaria control. The Kenyan government, in collaboration with donors and other partners, is confident that the country is on track to achieve the goals set out in the NMS 2009-2018, the Vision 2030 and the SDGs.

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Table of Contents

Abbreviations

ACT	Artemisinin based Combination Therapy
AL	Artemether-Lumefanthrine
ANC	Ante-Natal Care
CBS	Central Bureau of Statistics
CDC	Centers for Disease Control and Prevention
CHW	Community Health Worker
CQ	Chloroquine
DEM	Digital Elevation Map
DFID	Department for International Development
DHMT	District Health Management Teams
DOMC	Division of Malaria Control
DSS	Demographic Surveillance System
DVBD	Division of Vector Borne Diseases
DVBND	Division of Vector Borne and Neglected Diseases
EA	Enumeration Area
EPI	Expanded Programme on Immunization
EVI	Enhanced Vegetation Index
FSD	Financial Services Deepening
GIS	Geographic Information System
GFATM	Global Fund to Fight AIDS, Tuberculosis and Malaria
GMP	Global Malaria Programme, WHO
GOK	Government of Kenya
HIMAL	Highland Malaria Project
HMIS	Health Management Information System
IEC	Information, Education and Communications
IEBC	Independent Electoral and Boundaries Commission
IMCI	Integrated Management of Childhood Illness
IPTp	Intermittent Presumptive Treatment in Pregnancy
IRS	Indoor Residual House Spraying
ITN	Insecticide-Treated Nets
INFORM	Information for Malaria
KAIS	Kenya Aids Indicator Survey
KDHS	Kenya Demographic & Health Survey
KEMRI	Kenya Medical Research Institute
KEMRI-WTRP	Kenya Medical Research Institute-Wellcome Trust Research Programme
KEMSA	Kenya Medical Supplies Agency
KEPI	Kenya Expanded Programme on Immunization
KNBS	Kenya National Bureau of Statistics
KNMS	Kenya National Malaria Strategy
KSPA	Kenya Service Provision Assessment
LLIN	Long-Lasting Insecticidal Net
LSHTM	London School of Hygiene & Tropical Medicine
M&E	Monitoring and Evaluation
MDG	Millennium Development Goal
MCH	Maternal and Child Health
MIP	Malaria in Pregnancy
MIS	Malaria Indicator Survey

MOE	Ministry of Education
MOH	Ministry of Health
MOMS	Ministry of Medical Services
MOPHS	Ministry of Public Health & Sanitation
MPHD	Malaria Public Health Department
NGO	Non-Governmental Organisation
NHFD	National Health Facility Database
NHSSP	National Health Sector Strategic Plan
*Pf*PR	*Plasmodium falciparum* parasite rate
$PfPR_{2-10}$	*Plasmodium falciparum* parasite rate standardised to ages 2 to 9 years
PMI	President's Malaria Initiative
PSI	Population Services International
QN	Quinine
RBM	Roll Back Malaria
RBM-HWG	Roll Back Malaria Harmonization Working group
RDT	Rapid Diagnostic Test
SP	Sulphadoxine-Pyrimethamine
TSI	Temperature Suitability Index
UN	United Nations
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
WHO	World Health Organization

1. Introduction

In 2012, county-level malaria epidemiological profiles of Kenya were developed by the National Malaria Control Programme (NMCP) with funding from the United States President's Malaria Initiative (PMI) and technical support from the Kenya Medical Research Institute-Wellcome Trust Research Programme (KEMRI-WTRP) and MEASURE Evaluation (Noor et al 2013). The county profiles have been the basis for sub-national malaria control planning since the devolution of health service delivery in 2013. This pioneering work represents the first initiative led by a Ministry of Health in sub-Saharan Africa to systematically assemble and analyze empirical malaria risk and intervention data and adapt control to the heterogeneous epidemiology of the disease. This approach to malaria epidemiological profiling has now been implemented in more than 20 countries in sub-Saharan Africa (SSA) through funding support from the United Kingdom Department for International Development (DFID)starting in 2013 (www.inform-malaria.org). At the same time, changes in the malaria funding landscape have led to an increasing demand for detailed epidemiological evidence as the basis for support and targeting of interventions.

The Department for International Development's support started as a Phase 1 pilot initiative in 2013-14 covering Ethiopia, the Democratic Republic of Congo, Ghana, Mali, Malawi, Nigeria, Tanzania and Uganda led by the KEMRI-WTRP's Information for Malaria (INFORM) Project (www.inform-malaria.org). Since then, DFID extended funding to the LINK project, which is a partnership between the London School of Hygiene & Tropical Medicine (LSHTM) and INFORM (www.inform-malaria.org), to implement a four-year Phase II project beginning October 2014 to re-profile Kenya and the eight pilot countries and develop profiles in 14 new countries.

The 2012 Kenya county epidemiological profiles generated considerable interest among malaria control stakeholders nationally and at the counties. A considerable amount of data relevant to malaria control has since become available in Kenya including: the largest ever Demographic and Health Survey (DHS) undertaken in 2014-15 designed to provide measures precise at the county level; the third national Malaria Indicator Survey (MIS) in 2015; the scale up of the second version of the District Health Information System (DHIS2); and the distribution data on the free mass distribution of long lasting Insecticidal Nets (LLINs) in 2014 and 2015.

In line with the NMCP's commitment to continuous assembly and use of the relevant evidence, it commissioned the LINK project team, in December 2015, to start the process of developing an updated county epidemiological profile in Kenya with the aim of providing information on sub-county variations in both malaria risk and intervention coverage to support better control planning at the county level.

This report therefore represents the outcome and extensive assembly and analysis of malaria data in Kenya, building on the experiences of Phase 1, to better guide policy and operational decisions to improve malaria control at national and county levels.

2. Country context

2.1 Geography and climate

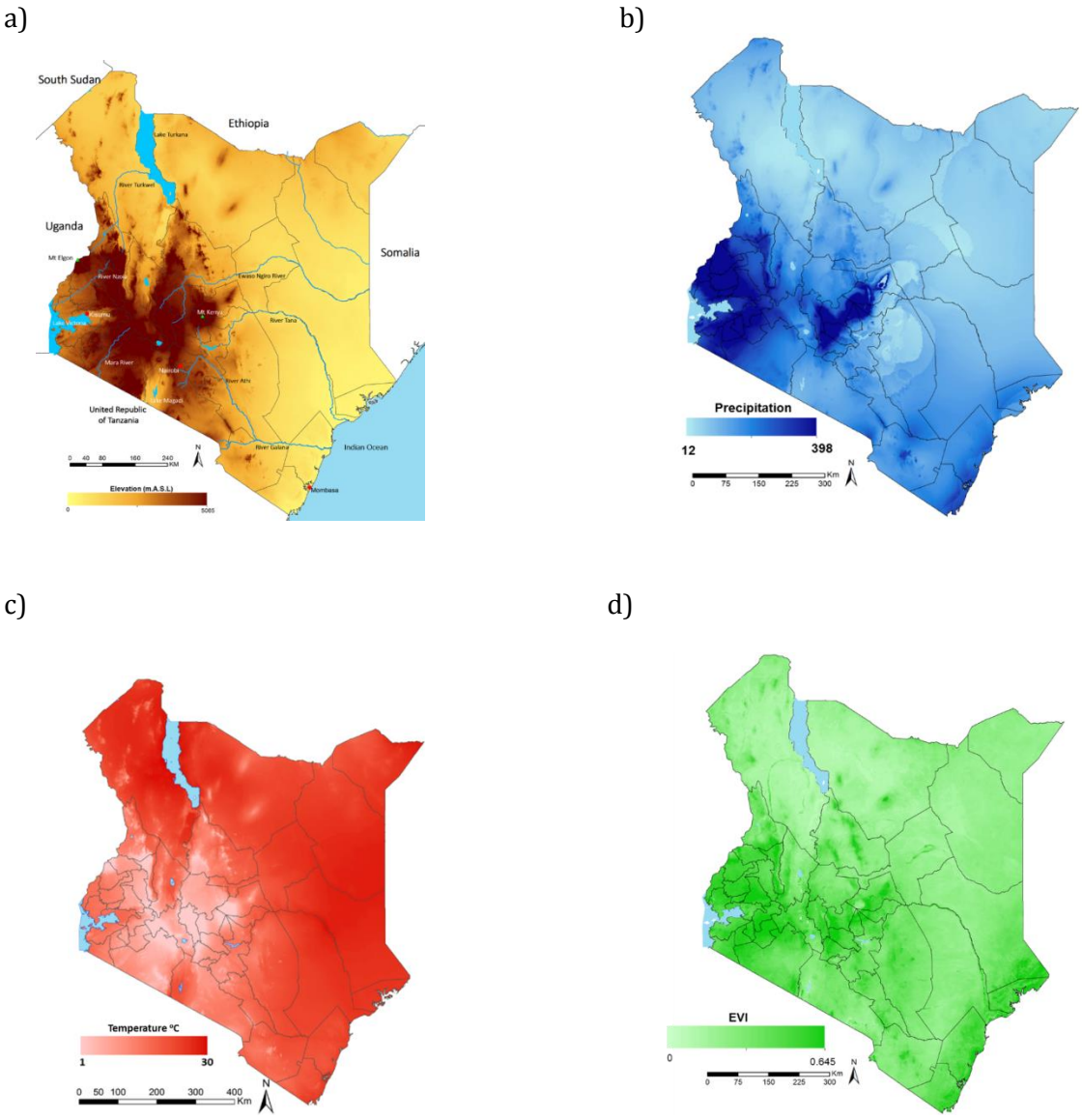
Kenya covers an area of 582,550 km^2 and has a diverse ecology – savannah, tropical, equatorial, volcanic and tectonic. It is bordered by Tanzania to the south, Uganda to the west, South Sudan to the north-west, Ethiopia to the north and Somalia to the north-east. Approximately 80% of Kenya's land is arid and semi-arid, only 20% is arable and only 1.9% of the total surface area is occupied by standing water (Figure 2.1a). The great East African Rift Valley extends from Lake Victoria to Lake Turkana and further south-east to the Indian Ocean. The country has a number of large rivers including the Tana, Galana, Turkwel and Nzoia.

The arid and semi-arid areas, the savannah plateau and the coastal hinterland have considerably lower rainfall (Figure 2.1b) that is acutely seasonal with an annual average of about <250–500 mm. The Lake Victoria region, the western and central highlands receive the highest rainfall in the country and exhibit less seasonality. The "long rains" occur from March/April to May/June. The "short rains" occur from October to November/December. The start of these seasons depends largely on the location and altitude, whether lowlands or highlands.

The hottest period is February and March, leading into the season of the long rains, and the coldest is in July, until mid-August. The varied topography and altitude contributes to large variations in ambient temperature (Figure 2.2c). The country has a warm and humid tropical climate on its 400 km Indian Ocean coastline, including the port city of Mombasa, which also serves as an importation gateway to other East African countries. The climate is cooler in the savannah grasslands around the capital, Nairobi, and increasingly cooler towards Mount Kenya. The Nyanza region experiences a hot and dry climate, which becomes humid around Lake Victoria. Away from the Lake, are the temperate and forested hilly areas in the neighbouring western highland region. The Kenyan Highlands comprise the greenest (Figure 2.1d) and one of the most successful agricultural production regions in Africa. The highlands are the site of the highest point in Kenya and the second highest peak on the continent: Mount Kenya (5,199 m above mean sea level). The north-eastern regions along the border with Somalia and Ethiopia are arid and semi-arid areas with some desert areas (Figure 2.1e).

A Temperature Suitability Index (TSI) for malaria transmission (Gething et al., 2011) shows that the Lake Victoria and Coastal regions have the ambient temperatures suitable for malaria transmission (Figure 2.1f) and have the necessary amount and seasonality of rainfall to sustain lengthy periods of transmission.

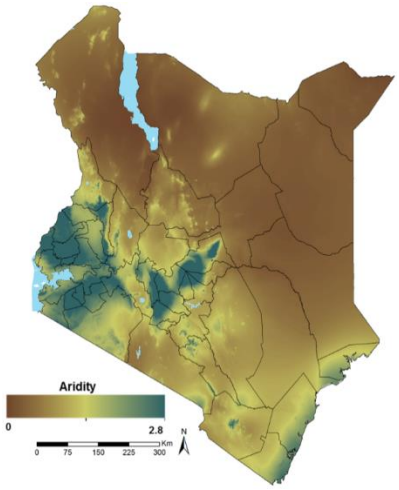
Figure 2.1 Maps of Kenya showing: a) elevation (0 to 5,199 m above mean seas level) and main water features; b) mean monthly rainfall (mm); c) mean temperature (°C); d) vegetation; e) aridity index f) Temperature suitability index (TSI) on malaria transmission.[1]



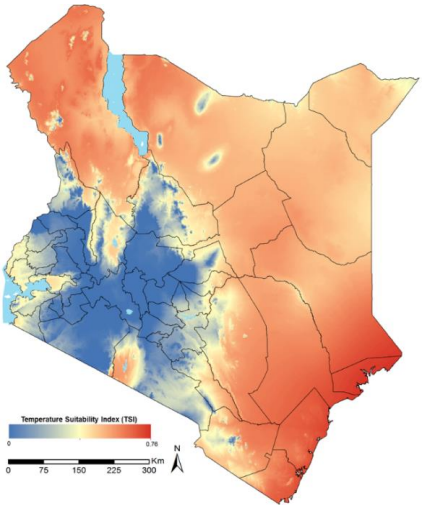
1. Figure 2.1a shows altitude in metres above sea level. The Kenya's Digital Elevation Models was downloaded from NASA's Shuttle Radar Topography Mission at the USGS Land Processes Distributed Active Archive Center (LP DAAC) website (http://gdex.cr.usgs.gov/gdex/ accessed 19 March 2013) at 30m resolution. The lakes surface was obtained from the Global Lakes and Wetlands Database (http://www.worldwildlife.org/pages/global-lakes-and-wetlands-database). The rivers were from International Livestock Research Institute (ILRI) GIS services portal provided at http://192.156.137.110/gis/ .
Rainfall (Figure 2.1b) is one of the determinants of vector abundance. Monthly rainfall surfaces exist that are produced from global weather station records gathered from various sources (1950-2000) and interpolated using thin-plate smoothing spline algorithm to produce a continuous global surface (Hijmans et al., 2005) and monthly average rainfall raster surfaces at 1 km ×1 km resolution available from the WorldClim website. Precipitation is shown in mm averages per pixel over this period of time (1950-2000).
For vegetation cover (Figure 2.4d), Fourier–processed Enhanced Vegetation Index (EVI), derived from the MODerate-resolution Imaging Spectroradiometer (MODIS) sensor imagery and available at approx. 1 km ×1 km spatial resolution (Scharlemann et al., 2008) was used to develop an annual mean EVI surface. EVI is an index of intensity of photosynthetic activity and ranges from 0 (no vegetation) to 1 (complete vegetation).

Figure 2.1 Maps of Kenya showing: e) aridity index f) Temperature suitability index (TSI)

e)[2]



f)



2.2 Population

Based on the 2009 census, the population of Kenya was 38,610,097 and projected to be more than 43 million by 2015 (KNBS, 2010). Kenya's population is over-dispersed with the highest densities along the west-east belt comprising of the Lake Victoria region, the western and central highlands, the Nairobi corridor through to the main coastal areas. The southern and northern regions are sparsely populated. This over-dispersion of population has consequences for disease distribution and health service delivery and requires mapping at the highest spatial resolutions possible.

To improve mapping of population distribution patterns, spatial modelling techniques have been developed to reallocate populations within census units to finer gridded surfaces (Linard et al., 2012). In brief, a dasymetric modeling technique (Mennis, 2009) was used to redistribute population counts within the 6,603 sub-locations used during the 2009 national census and land cover data sets derived from satellite imagery. A different population weight was assigned

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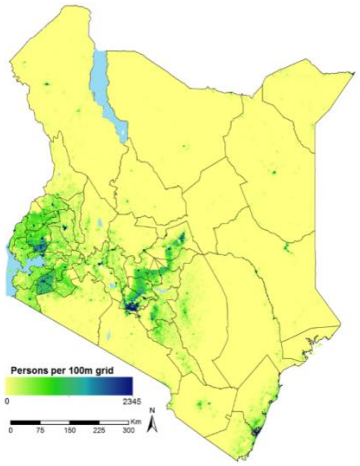
2. Global mean Aridity Index for the period 1950-2000 at 30' spatial resolution has been developed as a function of precipitation and eva-transportation (Trabucco et al,. 2009). The Aridity Index (AI) = Mean Annual Precipitation (MAP)/Mean Annual Potential Evapo-Transpiration, where values increase for more humid conditions, and decrease with more arid conditions. Mean annual precipitation (MAP) values were obtained from the WorldClim Global Climate Data (Hijmans et al., 2005) for the years 1950-2000. The Global Potential Evapo-Transpiration (PET) layers estimated on a monthly average basis were used to generate/aggregate mean annual values (MAE). PET is a measure of the ability of the atmosphere to remove water through Evapo-Transpiration process. PET is calculated as PET = 0.0023 • RA • (Tmean + 17.8) • TD0.5 (mm / day) where Tmean is mean monthly temperature, TD is mean monthly temperature range and RA is the mean monthly extra-terrestrial radiation. The Hargreaves method has been used, monthly average temperature has been sourced from WorldClim database, and monthly extra-terrestrial radiation, calculated using a methodology presented by Allen et al. (1998). Temperature range (TD) is a proxy to describe the effect of cloud cover on the quantity of extra-terrestrial radiation reaching the land surface.
TSI (Figure 2.1.f) is a metric for the effect of temperature on malaria transmission. A TSI has been developed at a spatial resolution of 1 km ×1 km (Gething et al., 2011). The TSI model uses a biological framework based on survival of vectors and the fluctuating monthly ambient temperature effects on the duration of sporogony that must be completed within the lifetime of a single generation of Anophelines and constructed using monthly temperature time series (Hijmans et al., 2005). On a scale of increasing transmission suitability, TSI ranges from 0 (unsuitable) to 1 (most suitable).

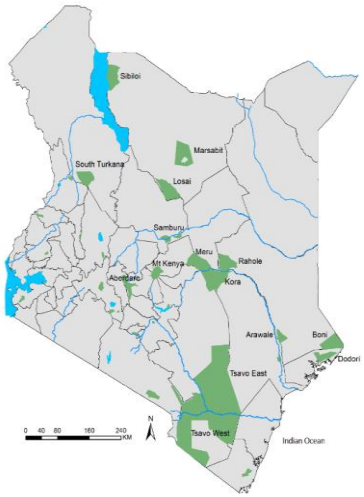
to each land cover class in order to shift populations away from unlikely populated areas, for example game reserves or arid deserts and concentrate populations in built-up areas. The net result was a gridded dataset of population distribution (counts) at 0.1 km × 0.1 km resolution. The population distribution datasets were projected to years used to predict malaria risk (see Section 4) using UN national rural and urban growth rates (UN, 2011) and made to match the total national population estimates provided by the UN Population Division (UN, 2010) for these years (Figure 2.2a). The population redistribution process accounted for restricted unpopulated areas such as national parks and game reserves (Figure 2.2b).

Figure 2.2 Maps of Kenya showing: a) population distribution at 1 km x 1 km spatial resolution; b) parks and game reserves (n=39, shown in green)[3]; and c) urban areas (shown in red).

a)



b)



c)

3. Data on Kenyan National Parks and Game Reserves was downloaded from the World Database on Protected Areas (WDPA) (IUCN and UNEP_WCMC, 2015). The WDPA is a joint project between the United Nations Environment Programme (UNEP) and the International Union for Conservation of Nature (IUCN), managed by UNEP World Conservation Monitoring Centre (UNEP-WCMC) (IUCN and UNEP_WCMC, 2015). There are 39 gazette and mapped protected areas in Kenya, the largest being the huge expanses occupied by Tsavo East and Tsavo West national parks north of the counties of Kilifi, Kwale and Mombasa.

Further classification of population by urban and rural is important to understand the variation of malaria risk and intervention coverage by residence. In malaria endemic settings, urban areas have been shown to have generally lower risk of malaria transmission (Hay et al., 2005). In Kenya an urban area is defined as an area with an increased density of human-created structures in comparison to the areas surrounding it and has a population of 2,000 and above. In this definition, urban areas include the following: Cities, Municipalities, Town Councils and Urban councils and even relatively small trading centres (KNBS, 2010). To develop an urban surface that would have a credible relationship with malaria transmission, the population surface was aggregated to 1 km × 1 km spatial resolution (Figure 2.2a). Areas with counts of people >=2000 per square kilometre were extracted from the population density map in the previous slide (n=233) and were overlaid on Google Earth (Google Inc Version 7.1.5) to capture the true extent of urban areas. The final urban areas identified were 69 (Figure 2.2c) and among those with a projected population of more than 100,000 include Nairobi (4,684,000), Mombasa (1,092,000), Nakuru (458,000), Kisumu (424,000), Eldoret (250,000) Ruiru (139,000), Thika (112,000), and Malindi (106,000).

2.3 Administration

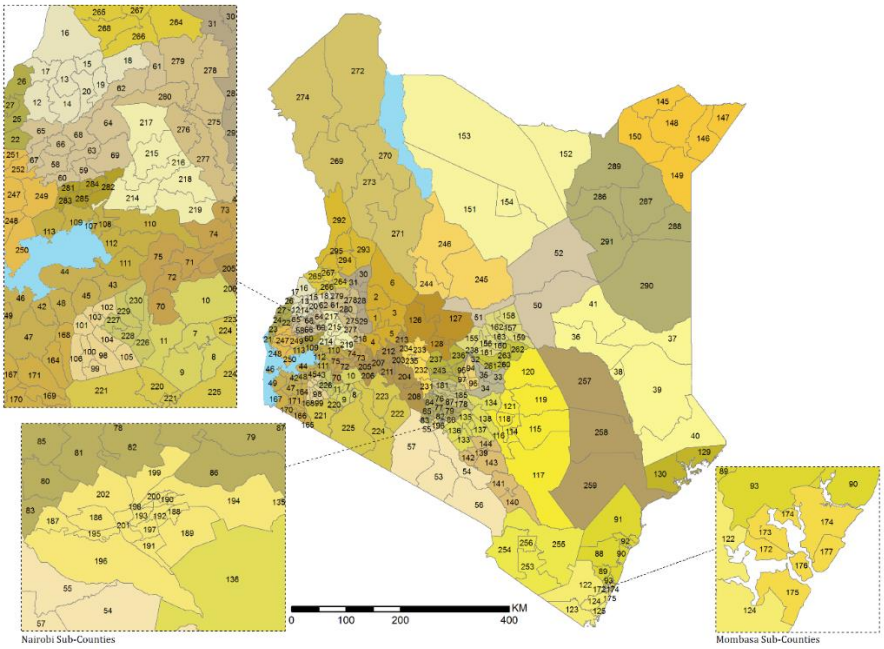
In August 2010, a new constitution moved governance from a centralised system to one that devolved political governance and the delivery of some key services to 47 county governments (Government of Kenya [GoK], 2010) with budgetary support and oversight from the national government. The fourth schedule of the constitution of Kenya identifies the need to facilitate progressive realisation by all to the right to health by assigning functions to both the national and county governments. The counties are assigned the service delivery functions while the national government provides national referral, policy guidelines, capacity building and technical assistance. The national government, in consultation with the county governments, develops legislative and administrative frameworks that guide the classification and operations of each level of the health service delivery system (Ministry of Health [MoH], 2014). The constitution empowers counties to determine the organization of the county and its various departments. The counties therefore have the freedom to modify the organisational structure in a manner that best promotes efficiency in the delivery of services and utilisation of resources (MoH, 2014). The functions and provision of services of each county government in theory are decentralised further to the sub-counties established under Article 89 of the Constitution (Country Government Act, 2012).

Following the general elections in 2013, the health service delivery function was formally transferred to counties in August of the same year, and one-third of the total devolved budget of KSh 210 billion was earmarked for health in the 2013/2014, enabling counties to become operational. The implementation of the Kenya Health Sector Strategic and Investment Plan 2013-2017 (KHSSP 2013-2017) takes into account the devolved system of governance. Thus, the arrangements and processes of the various institutions are being re-oriented. The strategy is also aligned to the Kenya vision 2030 policy framework and other global health commitments, using a three-pronged framework (comprehensive, balanced and coherent) to define policy direction (KPMG, 2013)

Figure 2.3 Maps of Kenya showing: a) counties (n=47); and b) sub-counties (n=295).[4] Inserts show the sub-counties of Nairobi, Mombasa, Kisumu and the densely populated western highlands areas. A list of sub-counties matching the numbers shown on the map is provided in Appendix A.

a)

b)



4. A shapefile of Kenya constituencies and wards as used by Independent Electoral and Boundaries Commission (IEBC) in the 2013 general elections was used [IEBC, 2015]. It had 290 constituencies and 1,439 wards. These boundaries were counter-checked against maps obtained in County Integrated Development Plans (CIDP) of each of the 47 counties. According to the CIDPs and other official publications of each county, all except Isiolo, Thatarka Nithi, Nyeri, Nyamira and Kilifi counties retained older constituency boundaries rather than revised boundaries suggested by the IEBC. Based on this information and using the 290 constituencies' shapefile, the sub-counties boundaries were delineated using the narrative in the CIDPs which was, in all cases, along ward boundaries. In total, we obtained 295 sub-counties in Kenya.

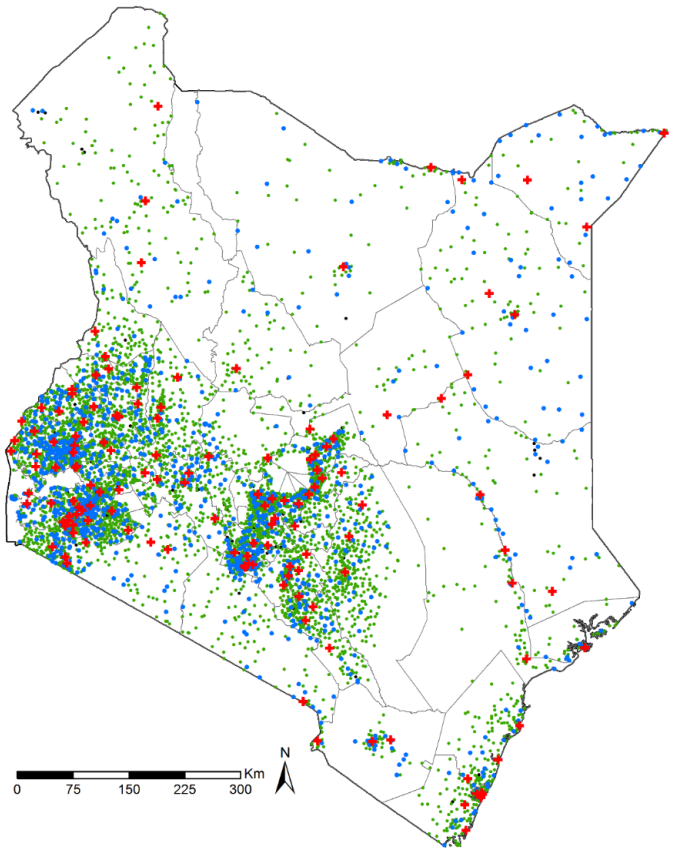
2.4 Health service delivery and mapping of health facilities

The health service delivery system in Kenya is guided by the KHSSP (2013-2017). The strategy is also aligned to the Kenya Vision 2030 policy framework and other global health commitments, such as the Millennium Development Goals, using a framework that is structured and comprehensive (KPMG, 2014). In this system, health service delivery is shared between the county and national governments. The national government has responsibility for referral services while counties are responsible for three levels of care: community health services, primary care services and county referral services. In the devolved system, healthcare service delivery is organised in a four-tiered system consisting of:

- **Community health services**: comprised of all the community based activities that identify the cases that need to be managed at higher levels of the health sector.
- **Primary care services**: comprised of all dispensaries, health centers and maternity homes from providers
- **County referral services**: comprised of former level four and district hospitals in specific counties and are operated and managed by the county governments
- **National referral services**: comprised of facilities that provide highly specialised services and includes all tertiary referral facilities

The Ministry of Health maintains a master health facility list using information supplied from district health records information officers. This list is available online from http://ehealth.or.ke/facilities/ and was downloaded 6 November 2015 (MoH, 2015). In total, the master facility list noted 6,589 (63%) public health facilities and 3,906 (37%) private facilities. The KEMRI-Wellcome Trust Research Programme also maintains geocoded databases of health facilities, which are periodically updated and contain information such as Facility Name; Administrative data (Province, district, division, location, sub-location); Facility type; Agency; Longitude and Latitude; EPI services (Y/N); ITN services (Y/N) and volume by month (Noor et al., 2004; 2009). These databases were reconciled, checked for duplicates and other incorrect information and mapped (Figure 2.4).

Figure 2.4 Map of Kenya showing the distribution of 7,087 public health facilities: Hospitals (142 Red), Health Centres (1,208 blue) and Dispensaries (5,737 green).[5]



5. Summary of Data cleaning: Public health facilities were first extracted from the MoH master facility lists, including those facilities owned by: Ministry of Health, Christian Health Association of Kenya, community development, humanitarian agencies, Kenya Episcopal Conference-Catholic Secretariat, local authority, Local Authority Trust Fund, Mission, NGOs, other faith-based organisations and SUPKEM. Public facilities were identified as dispensaries, district hospitals, health centres, hospitals, other hospitals, medical centres, medical clinics, provincial general hospitals, sub district hospitals.
The MoH master facility was compared to the KEMRI/Wellcome Trust database, where 3,892 matched in both name and master facility code, while 4,418 health facilities could not be matched. These contained 2,068 from the Welcome trust database and 2,352 from the updated master facility list. These two lists were then subjected to a rigorous exercise that included checking for unique facilities in either of the lists. There were 7,237 public health facilities and 3,905 private health facilities. Another list, provided by Population Services international was also obtained and after merging with the two, from which an additional 20 health facilities were added.
In the merged database, only 5,157 were geocoded. A rapid cross-referencing exercise was implemented with other available digital sources to geocode the master list. First, an online list maintained by the Development partners for Health in Kenya (DPHK) (Development Partners for Health in Kenya, 2015), was used. This website contains latitude and longitude information of facilities, with geolocated information provided by the MoH.
The coordinates were checked with health administrative boundary maps to locate those facilities that were in the wrong administrative boundary. In addition, points along the coastline were checked using the Global Administrative Unit Layers (GAUL) 2008 coastline shape file. The Global Lakes and Wetlands (GLWD) database developed by the World Wildlife Fund was used to ensure facilities were not located on water features. The geocoded list included some other facilities, such as stand-alone voluntary counselling and testing (VCT) centres and health programmes (53) which were excluded in the mapping. The final list mapped was 7,087. In the final public health facilities database, 7,140 (98%) were geocoded.

3. Malaria control in Kenya – Milestones

1990
Reports of use of larviciding with Reskol and HS Oil at Aldai, Mosop, Kilibwoni, and Tinderet Divisions of Nandi district to prevent epidemics.

1991
Widespread CQ clinical failures across the country.

1992
National plan of action designed with continued emphasis on case-management including use of CHWs and community promotion of ITN through BI sites through to 1997; national strategy defines strata of risk based on maps developed during 1960s: stable, epidemic, low risk and malaria free but not used to tailor interventions

BI sites located in 25 districts in Western and Nyanza provinces covering approximately 235 communities where malaria prevention gradually was introduced by DVBD and Division of Environmental Health.

1993
Large-scale ITN trial in Kilifi, Coast Province among 53,000 people.

1994
April – Malaria Control Unit (MCU) was established within DVBD under Communicable Diseases Department.

Operational plan included use of CHWs to promote ITN use through BI sites and presumptive treatment of uncomplicated malaria cases.

More challenges of Epidemics in highlands were experienced particularly in: Nandi, Kericho, Uasin Gishu, Trans Nzoia, Kakamega, Kisii, Nyamira, Trans Mara, Narok, West Pokot and Turkana. High morbidity and mortality among all age groups were experienced.

1995
Permethrin impregnated nets trial against Bancroftain filariasis and malaria in Kwale, in Coast Province.

1996
More than 50% of studies of CQ efficacy showed significant treatment failure rates nationwide.

Large-scale ITN trial at Asembo and Gem in Nyanza Province among a population of 125,000 people.

Trials on impregnated bednets for prevention of malaria in pregnancy were conducted in Bondo and Kilifi Districts.

Integrated management of childhood illnesses (IMCI) introduced for first time in Bungoma as part of the Bungoma District Malaria Initiative (BDMI) that continued through to 2000.

1997/1998

El Nino related epidemics nationwide notably in Kenyan highlands and arid and semi lowlands of northern Kenya with large, excess mortality leading to an emergency task force being established.

East African Network for Monitoring Antimalarial Treatment (EANMAT) sub-regional network of Ministries of Health and research agencies was established in 1997 and begins standardised testing of CQ, SP and AQ; in Kenya at seven epidemiologically representative sites among other sites in East Africa.

1998

CQ replaced with SP as first line treatment and national treatment guidelines developed accordingly.

African Medical Research Foundation (AMREF) launched an Employer Based ITN scheme with commercial and industrial partners including several tourist companies and hotels and others such as the Kenya Ports Authority, Bamburi and Simbarite cement industries, the Athi River Mining Company at Kaloleni, Umoja Rubber Company and the Kilifi and Vipingo Sisal Plantations, Muhoroni and Mumias Sugar companies, Malakisi Tobacco Company, Webuye Paper Mills.

1999

Policy changed from weekly CQ to two doses of SP to pregnant women living in malaria endemic areas during their second and third trimester.

Lambda-cyhalothrin IRS +/- ITNs distributed in epidemic prone of Gucha, Kisii, Nandi and Uasin Gishu districts.

2000

Malaria Control Unit became a Division of Malaria Control (DOMC) at the same time staff who were housed at different office locations moved into a new office building which was part of the government and partner commitment to malaria control.

Rapidly emerging SP resistance experienced through to 2003.

The role of DVBD's 48 field stations becomes more about providing support to hospital services than surveillance vector control.

Lambda-cyhalothrin IRS and ITNs expanded across epidemic prone highland districts.

Focused Antenatal Care (FANC) approach to promote the health of pregnant women launched.

2001

National Malaria Strategy 2001-2010 launched with an emphasis on scaling up distribution of ITNs, improving access to effective medicines for treatment and epidemic preparedness and response. Strategy provided evidence of different epidemiological strata but used only to defined epidemic prone areas for special intervention.

National ITN strategy launched promoting an enabling environment for public private sector public sector partnership through retail sector and subsidised public sector distribution.

UNICEF provided 700,000 ITNs to pregnant women living in 35 of 69 districts through ANC clinics at no cost to beneficiaries.

kdr resistance mutations in vector populations remained low in Western and Coast regions.

IMCI rolled out to include Vihiga, Embu and Kajiado followed by slow adoption in other districts supported by NGO partners through to 2009.

2002

Larviciding pilots using *Bacillus thuringiensis israelensis* (*Bti)* at Mbita, Suba District protecting 8,000 people by ICIPE.

Social marketing through retail sector and minimal subsidised cost recovery through special franchised kiosk launched and distributed 5 million ITN nationwide by 2004.

Focused ANC and Malaria in Pregnancy programme (FANC) scaled up nationwide to improve coverage of IPTp in additional 19 endemic prone districts.

Malaria epidemic in western highlands with approximately 400 deaths (Nandi, Kericho, Uasin Gishu, Buret, Bomet, West Pokot, Trans Mara, Trans Nzoia, Kisii, Gucha and Nyamira) experienced.

Annual single round seasonal focalised IRS using pyrethroids to prevent epidemics in16 classified epidemic prone districts.

2003

4.3% of children slept under an ITN and only 4% of pregnant women had received two doses of SP in their last pregnancy (April-August, Kenya National Demographic and Health Survey 2003).

Four epidemiologically representative sentinel districts (Kwale, Makueni, Bondo and Kisii/Gucha) established to provide core indicators for malaria control and prevention from random household surveys, case-management indicators from facilities and hospital admission data through to 2007 when they were stopped.

2004

Global Fund approved Round 2 funding awarded USD 33,586,790 to support the use of nets by pregnant women and children under five years; scaling up IPTp in conjunction with reproductive health services; effective case management through the implementation of IMCI in conjunction with child health; improve dispensing practices in retail outlets

The distribution of heavily subsidised nets through ANC and MCH clinics begins and this policy complimented the social marketing approach to ITN (nets and re-treatment kits) distribution approach which was conducted by PSI with support of the UK Government.

Consensus approval of policy change from SP to ACT (Artemether-Lumefantrine) for first-line treatment of uncomplicated malaria. A transitional plan was put in place. Treatment guidelines

were revised, and training undertaken. However, commodities were procured until 2006 when GF round was secured.

2005

Larviciding and ITN trials (*Bti and* Bacillus sphaericu (*Bs))* in Kakamega and Vihiga through to 2007.

Biological control, *Bti*, in Nyabondo and Kisii around brick making rural areas that continues through to 2006 covering circa 150,000 people under ICIPE.

Combinations of *Bti* and *Bs* piloted in Malindi, Coast Province by KEMRI Wellcome Trust.

Heavily subsidised Supanet-branded long-lasting insecticidal nets (LLINs), Olyset and Permanet receives additional funding from UK Government.

23.9% of children slept under an ITN (August, National PSI TRac Survey).

2006

Global Fund Round 4 funding awarded over USD 150 million through to 2010, although only 102 million spent; PMI begins country-level annual support *circa* USD 6 million USD in 2007, with a total investment of approximately 263 million by 2015.

July-September, mass free LLIN distribution of 3.4 million nets combined with measles vaccination catch-up campaign during first phase and not during second phase.

ACT policy to replace SP implemented with AL drug supply, in-service training and -production of new standard treatment guidelines, 32 months following 2004 decision.

The "Advocacy and Public Awareness Campaign for Artemisinin Combination Therapy (ACT) in Kenya" plan was launched, including multimedia, print media advertisements, television, national and regional vernacular radio, community road shows, circa 100,000 posters and 500,000 brochures distributed nationwide; emphasis on AL free-of-charge.

During Africa Malaria Day commemoration, President Mwai Kibaki launched the launched the new treatment policy under the campaign branded "*Komesha Malaria, Okoa Maisha*" ("Stop Malaria, Save Lives").

IMCI partners also adopt the new treatment guidelines.

Trial of IPT using SP+AQ among school children in Bondo, Nyanza Province.

Biological control, *Bti*, of larvae in urban centres of Malindi began, expanding to peri-urban core in 2013 and by 2016 covered 400,000 people in urban and rural areas around Malindi as part of integrated vector management (IVM).

2007

38.8% of children slept under an ITN and 12.5% of women reported taking at least two doses of SP in their last pregnancy (KMIS 2007).

31.6% of children slept under an ITN (September, National PSI Trac Household Survey).

RTS,S/AS01E malaria vaccine trial in Kilifi, Siaya and Kisumu Districts starts.

Malezi Bora weeks launched by Ministry of Public Health as door-to-door campaigns on broad child health issues, including malaria messages.

National Guidelines for laboratory diagnosis of malaria developed and launched.

A more systematic approach to pyrethroidn IRS each year in April, targeting about 1.2 million households, covering a population of 3.8 million people, 97% operational coverage, in 16 epidemic prone districts.

MENTOR Initiative started IRS in Tana River and Garissa Districts using pyrethroids and 1,493 trained volunteers covering 36,337 households.

EANMAT regional, sentinel drug sensitivity testing programme ends.

December-March 2008, post-election violence disrupts basic health services and malaria control

2008

IRS continues at scale in 14 epidemic prone districts. However, two of the epidemic prone (Nandi North and South) districts and one endemic district (Rachuonyo) undertook intensive IRS supported by PMI. Rachuonyo was adopted as part of trial to determine the added value of combining IRS with LLIN in endemic regions.

Mass re-treat campaign in October for nets using longer lasting retreatment kits to convert 1.9 million nets owned by communities then to long lasting while 270,000 disused nets were replaced.

47% of children slept under an ITN and 15% of women reported taking at least two doses of SP during their last pregnancy (KDHS 2008-2009).

Evidence of declining malaria admissions in Coast province but not in areas surrounding Lake Victoria since 2000. However, there was evidence of reduced mortality in Siaya.

Trial of delivery of ITNs through school children in Tana River.

National school-based malaria surveillance continued through to 2013.

2009

Malaria Programme Review undertaken to prepare for new eight-year strategic plan.

National Malaria Strategy launched with a vision of a malaria free Kenya where the goal was to have reduced morbidity and mortality caused by malaria in the various epidemiological zones by two-thirds of the 2007/08 level by 2017; for the first time all intervention recommendations were based on malaria prevalence in the county.

IPTp intervention using SP was restricted only to areas of Coast endemic and Lake Victoria regions.

Integrated Vector Management policy guidelines developed to encompass a range of disease vectors and control methods.

Revised case-management guidelines that promote Test, Treat and Track (TTT) leading to expansion of diagnostic capacities nationwide including use of rapid diagnostic tests (RDTs) for all age groups and in all malaria transmission settings.

32.6% of children slept under an ITN (January-March, National Financial Services Deepening Household Survey).

2010

Kenya adopts new constitution that radically devolved management of health service delivery to 47 county governments.

Blanket IRS in 16 epidemic prone districts stops and strategy changes to IRS only in epidemic foci detected.

Three stable endemic sub-counties (Ranchonyo, Migori and Nyando) included in pyrethroid-based IRS covering about 2.2 million people.

Since 2008 about five million LLIN distributed through routine ANC/CWC clinics.

42% of children slept under an ITN and 26% of pregnant women reported taking at least 2 doses of SP their last pregnancy (KMIS 2010).

AMFm quality assured ACTs through private sector launched through to 2011 with Global Fund support.

Treatment policy further revised to recommend diagnosis before treatment and dihydroartemisinin-piperaquine (DHA-PPQ) for the second-line treatment, and the use of AL in the second and the third trimester of pregnancy across all weight bands.

AL dispersible tablets introduced into Kenya Public Health Sector.

Step-wise in-service training reached 5,000 health workers for new malaria case-management.

3T guidelines, provided with printed copies and wall charts, completed in 2013.

Bi-annual national health facility Quality of Care audits continued through to 2015 totalling 10 surveys.

2011

Focalised IRS continued targeting 12 high-risk highland epidemic prone counties using pyrethroids.

Endemic counties (Ranchuonyo, Migori and Nyando) continue pyrethroid-based IRS where the entire Homa Bay county was included.

High levels of pyrethroid and DDT resistance detected in Bondo, Rachuonyo, Nyando, Busia, Kisumu, Siaya, Homa Bay, Migori, Teso counties; no evidence of resistance to Bendiocarb (carbamate) or malathion (organo-phosphate).

Trial of screening and treatment with AL among school children at 160 schools in Kwale county, Coast region.

Free mass LLIN distributions begins in Nyanza and Western regions.

2012

Global Fund approved Round 10 funding where malaria component was awarded USD138 million through to 2017.

mRDT implementation plan was developed with roll out targeted initially in low transmission districts.

AL and RDT supply transitions from push-pull combination to entirely pull system from the central medical stores to counties based on their estimated requirements.

mRDTs completely rolled out nationwide in public sector.

July, epidemic of malaria in North Pokot.

December, completion of mass free LLIN distributions in target areas in Nyanza, Western, Coast regions and the epidemic prone counties in Rift Valley region (Trans Nzoia, Bomet, Kericho, Nandi, Uasin Gishu, West Pokot, Transmara and Loima), delivering about 10.6 million nets in total.

Case management policy revised to recommended parenteral artesunate for pre-referral and severe malaria treatment, while quinine remained recommended treatment only in the first trimester of pregnancy.

Medical practitioners, Pharmacy and Poisons Board approved in November the use of AL by community health workers.

Pyrethroid resistance among *An. gambiae s.l* and *An. funestus* populations in Bondo, Siaya, Busia, Nyando, Bungona and Homa Bay; however, susceptible to Bendiocarb.

An. gambiae sl populations 100% sensitive to DDT and Fenitrothion. Bendiocarb sensitive in Kwale and Kilifi counties but resistance shown in Taveta county, three and four of eight sentinel sites showed reduced sensitivity to deltamethrin and lambdacyhalotrin respectively.

2013

August, health functions fully devolved to 47 county governments with full responsibility for design, priorities, commodity procurement, staffing and monitoring/ evaluation of health sector service delivery.

In the quest for insecticides resistance management and in conformity with WHO guidelines for using non pyrethroids in areas where LLIN coverage is high, IRS with pyrethroids was suspended.

Fire in January at Kenya medical supplies agency stores destroys more than four million RDTs resulting in major stock outs.

MSAT trial of three rounds where target populations were screened with RDTs and treated DHA-piperaquine treatment among 30,000 people in Gem, Karemo in Siaya county, Nyanza Province.

Malaria surveillance curriculum developed for health workers.

DHA-PPQ had not been distributed to facilities despite policy change, through to 2016, and parental artesunate had only been supplied on a very limited scale.

Division of Malaria Control, becomes Malaria Control Unit again under the Division of Communicable Disease Prevention and Control.

UK Government support to malaria in Kenya comes to an end. From 2000 it had provided about USD 15 million per annum to the national strategic plan.

Integrated Community case management of childhood illness (iCCM) plan of action launched with a component for CHWs to diagnoses malaria with an mRDT and treat with AL at household levels.

Pilot trial of iCCM in Bondo county, including malaria case-management at household levels.

Artesunate replaces quinine as drug policy recommendation for severe and complicated malaria.

First detailed national malaria control and epidemiological profile launched.

2014

42% of children slept under an ITN (May-June, PSI TRac National Household Survey).

54% of children slept under an ITN and 15% of pregnant women reported taking at least two doses of SP, and 10% taking three doses and about 30% of women received one or more doses of IPTp (KDHS 2014-2015).

LLIN distribution catch-up campaign, first phase began in September in Migori launched by President and then in, Homa Bay, Kisumu, Siaya and Vihiga in 2014 distributing about three million nets.

LLIN distribution second phase began in November in West Pokot attributing 350,000 nets.

Pyrethroid resistance remains high, but *An. gambiae* populations remain susceptible to Bendiocarb and Malathion at sentinel sites located in counties of Western and Nyanza. The 24-hour mortality of less than 50% among *An gambiae* and *An funestus* populations to deltamethrin and permethrin were recorded in Siaya, Homa Bay, Kisumu and Migori; 75-80% mortality rates resistance among *An gambiae* in Siaya to Bendiocarb.

About 6,000 private and public health workers training in TTT case-management guidelines.

CCM with test and Rx rolled out in Western/Nyanza.

2015

Mass LLIN distribution Phase 3 completed by June distributing 2.8 million nets in Uasin Gishu, Nandi, Kericho, Narok and Bomet.

Mass LLIN distribution Phase 4 was completed by September distributing 2.6 million nets in Trans-Nzoia, Mombasa, Lamu, Tana River, Taita Taveta, Kilifi, and Kwale.

Mass LLIN distribution Phase 5 was completed by December distributing 3.8 million nets in Kakamega, Kisii, Nyamira, Bungoma, and Busia Counties.

56% of children slept under an ITN and 22% of pregnant women reported taking at least three doses of SP after quickening, 38% of women in endemic focus areas (KMIS 2015).

More than 10,000 health workers from private and public sectors received in-service training in TTT case management policy.

More than 3000 health workers from 13 epidemic prone and seasonal transmission sub-counties trained in malaria surveillance and epidemic preparedness.

Global Fund comes up with the new funding model and the NMCP is asked to re-programme its funds (Round10) with an additional USD 25 million; the total grant comes to USD 68.4 million.

2016

Insecticide resistance management strategy and plan developed through to 2018.

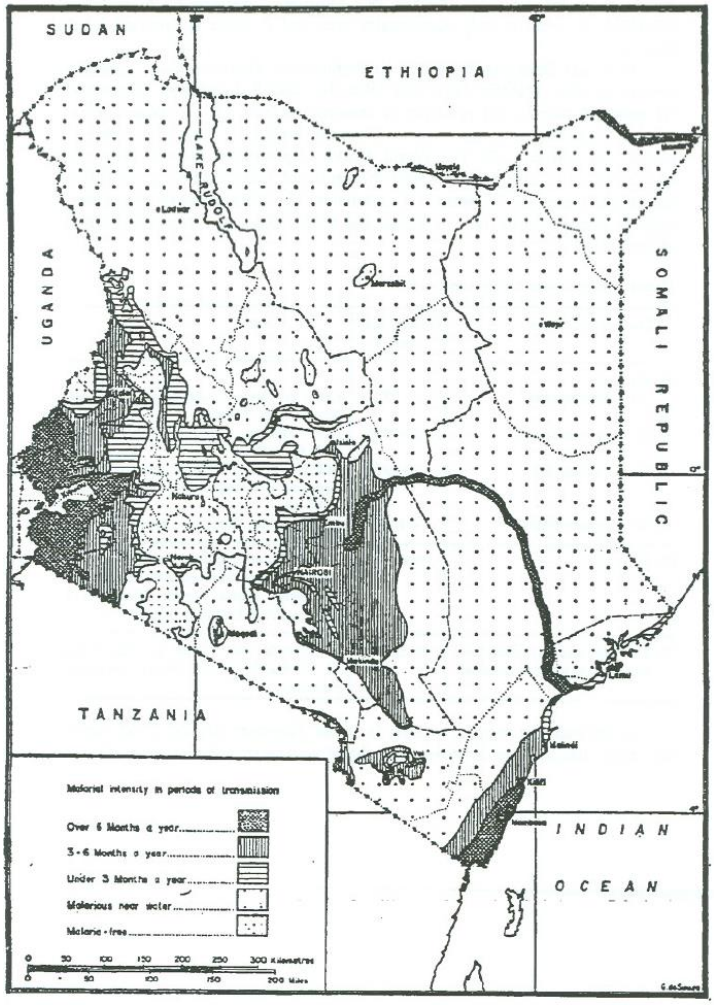
In May 2016, IPTp strategy revised prevention to a minimum three doses of SP every four weeks after quickening.

4. Mapping malaria risk

4.1 Previous mapping of malaria risk in Kenya

The use of malaria risk mapping to guide interventions in Kenya began during the 1990s (MoH, 1992), based on maps of climate associated risk developed in the 1950s (Butler, 1959). However, it was not until the launch of the National Malaria Strategy 2009-2017 (DOMC, 2009) that a more empirical basis for targeting different mixes of interventions was proposed based upon malaria prevalence by district (Noor et al., 2009) to accelerate progress toward a "malaria free" Kenya. At the time Kenya represented one of very few sub-Saharan African countries with a strategic plan based on strong epidemiological stratification that allowed for the vast differences in the sub-national risks of malaria (Omumbo et al., 2013).

Figure 4.1 First representation of the cartography of malaria risk developed from information on length of transmission and seasonality of malaria (Butler 1959).



The first cartography of malaria risk in the country was produced as part of an atlas by the Government of Kenya in 1959 (Butler 1959). This map was developed as a length of transmission season map, based on a combination of expert opinion and climatology. There is no evidence that this map was ever used in any formal way to guide control decisions at the time, but it represented an early recognition that all was not equal across the country. This map was used for a further 20+ years and featured in descriptions of national malaria risk in the

1970s (Roberts, 1974), who also attempted to use topography and climate to classify areas of the country into endemicity zones based on best approximations of spleen rates in children aged 2-9 years. This map was used for the formulation of Kenya's malaria plan in 1992 (MoH 1992). However, other than a recognition of the epidemic potential of the Kenyan highlands, there were few attempts to stratify control measures based on the country's diverse malaria ecology.

It wasn't until the mid-1990s, with the launch of the MARA initiative (Snow et al., 1996), that empirical malariometric data was used to map a revised cartography of malaria risk in Kenya (Snow et al., 1998; Omumbo et al., 1998). The 1990s were a decade of unprecedented epidemics across Kenya and as such strategic plans developed during the early 2000s promoted a universal set of recommendations, with the exception of epidemic early warning systems in the Kenyan highlands. In 2009, a malaria risk map for Kenya was developed based on 2,682 parasite surveys undertaken between 1975 and 2009 and using modern statistical approaches for interpolating survey data collected in different places at different times (Noor et al., 2009). The map was based on the largest parasite survey data for a single country in the SSA region and included data from the Kenya Malaria Indicator Surveys (KMIS) of 2007 and 2010.

With the publication of this map of the prevalence of *P. falciparum* in 2009, Kenya led the way as one of the first countries in sub-Saharan Africa to develop a formal sub-national framework of "suites of control packages" using empirical data on malaria transmission (Figure 4.2), serving as a platform to single out the 16 most intractable districts around Lake Victoria for special, concerted interventions to significantly reduce their endemicity. This map was updated in 2012 when the first comprehensive malaria epidemiological and control profile was developed (Noor et al 2013) and was used to stratify counties into varying levels of average malaria endemicity to the planning of devolved governance in Kenya in 2013 (Figure 4.3).

Since then, the KEMRI-Wellcome Trust/INFORM programme has continued to work with the NMCP to update information on malaria prevalence nationwide through school surveys, providing technical support during the KMIS 2015 and assembling evidence from various research groups across the country. The present profile, therefore, provides an opportunity to update and review the levels of malaria risk nationwide and by county. It also improves on the 2012 profile with the presentation of malaria risk and intervention coverage by sub-county to support within county decision making.

Figure 4.2 Map of 2009 malaria endemicity showing estimated *P falciparum* prevalence among children 2-10 years of age ($Pf PR_{2-10}$) in Kenya (Noor et al., 2009) showing a suite of interventions by transmission zone developed for the Kenya National Strategic Plans for Malaria 2009-2017 (NMCP 2009).

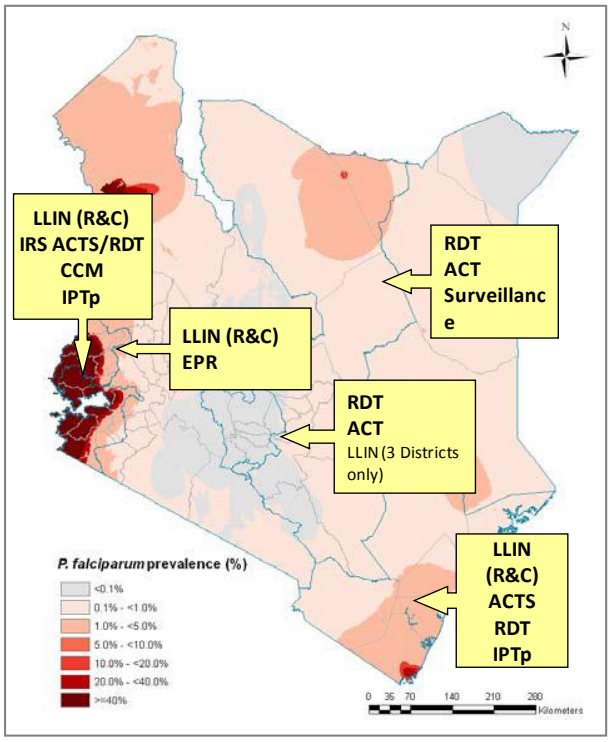
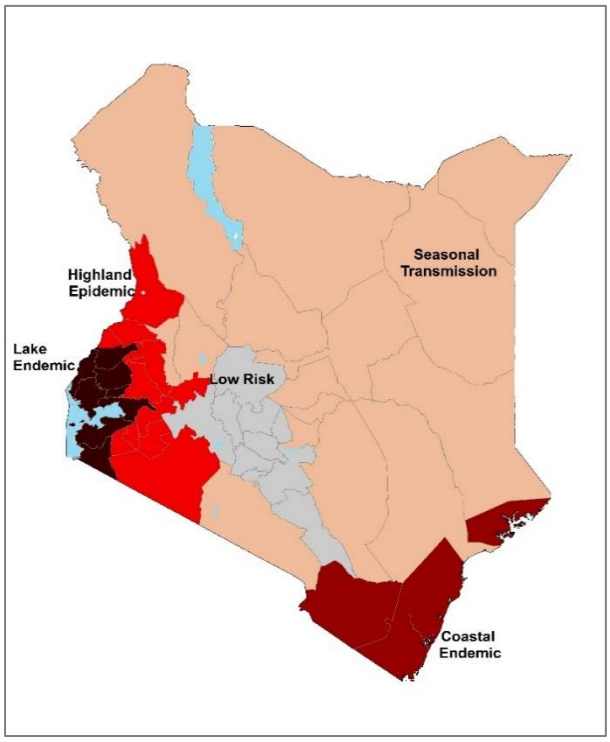


Figure 4.3 Map of county malaria endemicity based on population adjusted estimates of ($Pf PR_{2-10}$) showing five transmission zones (Noor et al., 2012). Low risk = 10 counties, 13.4 million population in 2015; Seasonal = 14 counties, 10.1 million population in 2015; Highland = 10 counties, 9.1 million population in 2015; Coastal endemic = 5 counties, 3.7 million population in 2015; Lake endemic = 8 counties, 9.4 million population in 2015.



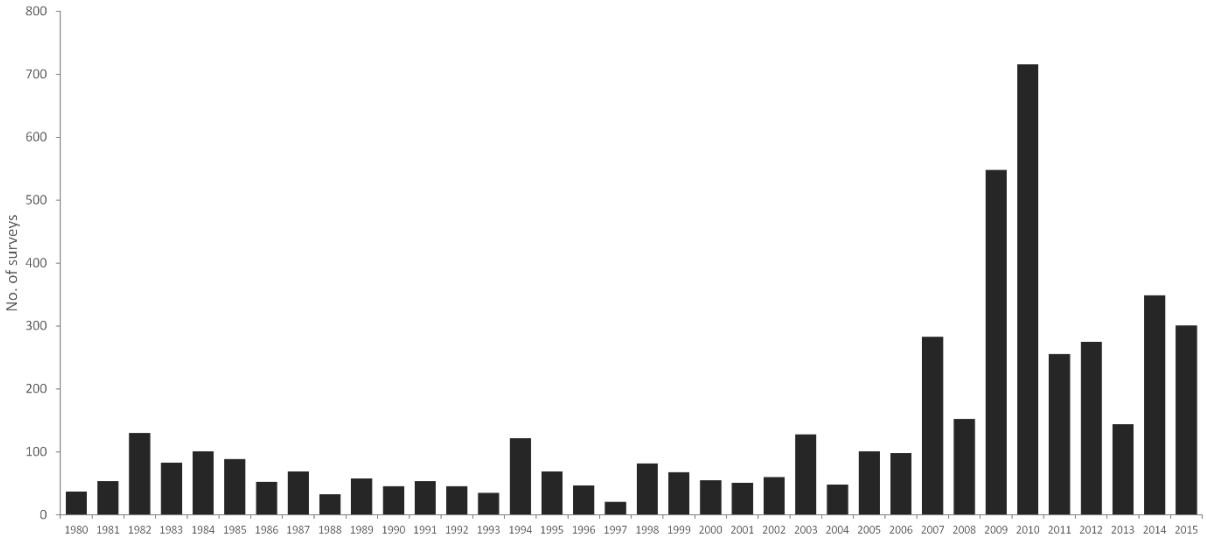
4.2 Mapping *P. falciparum* malaria risk from 2000-2015

4.2.1 Parasite prevalence data

Community-based surveys of malaria parasite prevalence have become the main source of data for mapping malaria transmission intensity (Snow et al 2015a). For Kenya, the data used in the 2012 profile (Noor et al 2012) were updated from a variety of sources including peer-reviewed journals, international and national ministry of health and academic archives, personal correspondence and more recent national household and school sample surveys. Methods used to identify, extract and geocode survey reports are presented elsewhere (Snow et al., 2015a).

Of the assembled data, inclusion was restricted to all surveys undertaken from January 1980 with a sample size of 10 or more individuals examined for malaria infection. Three survey sites could not be geolocated and 19 had sample sizes less than 10 individuals. Fifty-four surveys were undertaken on islands off Lamu on the Coast or Suba/Homa Bay in Lake Victoria and for the purposes of continuous spatial modelling these were modelled separately. The remaining data used for mapping malaria consisted of **4,862** (Figure 4.4) surveys at **3,684** unique locations (Figure 4.5a and b). This assembly of survey data in time and space, represents one of the largest of any country in Africa and includes national community/school surveys from 1980-1984 conducted by: Division of Vector Borne Diseases (DVBD); MIS 2007; National school surveys 2009/10; MIS 2010; partial national schools survey 2014; and the MIS 2015. Despite repeated attempts, it was not possible to obtain the malaria infection data collected as part of the MoH/UNICEF nutritional survey of 2010. Of the 4,862 survey prevalence measures, 3,274 used microscopy alone, 953 used RDTs alone, 634 used RDTs confirmed by microscopy; and one used microscopy confirmed by PCR.

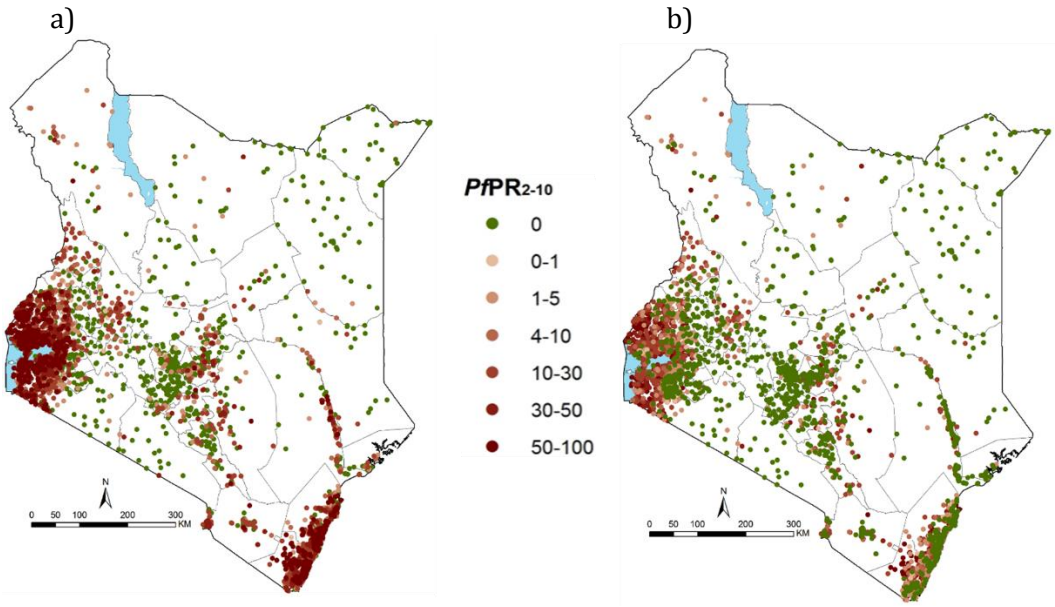
Figure 4.4 Frequency of communities surveyed for malaria infection between 1980 and 2015 (4,862 surveys in 3,684 unique locations)



At 1,926 survey/time specific sites between 1980 and 2015, 183,643 individuals were examined using microscopy, RDTs confirmed by microscopy or microscopy confirmed using PCR to determine the malaria parasite species. Of those surveyed 32,348 were infected with *P. falciparum*, 2160 with *P. malariae* and 792 with *P. ovale*. There were four cases of *P. vivax* described at Nganja (Kwale) (Sutherland et al., 2011) and Asembo Bay (Siaya) (KEMRI-CDC 2015, unpublished data). While there is an incredibly low likelihood of *P. vivax* in Kenya, the red

cell duffy-negative protection among people in Nyanza and Coast is not completely refractory (Ryan et al., 2007). Of all infections detected the majority were *P. falciparum* (92%), followed by *P. malariae* (6%) and *P. ovale* (2%). All data assembled is provided to the NMCP accompanying this report, for future use and updating.

Figure 4.5 Locations of communities surveyed for malaria infection between 1980 and 2015 (4,862 surveys in 3,684 unique locations) a) highest *Pf*PR$_{2-10}$ values on top; b) lowest *Pf*PR$_{2-10}$ values on top.



4.2.2 Geostatistical modelling of P. falciparum prevalence

To develop continuous malaria risk maps from the community parasite survey data, geostatistical methods were used to interpolate the observed parasite prevalence from sampled locations in space and time to provide predictions at locations and times where data did not exist. These methods operate under Tobler's First Law of Geography, which states that things that are closer in space and time are more similar than those more spatially and temporally distal (Tobler, 1970). When applied within a Bayesian inference framework, these methods are referred to as model-based geostatistical (MBG) methods (Diggle et al., 1998). Bayesian inference allows for better use of sparse data and the application of prior knowledge of an outcome in an iterative process that is useful for robust estimation of uncertainties around the mean estimates of the outcome variable.

The procedures used to model and validate the transformation of empirical *P. falciparum* parasite prevalence data to continuous predictions of age-corrected mean prevalence in children aged 2-10 years (*Pf*PR$_{2-10}$) are provided elsewhere (Noor et al., 2014). In brief, information from available age-corrected survey data (sample size and numbers positive) at known locations (longitude and latitude) and times (year) all data assembled from 1980-2014 were used together with a minimal set of conservative, long-term covariates traditionally used in vector-borne disease mapping. The data were used within a Bayesian hierarchical space-time model, implemented through an adapted Stochastic Partial Differential Equations (SPDE) approach using Integrated Nested Laplace Approximations (INLA) for inference (R-INLA 2013; Rue et al., 2009) to produce continuous maps of *Pf*PR$_{2-10}$ for 2008, 2012 and 2015 at 1 km x 1 km spatial resolutions. See Appendix B for methodological details.

The environmental covariates whose relationship with *Pf*PR$_{2-10}$ was examined were rainfall, vegetation, temperature suitability index and urbanization – all of which were found to have a statistically significant relationship with malaria prevalence and were included in the MBG model.

Figure 4.6 Maps of PfPR2-10 at 1 km × 1 km spatial in Kenya in a) 2000; b) 2005; c) 2010; and d) 2015

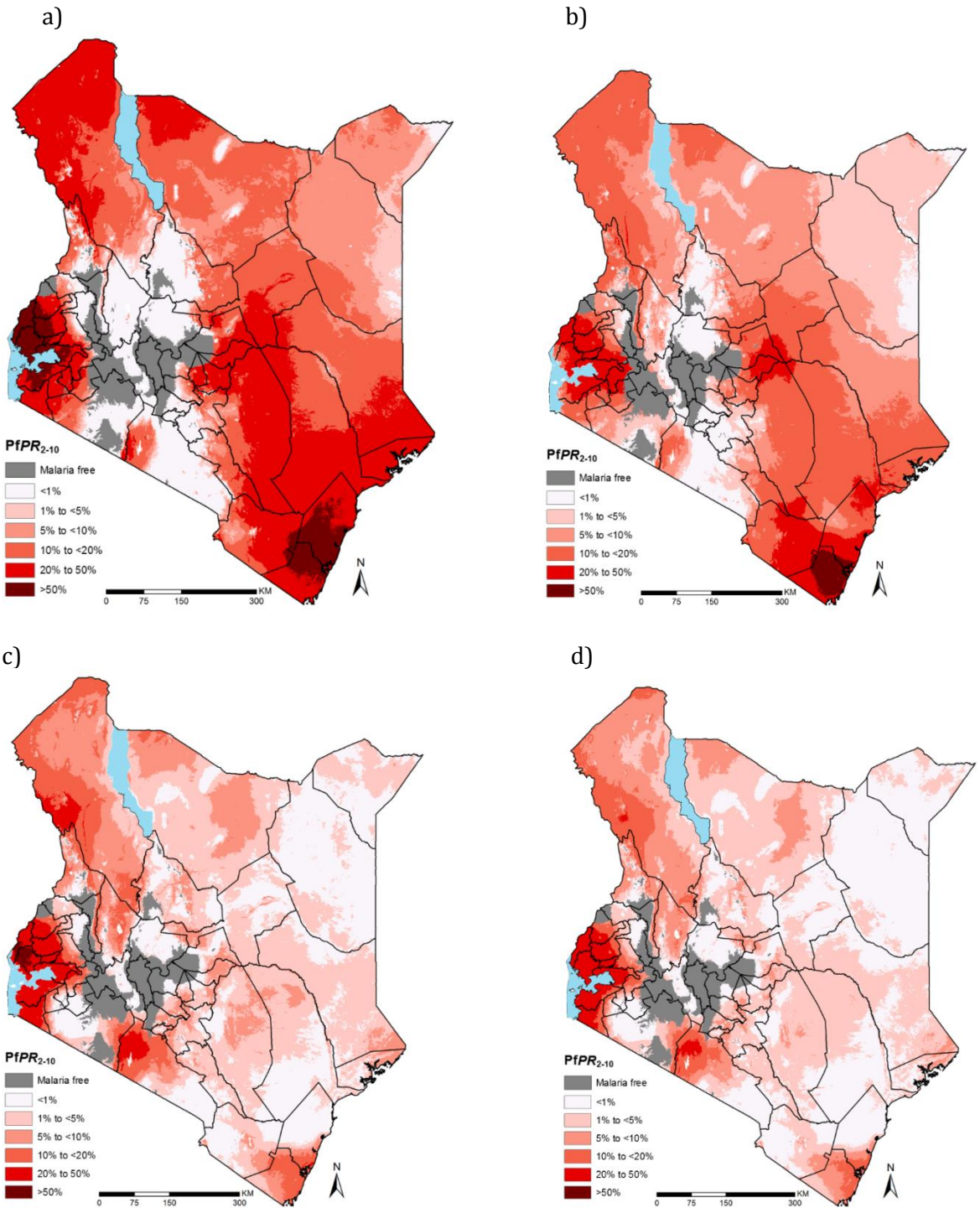
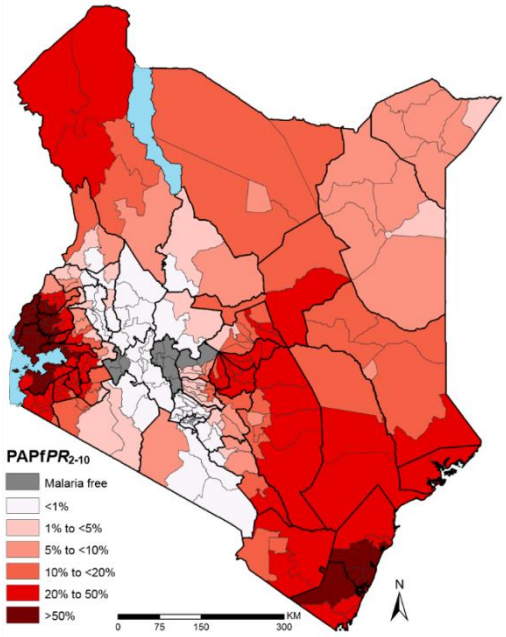
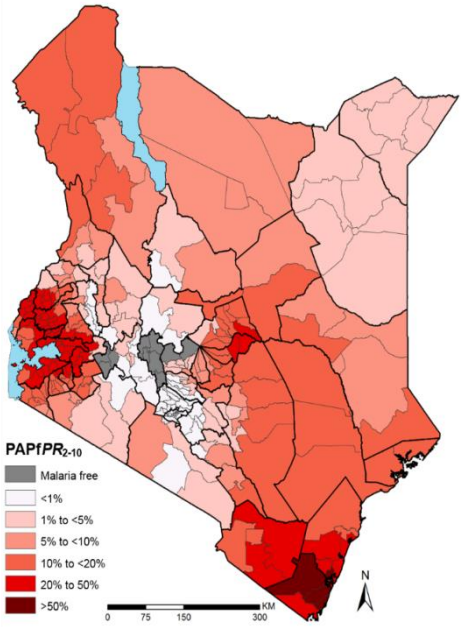


Figure 4.7 Maps of population adjusted P*f*PR$_{2-10}$ (PA P*f*PR$_{2-10}$) at 1 km × 1 km spatial by sub-county in Kenya in a) 2000 b) 2005; c) 2010; and d) 2015.

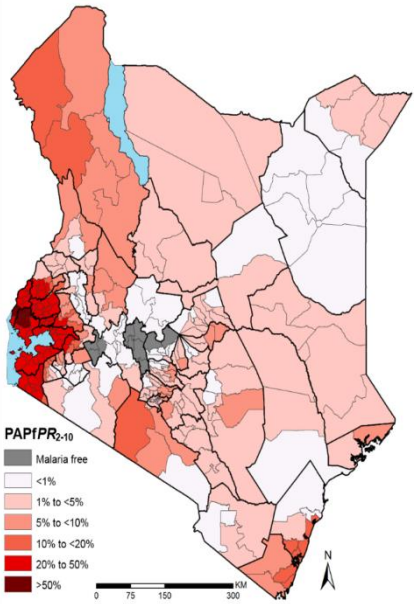
a) 2000



b) 2005



c) 2010



d) 2015

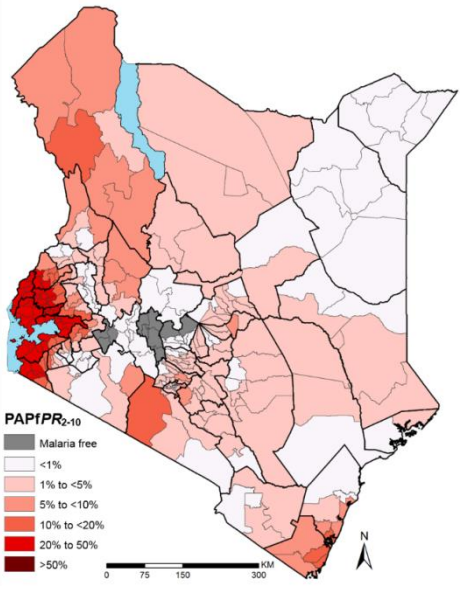
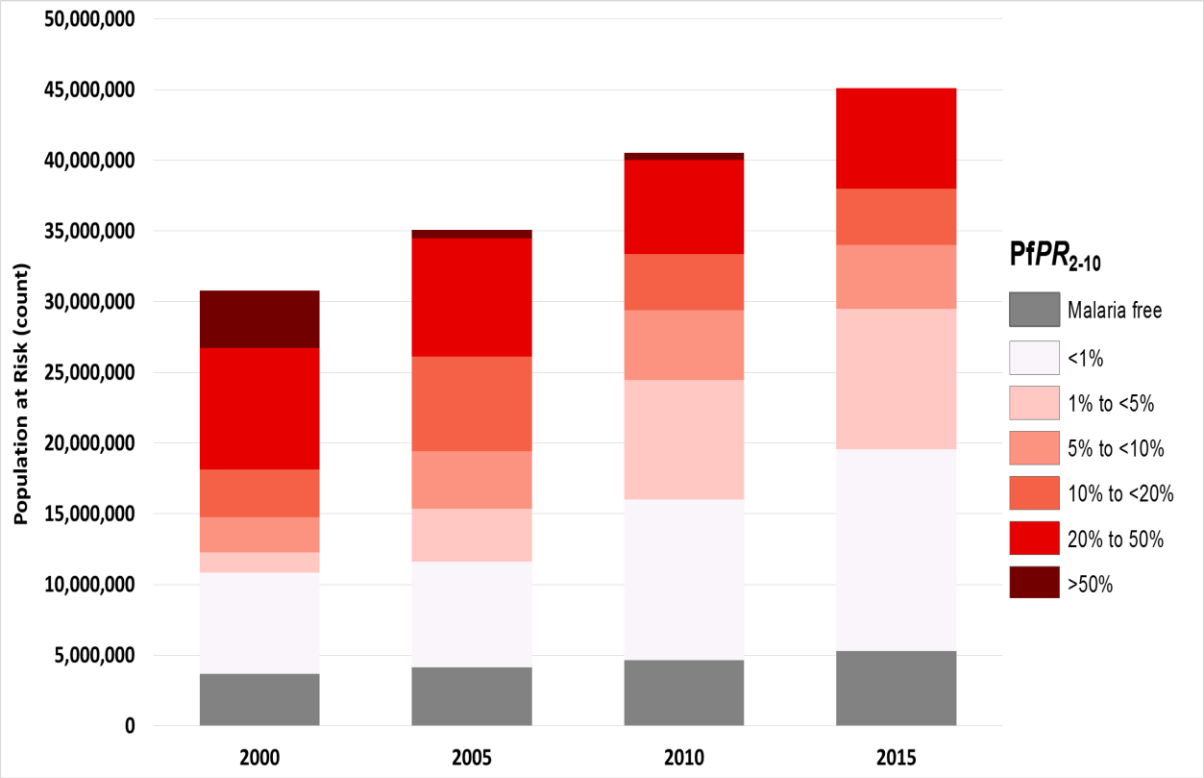
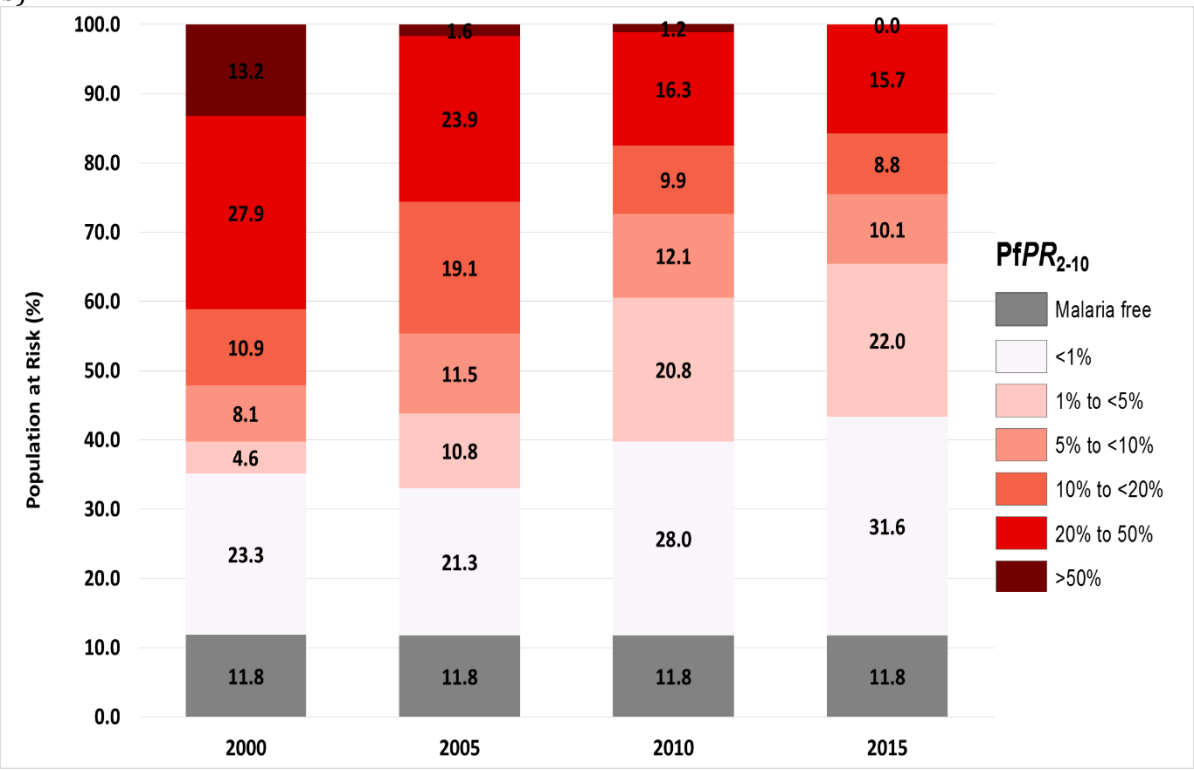


Figure 4.8 Changing population at risk of malaria by $Pf PR_{2-10}$ endemicity from 2000-2015: a) count b) percentage

a)



b)



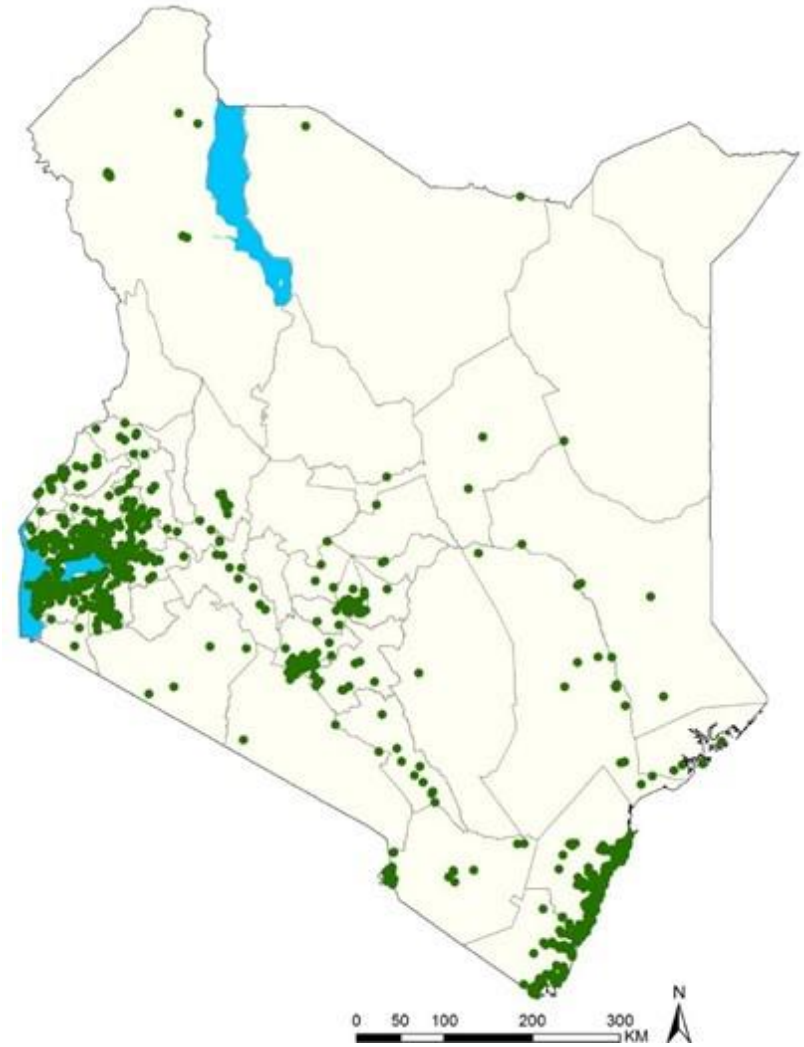
4.3 Mapping the distribution of vectors

The first map of the Anopheles vectors in Kenya was published nearly 40 years ago and shows the distribution of the *An. gambiae* complex and *An. funestus* (Roberts, 1974). A national inventory of dominant malaria vectors was developed in 2009 covering largely only members of the *An. gambiae* and *An. funestus* complexes (Okara et al., 2010) and this provisional assembly of data was used to show the distribution of dominant vectors in the National Insecticide Resistance Management Strategy 2015-2018 (NMCP, 2015). This has been significantly updated through a more detailed search of historical archives, graduate and post-graduate theses, grey literature and published sources, with increased documentation of potential secondary vectors. Full details of the data assembly, geocoding methods and classifications of species according to their role in malaria transmission are provided elsewhere (Snow et al., 2015b). The database has been arranged as a site-specific, referenced inventory to capture details of species identification recorded since the earliest surveys in 1900 through to the latest records in 2014. The full digital PDF library, database and bibliography accompanies this report.

From each identified report, data extraction included whether a species was identified at a given site, methods used to capture adults or larvae and methods used to speciate each anopheline collection. "Y" was recorded if species was identified and "N" was only recorded when the true absence of the species was reported. The database is therefore one of species presence, not absence and nor proportional presence of various vectors. The final database contained 1,028 site/time specific reports of anopheline vectors occurring in Kenya between 1900 and 2014 for which coordinates were available. Geolocation data for seven (0.68%) survey sites were unavailable from all accessible sources. The database includes records from some of the earliest national inventories undertaken during the 1930s (Evans and Symes, 1937); more recent national mosquito surveys done by Ochieng and colleagues from 2007 to 2012 (Ochieng et al., 2013) for a mosquito-borne arbovirus study in Kenya; and resistance surveillance sites managed by the NMCP and its partners. Since January 2005, there have been 440 sites surveyed in Kenya.

Major malaria vectors have never been recorded in Kitui county, while in Bomet, Elgeyo Marakwet, Laikipia, Mandera, Meru, Nyandarua and West Pokot counties, no malaria vectors have ever been described. Although there has been a substantial number of vector surveys since 2005, the precise detection of sibling species using PCR has not been as prolific as previous vector sampling surveys. Among 502 sites where *An. gambiae* s.l have been reported since 2000, 105 (21%) have not used molecular techniques to define the sibling species. There are no definitions of *An. gambiae* sibling species in Garissa, Isiolo, Mombasa, Nyamira, Samburu, Uasin Gishu and Wajir. Where sibling species have been distinguished, *An. arabiensis* and *An. gambaie s.s.* appear to be sympatric in their distribution, however, there is evidence that *An. arabiensis* has, with time, begun to displace *An. gambaie* s.s. as the more dominant vector where both coincide. There have been few attempts to distinguish the s.s sibling species into M forms, S forms or *An. coluzzii.* Where records exist, the M form has been recorded in Kilifi and Kwale counties in the Coast region and Siaya and Kisumu counties in Nyanza. The S form has never been described in Kenya.

Figure 4.9 Location of mosquito sampling sites for 1,029 surveys undertaken between 1900 and 2014



An. merus has a distribution largely within a 25 km inland extent from the Kenyan coast and is an important secondary vector within its range. An. quadriannulatus has been identified in Kenya but is not a malaria vector. Molecular characterisation of the members of the An. funestsus complex in Kenya has only recently been possible (Kamau et al., 2002), therefore where An. funestus has been reported we have assumed these are predominantly An. funestus s.s. However, there have been multiple reports of An. rivulorum from the Funestus complex and are regarded as a potential vector for malaria in Kenya (Kamau et al., 2002; Kamau et al., 2003; Kawada et al., 2012). The presence of the An. gambiae complex and the An. funestus group are sympatric across the entire county, except in two counties namely Narok and Tharaka Nithi where An. funestus was not recorded. An. pharoensis has been described in all central, eastern Nyanza and Western regions in Kenya. Although an important vector in Egypt and Sudan, and previously thought to transmit malaria during the 1940s in Kenya (Garnham, 1945), the precise role of this vector in malaria transmission today in Kenya is poorly described. An. nili has been recorded in only a few locations scattered throughout the country, at 26 sites along the coast, the Taveta area, Thika, the Mwea Tebere Rice Irrigation Scheme, Kaimosi Forest in Vihiga county, and Trans Nzoia. The precise role of this vector in malaria transmission in Kenya is poorly described. An. coustani, has been implicated as a potential vector in Taveta (Mwangangi et al., 2013), although not unambiguously implicated in human infections and therefore not currently regarded as a secondary vector in Kenya (M Coetzee, personal communication). An. moucheti has only been described in Mwea rice irrigation scheme in Kirinyaga county (Muturi et al., 2008). It is not clear whether it plays any role in transmission of malaria in the area. An. hancocki has never been described in Kenya.

Figure 4.10 Distribution of dominant vector species in Kenya

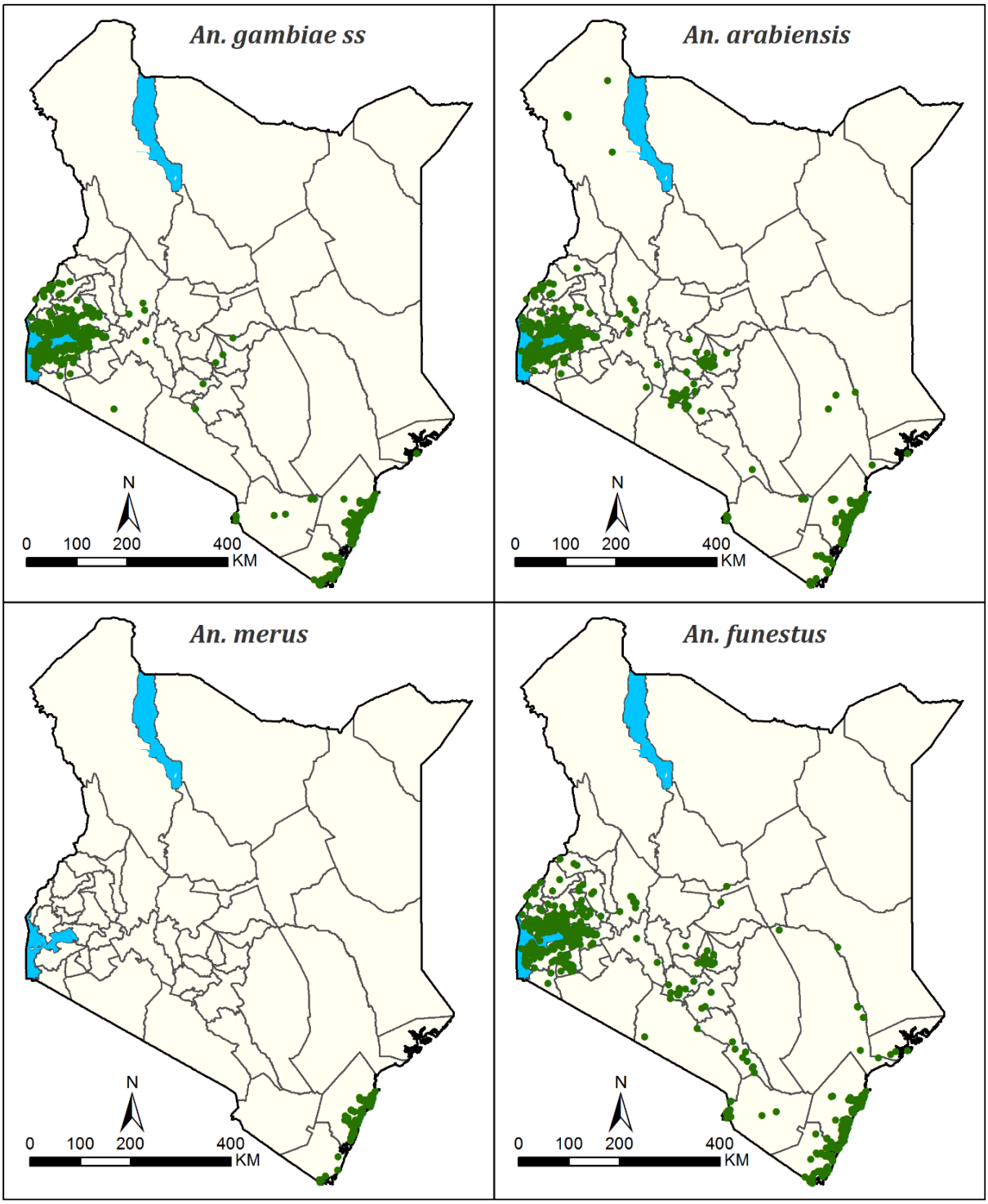
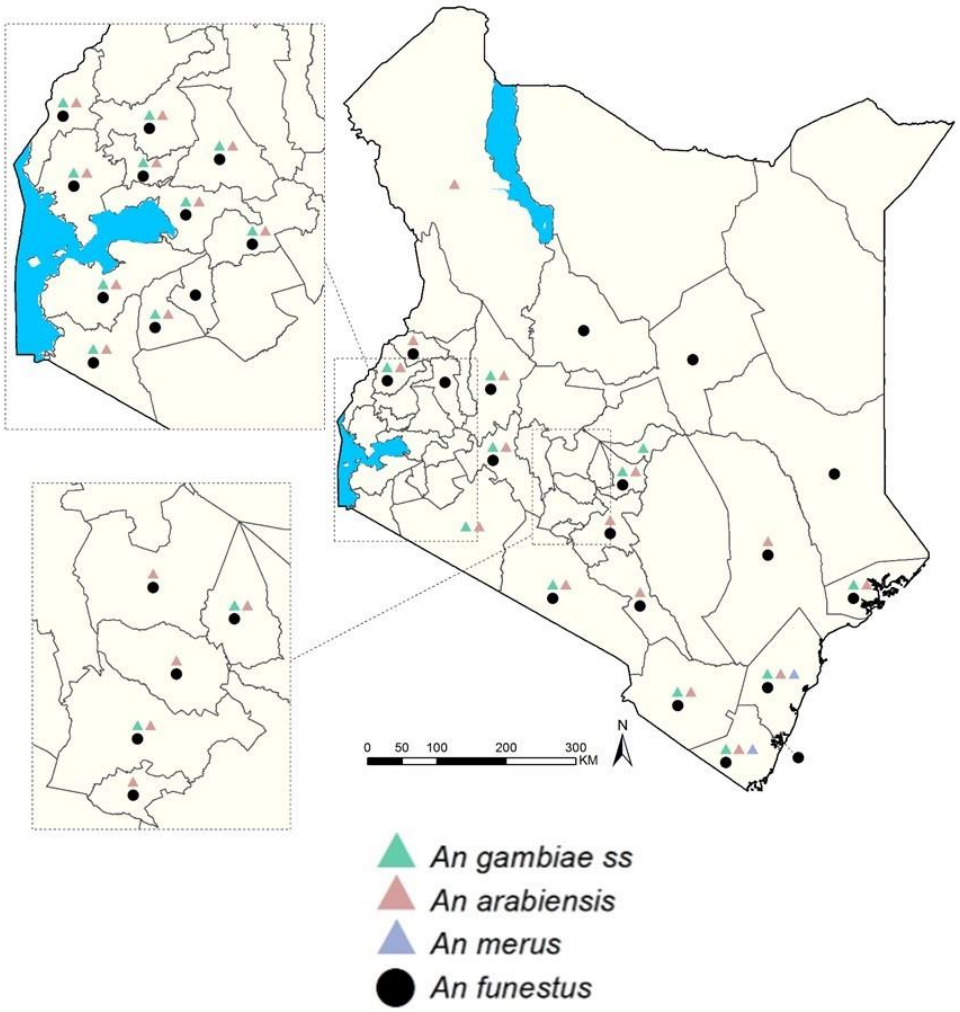


Figure 4.11 Recorded species identifications across all surveys by county



There are records of 41 other anopheline species in Kenya, either non-vectors or considered incidental vectors of malaria since 1900
An. ardensis, An. azaniae, An. christyi, An. cinereus, An. confusus, An. coustani, An. demeilloni, An. d'thali, An. flavicosta, An. garnhami, An. gibbinsi, An. harperi, An. implexus, An. keniensis, An. kingi, An. leesoni, An. longipalpis, An. macmahoni, An. maculipalpis, An. marshalli, An. mauritianus, An. multicinctus, An. natalensis, An. paludis, An. parensis, An. pitchfordi, An. pretoriensis, An. quadriannulatus, An. rabaiensis, An. rhodesiensis, An. rufipes, An. smithii, An. squamosus, An. swahilicus, An. symesi, An. tenebrosus, An. theileri, An. transvaalensis, An. vaneedeni, An. wilconi, An. ziemanni

Data in space and time related to vector resistance that have been carefully curated, validated and mapped by the IRBase initiative (IRBase; Knox et al., 2014) but were not assembled for this report although their availability is described in Chapter 3. However, it should be noted that resistance to pyrethroids and other classes of insecticides has now been recorded in almost all high burden counties (see Section 3).

5. Mapping of vector control interventions

5.1 Scale-up of vector control in Kenya

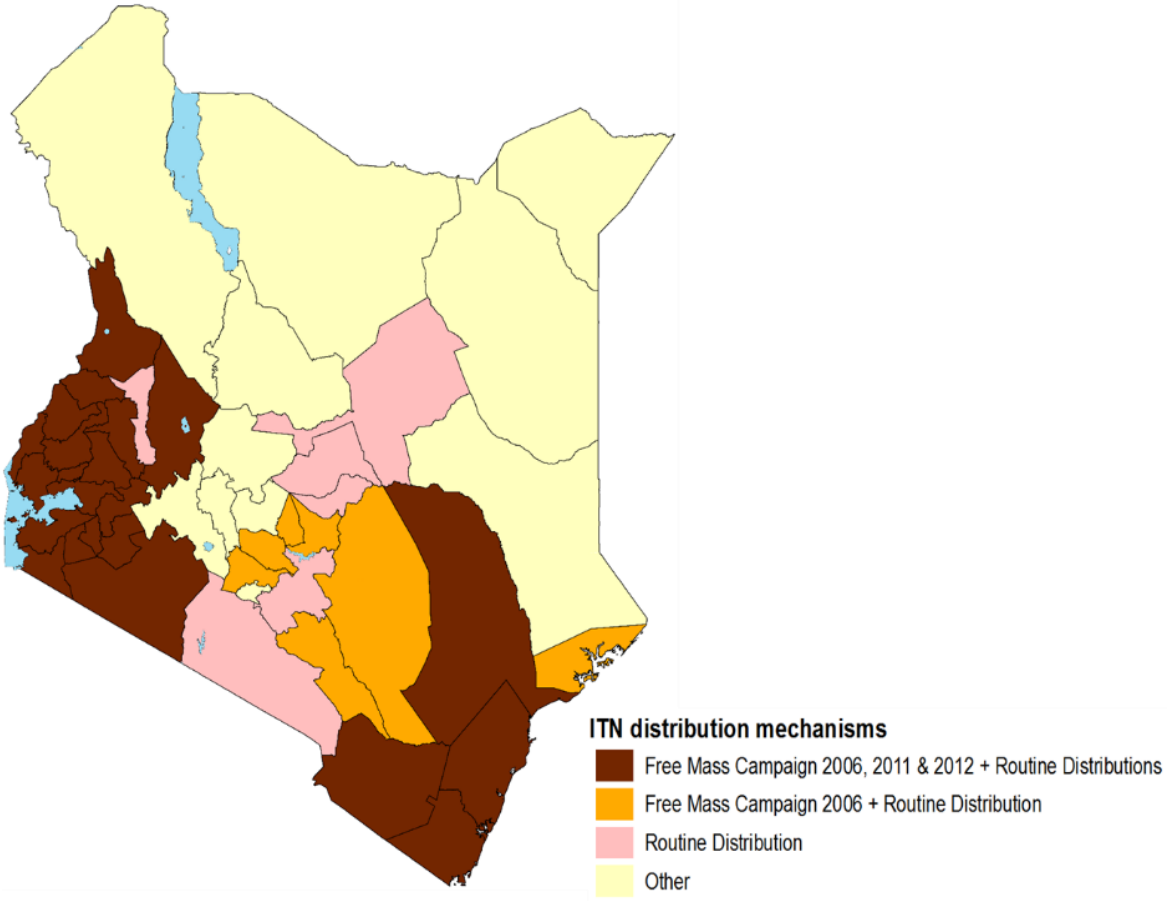
In 2000 the Ministry of Health (MoH) and partners developed an ITN strategy paper in which various approaches to scale-up ITNs were outlined to reach a target of 60% coverage of populations at risk by 2005 (MoH, 2001). Since then, several mechanisms for ITN distribution to populations at risk have been implemented. These include: commercial distribution; social-marketing; routine subsidised and free distribution; and free mass distribution campaigns (Noor et al., 2007; Noor et al., 2010; Snow et al.,2010).

At the beginning of this period, ITNs were accessed mainly from the private-for-profit retail sector, while a few were distributed by research projects or NGOs (Shretta, 1999; Snow et al., 2010). This was followed by various attempts to socially market retail sector nets or heavily subsidised nets through clinics run by the government that met with only limited success in reaching the rural poor and ensuring maximal coverage of at risk populations (Noor et al., 2007: DOMC and MPHEG, 2007; Snow et al., 2009). However, a free mass-campaign was launched in 2006 using USD 17 million from the GFATM Round II funding to distribute 3.4 million nets free-of charge to children under the age of five years within two weeks in July and two weeks in September 2006 (Noor et al., 2007; 2010; Snow et al., 2009). Soon after, a study evaluating which of the delivery mechanisms was most effective in terms of increased coverage and equity in communities from four districts of different malaria ecologies was published (Noor et al., 2007). This study showed that free mass campaign was the most effective and equitable mechanism. A parallel study in the same communities also showed a significant impact of the nets in averting malaria mortality (Fegan et al., 2007). Using this evidence, the WHO consequently revised its ITN guidelines recommending the free distribution of nets to vulnerable individuals of all ages (WHO, 2008).

Following this recommendation, PSI replaced its highly subsidised routine distribution targeting mothers of children and pregnant women for LLIN (Permanet®) to providing the nets free of charge using a grant of close to USD 50 million funding from DFID with supplementation from the GFATM (Snow et al., 2009). In 2008 a national campaign to re-treat untreated nets with *K O-TAB 1-2-3*, and replace torn or damaged nets was undertaken in 55 districts with funding support from DFID, WHO-Kenya and USAID and some support from GFATM Round II (Snow et al., 2009). A total of 1.93 million nets were re-treated and 207,290 torn nets were replaced (DOMC, 2008).

Between 2008 and the end of 2011, routine distribution of LLINs was provided through ANC and MCH clinics in priority districts. In 2011, mass "catch-up" campaigns were re-launched starting in Nyanza and Western. In December 2012, mass free LLIN distributions in target areas in Nyanza, Western, Coast provinces and the epidemic prone districts in Rift Valley province (Trans Nzoia, Bomet, Kericho, Nandi, Uasin Gishu, West Pokot, Transmara and Loima) were completed. LLIN distribution catch-up campaigns, began again in September 2014 in Migori, Homa Bay, Kisumu, Siaya, Vihiga and West Pokot. In June 2015, mass LLIN distribution in Uasin Gishu, Nandi, Kericho, Narok and Bomet; in September 2015 nets in Trans-Nzoia, Mombasa, Lamu, Tana River, Taita Taveta, Kilifi, and Kwale; and in December 2015 in Kakamega, Kisii, Nyamira, Bungoma, and Busia counties. The mechanisms of ITN distribution used in each county since 2004 are illustrated in Figure 5.1.

Figure 5.1 Map of counties showing the dominant mechanisms for ITN distribution. Routine distributions have been implemented in 41 counties since 2004-2015 and in 37 counties since 2009; free mass campaigns have occurred in 32 countries since 2006 and 25 counties since 2009.



5.2 Number of ITNs distributed in Kenya, 2004-2015

Over the period 2004 to 2015, approximately 50.2 million ITNs, of which almost 49 million were of the LLIN variety, were distributed in Kenya. The distribution was undertaken through a routine system that began in October 2004 (23.3 million nets) and the free mass campaigns in 2006, 2011-12 and 2014-15 (26.9 million nets). The free mass campaigns of 2006 targeted 32 of the current 47 counties. Following the development of an empirical malaria risk map (Noor et al., 2009), better targeting of the LLIN distributions (Figure 5.1) was implemented and subsequent campaigns were implemented in 25 counties. Between 2012 and 2015, more than 23.8 million nets were distributed in Kenya through the two main channels. More than 50 million ITNs, of which 49 million were of the LLIN variety, were distributed in Kenya from 2004 to 2015 (Figure 5.2). Among the highland epidemic, lake and coastal endemic zone that are targeted for universal coverage of LLIN, the fewest number of LLINs were distributed in Lamu and Tana River (Figure 5.3), although these counties also have relatively low population. Annual ITN distributions by sub-county in Kenya from 2004 to 2015 are presented in the maps shown in Figure 5.4.

Figure 5.2 Annual ITN distribution by mechanism and overall since 2004

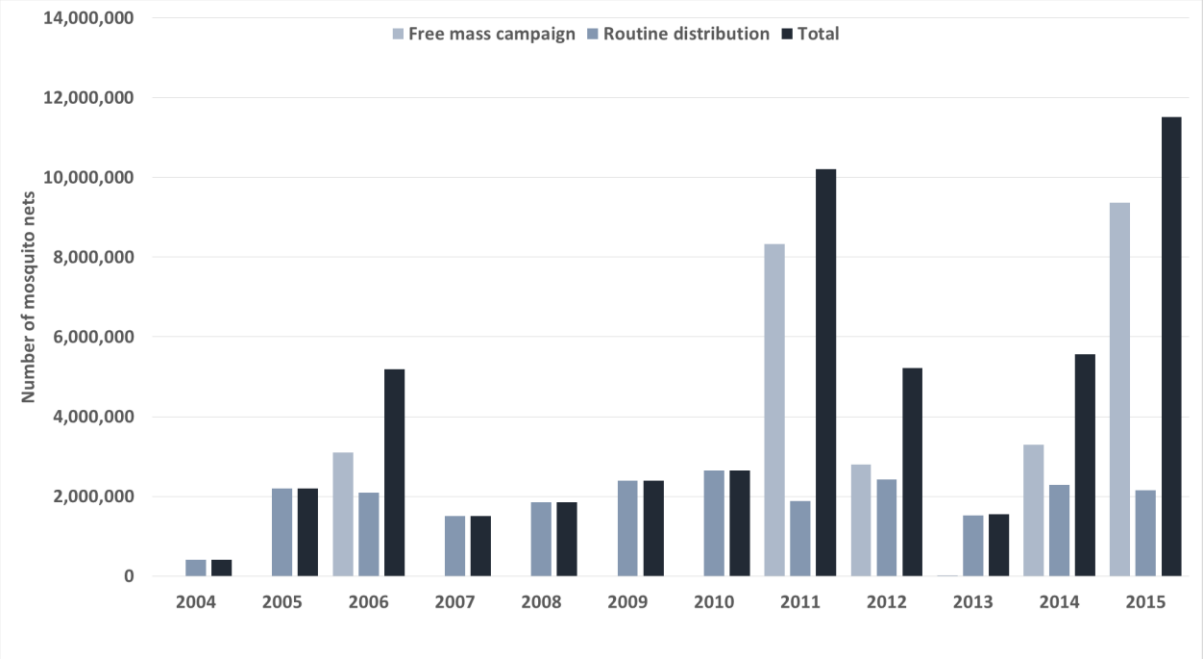


Figure 5.3 Total ITN distributions in Kenya by county grouped by malaria endemicity from 2004-2015.

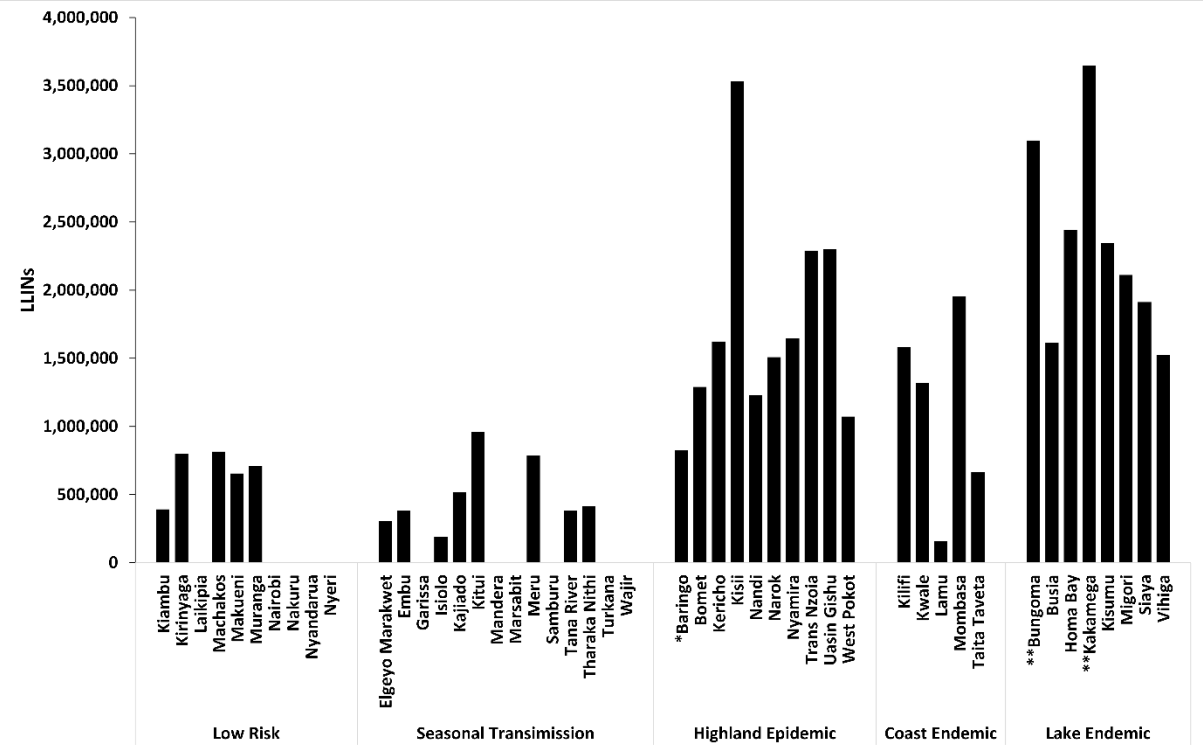
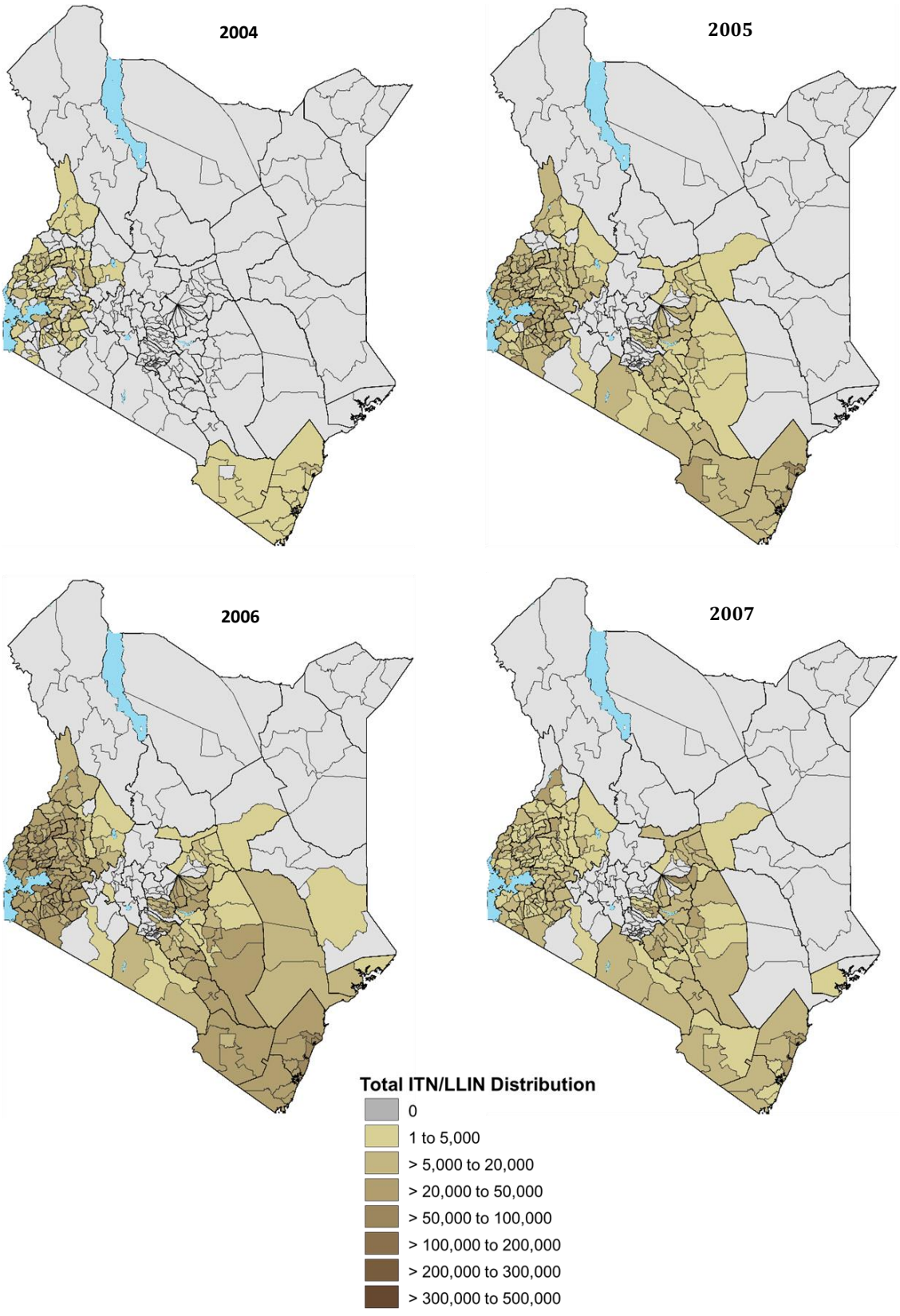
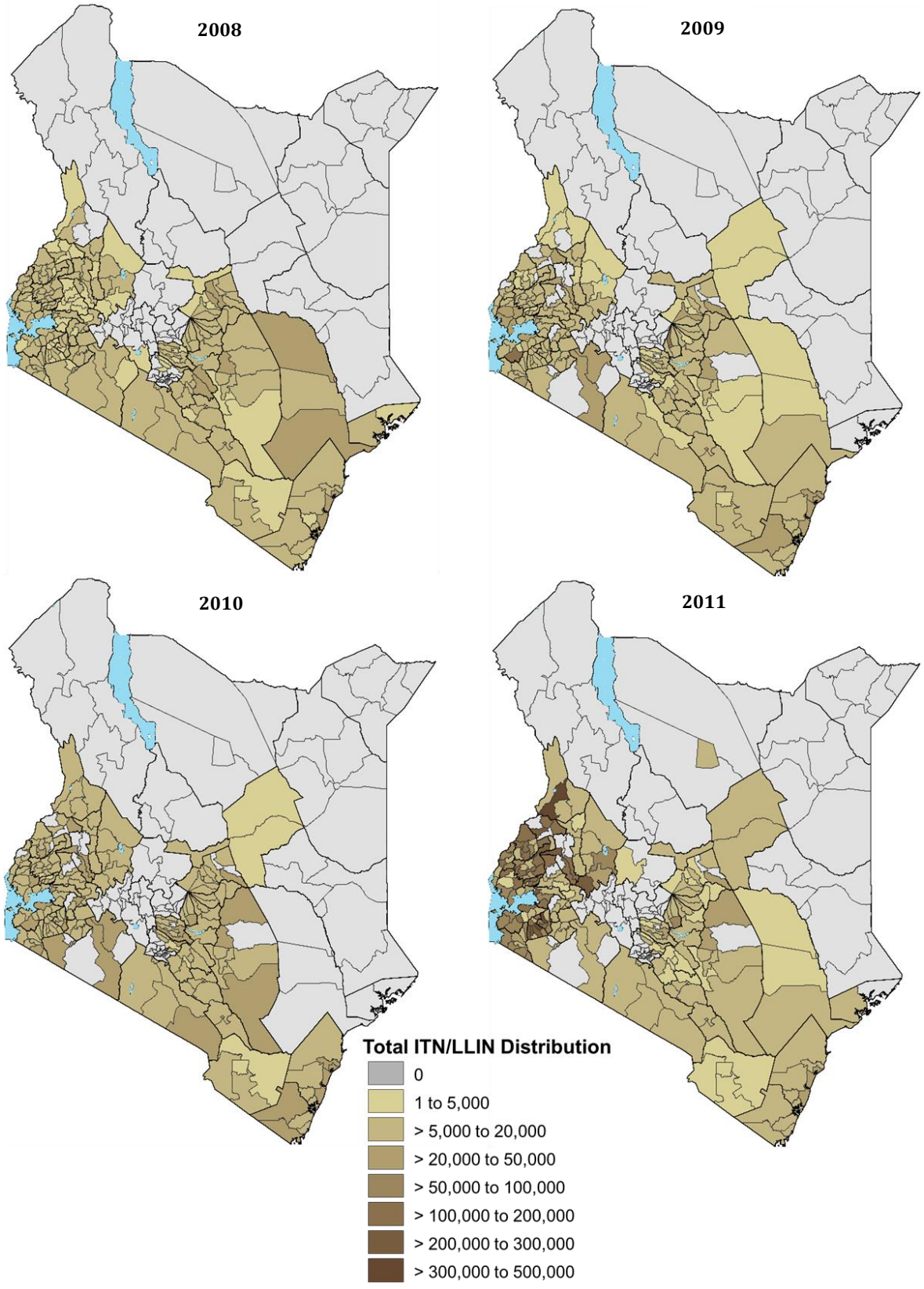
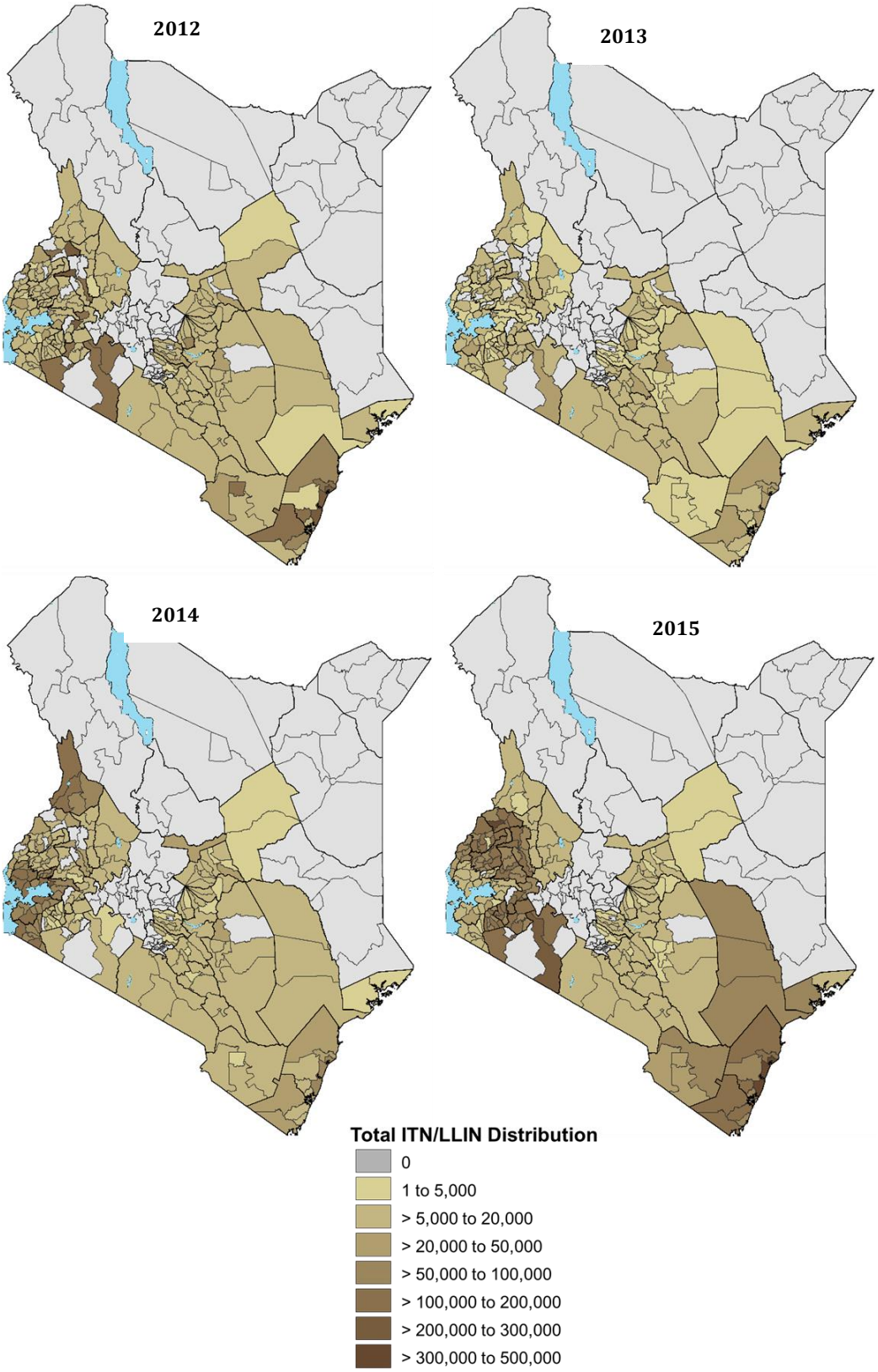


Figure 5.4 Annual ITN distribution by sub-county in Kenya from 2004-2015. Distribution of LLINs started in May 2005




2008
2009
2010
2011
Total ITN/LLIN Distribution
0
1 to 5,000
> 5,000 to 20,000
> 20,000 to 50,000
> 50,000 to 100,000
> 100,000 to 200,000
> 200,000 to 300,000
> 300,000 to 500,000


2012
2013
2014
2015
Total ITN/LLIN Distribution
0
1 to 5,000
> 5,000 to 20,000
> 20,000 to 50,000
> 50,000 to 100,000
> 100,000 to 200,000
> 200,000 to 300,000
> 300,000 to 500,000

5.3 Coverage and use of vector control in Kenya

Typically, intervention coverage and use indicators are obtained from national household surveys that are designed to be precise at national and regional levels and rarely at lower levels, such as counties. In Kenya, there have been several national household surveys designed to capture indicators of malaria intervention and/or prevalence. For this study, data from six national surveys implemented from 2003-2015 (Table 5.1) was used. Excluded were data from the household budget surveys of 2005-6 and the Financial Strength Deepening survey of 2010 (Noor et al., 2012) because they had only a limited set of ITN use indicators. The PSI TRaC surveys of 2005, 2007 and 2014 were also not used as these were focused on specific implementation districts. The DHS 2014-15, was the first survey in Kenya specially designed to be representative by county for a number of key indicators, and allowed for sub-county modelled estimation of intervention coverage.

Sub-national modelling of intervention data was undertaken using spatial and spatial-temporal small area estimation (SAE) methods that handle the problem of making reliable estimates of a variable at preferred areal units under conditions where the information available for the variable, on its own, is not sufficient to make valid estimates, primarily because of sampling inadequacies (Rao et al., 2003; BIAS, 2007). The geocoded national household survey data (Figure 5.5) was used to model national intervention indicators at county level for all six household surveys and by sub-county using the combined DHS 2014-2015 and MIS 2015 data. The indicators that have been estimated included: household ownership of at least one ITN; universal coverage of ITNs; and utilisation of ITNs by the general population and among pregnant women. In addition, access to IPTp and first-line recommended treatment were analysed and are presented in Sections 6 and 7 respectively.

Table 5.1 Summary of survey data used for the analysis of intervention indicators

	DHS 2003	MIS 2007	DHS 2008-9	MIS 2010	DHS 2014-15	MIS 2015
Sampling domain	8 provinces	8 provinces	8 provinces	8 provinces	47 counties	8 provinces
Number of counties	46	42	47	47	47	47
Number of clusters	399	200	397	240	1,594	245
Number of households	8,543	6,818	9,033	6,308	36,430	6,481
Number of persons interviewed for ITN use	37,504	30,049	38,384	27,321	153,840	25,430
Number of pregnant women interviewed for ITN use	645	524	629	409	2,113	369

To analyse intervention coverage data, hierarchical Bayesian spatial and temporal SAE techniques using a geo-additive regression approach was used (Banerjee et al., 2004; Best et al., 2005). This method uses survey data from a county/sub-county and neighborhood information from adjacent counties/sub-counties to smooth values at the county/sub-county. For ITN utilisation, data was analysed by all ages to measure universal coverage which is the intervention metric necessary when computing likely impacts on malaria transmission (Smith et al., 2009; Griffin et al., 2010). See Appendix C for details of the SAE methods.

5.3.1 Coverage and use of insecticide treated nets (ITNs)

Figure 5.5 Percentage of households with at least one ITN by county and survey year. For 2015, the data from the DHS 2014-15 and MIS 2015 were combined to produce both county and sub-county estimates.

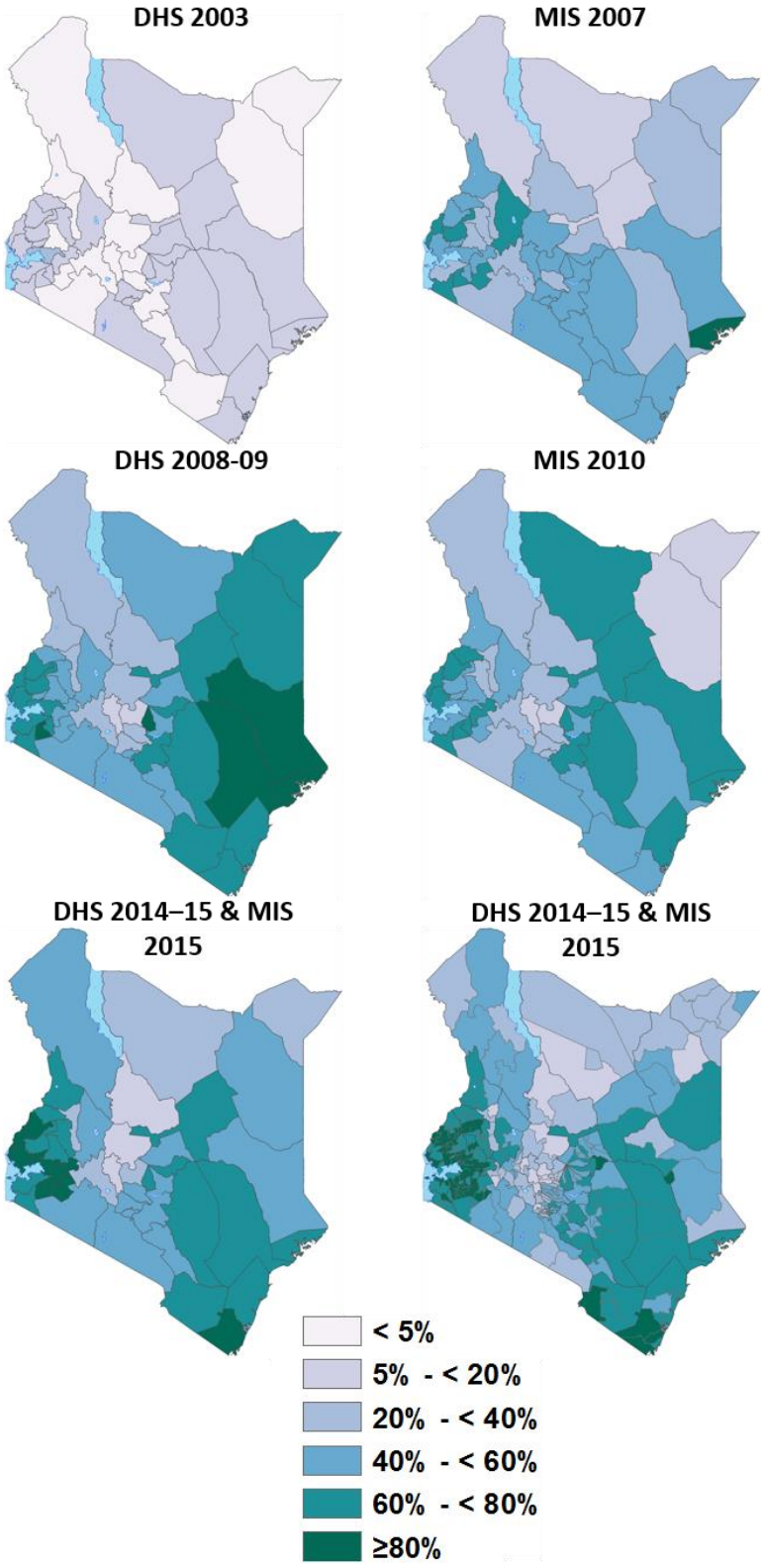
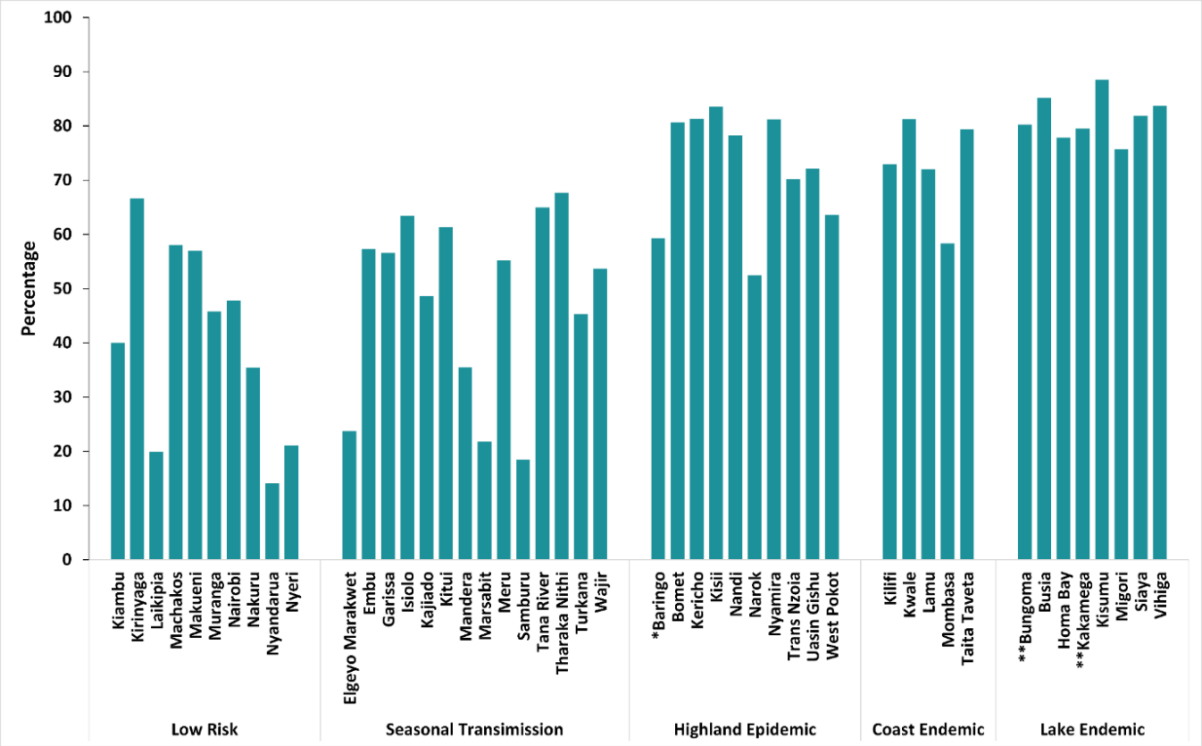


Figure 5.6 Percentage of households with at least one ITN by county and malaria endemicity in 2015. Estimated ITN ownership for 2015 was computed using the combined DHS 2014-15 and MIS 2015.



*County is predominantly in the highland epidemic zone with few parts experiencing seasonal transmission. **County is predominantly in the lake endemic zone with few parts in the highland epidemic zone.

Figure 5.7 Percentage of households with universal ITN coverage (≤ 2 persons per ITN) by county and survey year. For 2015, the data from the DHS 2014-15 and MIS 2015 were combined to produce both county and sub-county estimates.

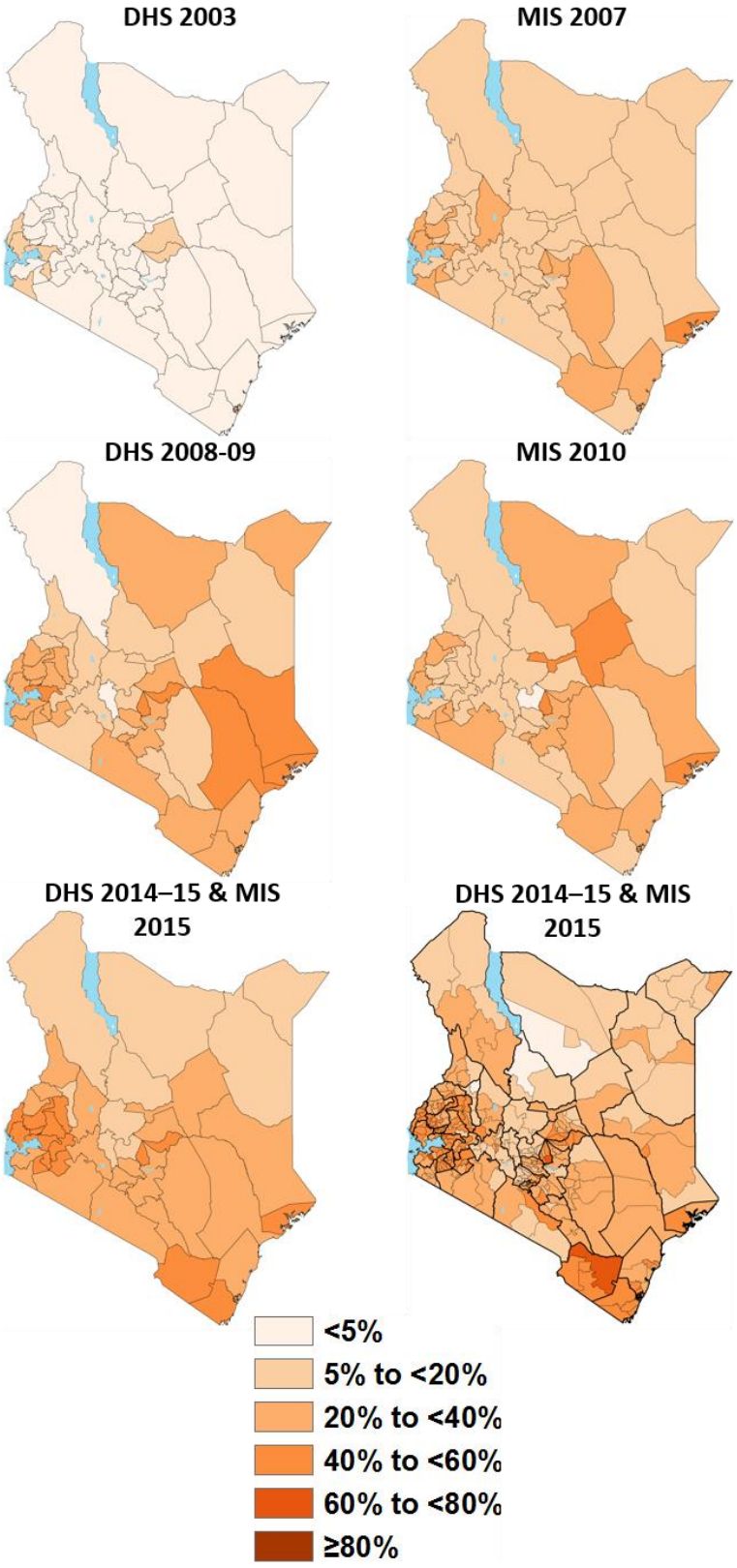
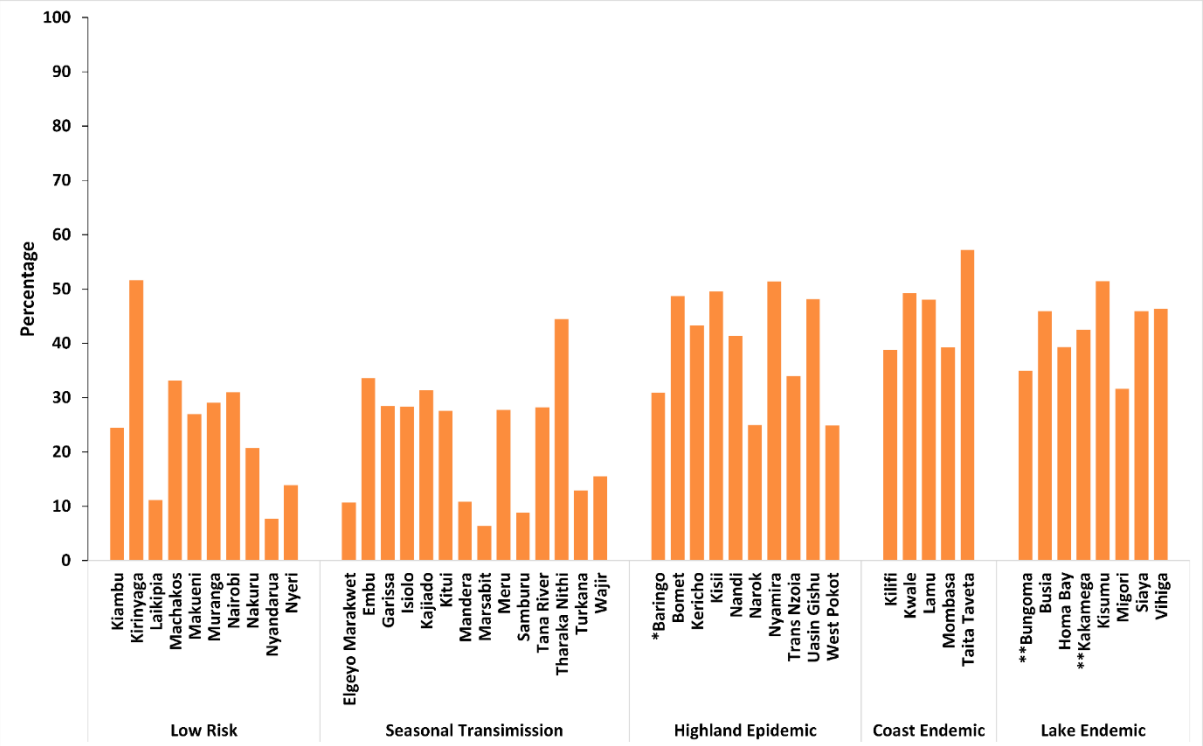


Figure 5.8 Percentage of households with universal ITN coverage (≤ 2 persons per ITN) by county and malaria endemicity in 2015. Estimated ITN ownership for 2015 was computed using the combined DHS 2014-15 and MIS 2015.



*County is predominantly in the highland epidemic zone with few parts experiencing seasonal transmission. **County is predominantly in the lake endemic zone with few parts in the highland epidemic zone.

Figure 5.9 Percentage of household population sleeping under ITN the night before survey by county and survey year. For 2015, the data from the DHS 2014-15 and MIS 2015 were combined to produce both county and sub-county estimates.

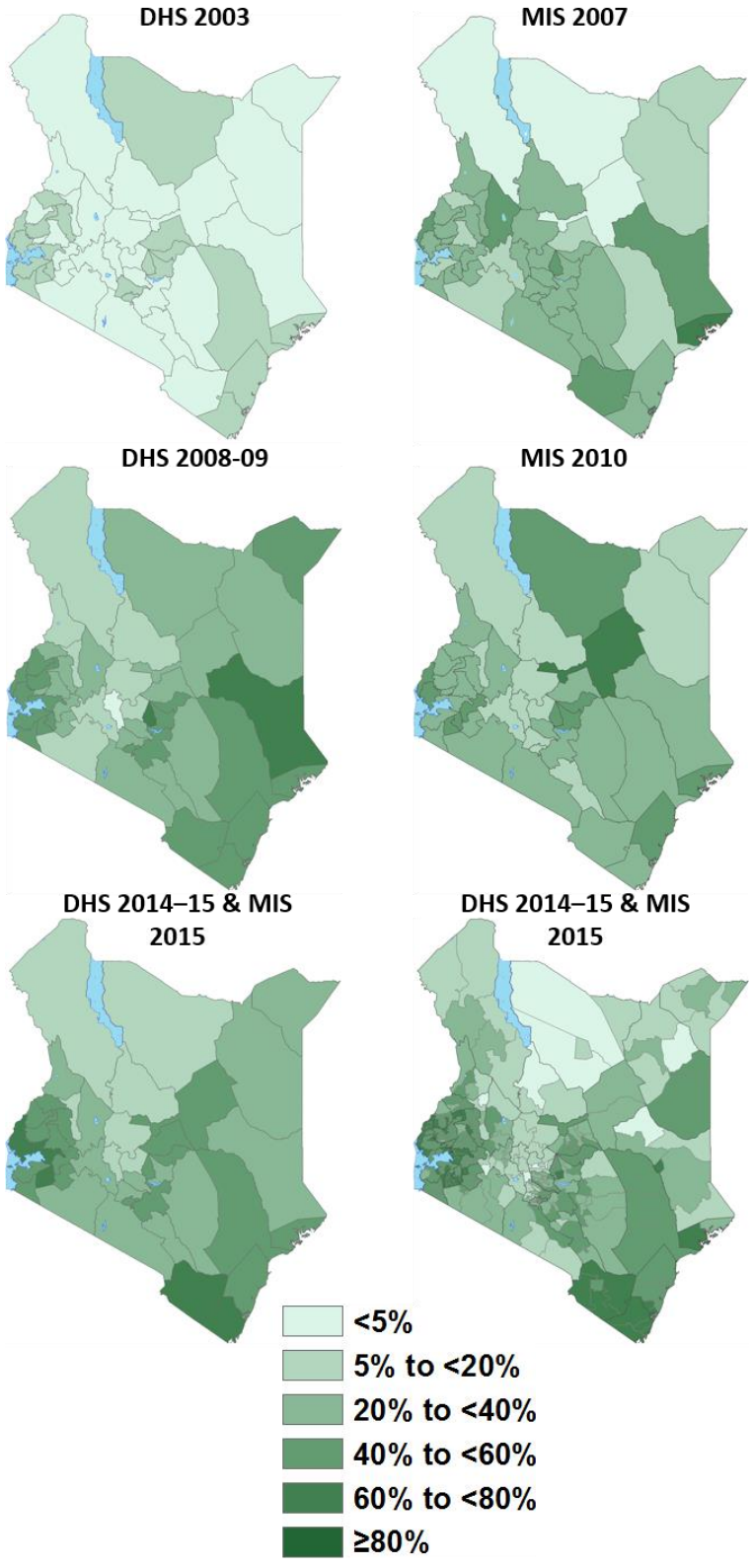
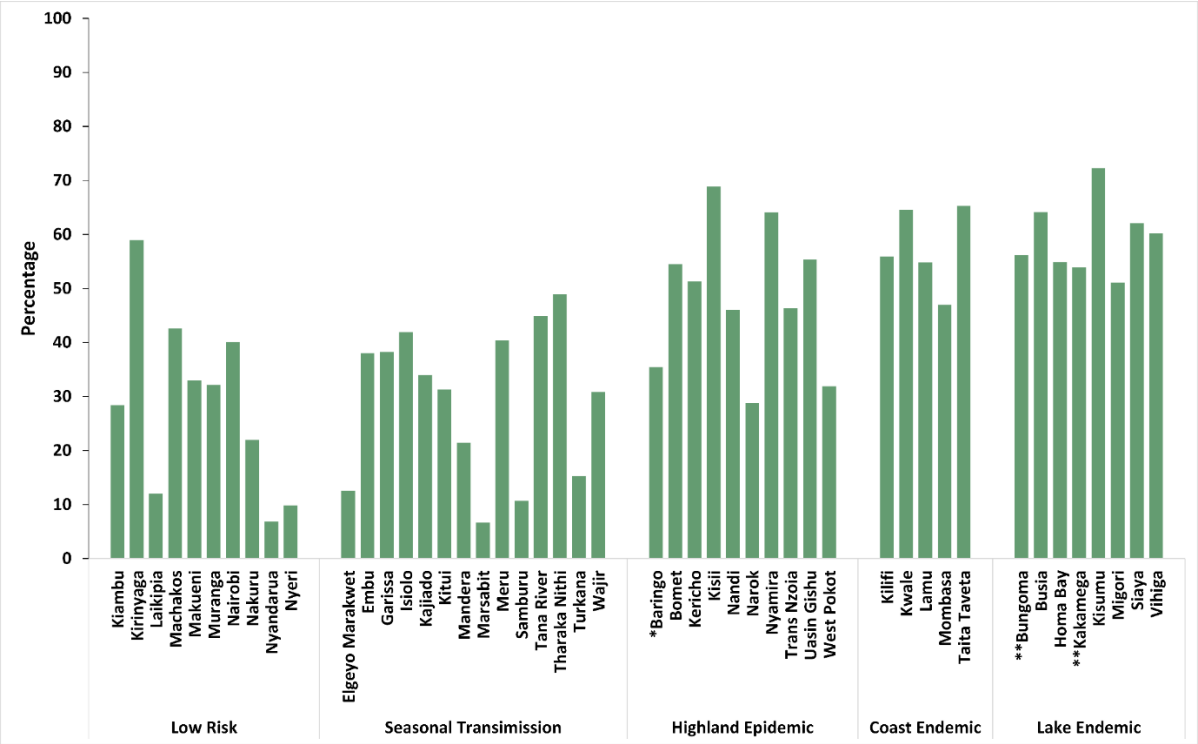


Figure 5.10 Percentage of household population sleeping under ITN the night before survey by county and malaria endemicity in 2015. Estimated ITN ownership for 2015 was computed using the combined DHS 2014-15 and MIS 2015.



*County is predominantly in the highland epidemic zone with few parts experiencing seasonal transmission. **County is predominantly in the lake endemic zone with few parts in the highland epidemic zone.

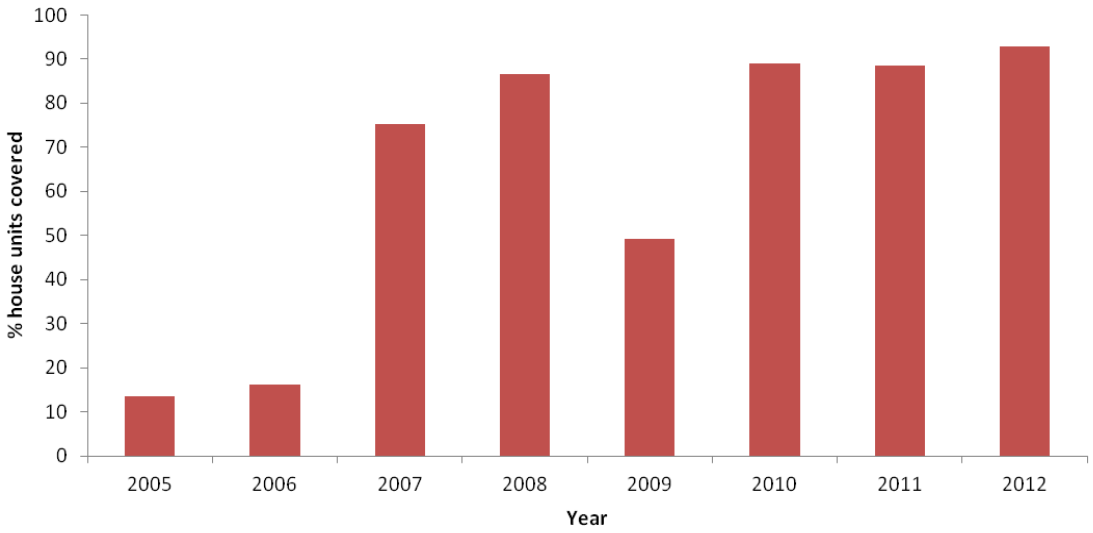
5.3.2 Coverage of indoor residual spraying (IRS)

Since the launch of the KNMS (2001–2010) the DOMC has focused IRS efforts in 12 "epidemic prone" counties and three endemic counties (Figure 5.11). The target was to annually spray 80% of households in these districts using lambda-cyhalothrin (ICON®) six to eight weeks before the onset of the heavy rains, usually May-August. Indoor residual house spraying was previously seen as an epidemic response measure following appropriate signals from an early warning system. Since 2007 a more systematic annualised approach has been taken as an epidemic prevention activity rather than an epidemic response measure.

In the three counties of Homa Bay, Migori and part of Kisumu where malaria transmission has been perennial, complete coverage with IRS began in 2010 (in Kisumu only Nyando district was targeted) as a pilot scheme to see if its combination with LLIN will bring down transmission rapidly. In the other 12 counties, IRS is targeted only at potential hotspots determined through weekly surveillance. There have been no IRS activities since 2013 according to WHO guidance on insecticide resistance management following the detection of high resistance to pyrethroids.

Figure 5.11 Counties where indoor residual spraying (IRS) was targeted in Kenya since 2005

Figure 5.12 Percentage of targeted housing structures covered in targeted areas during IRS implementation from 2005 to 2012



6. Prevention of malaria in pregnancy

Figure 6.1 Percentage of currently pregnant women who slept under an ITN the night prior to survey by county and survey year. Sample sizes were too small to analyse data by county using the MIS 2003. Reliable sub-county estimates were not possible for all surveys due to few observations at this level. Estimates related to pregnant women from household surveys are normally associated with a higher margin of error sub-nationally due to the small denominator of pregnant women.

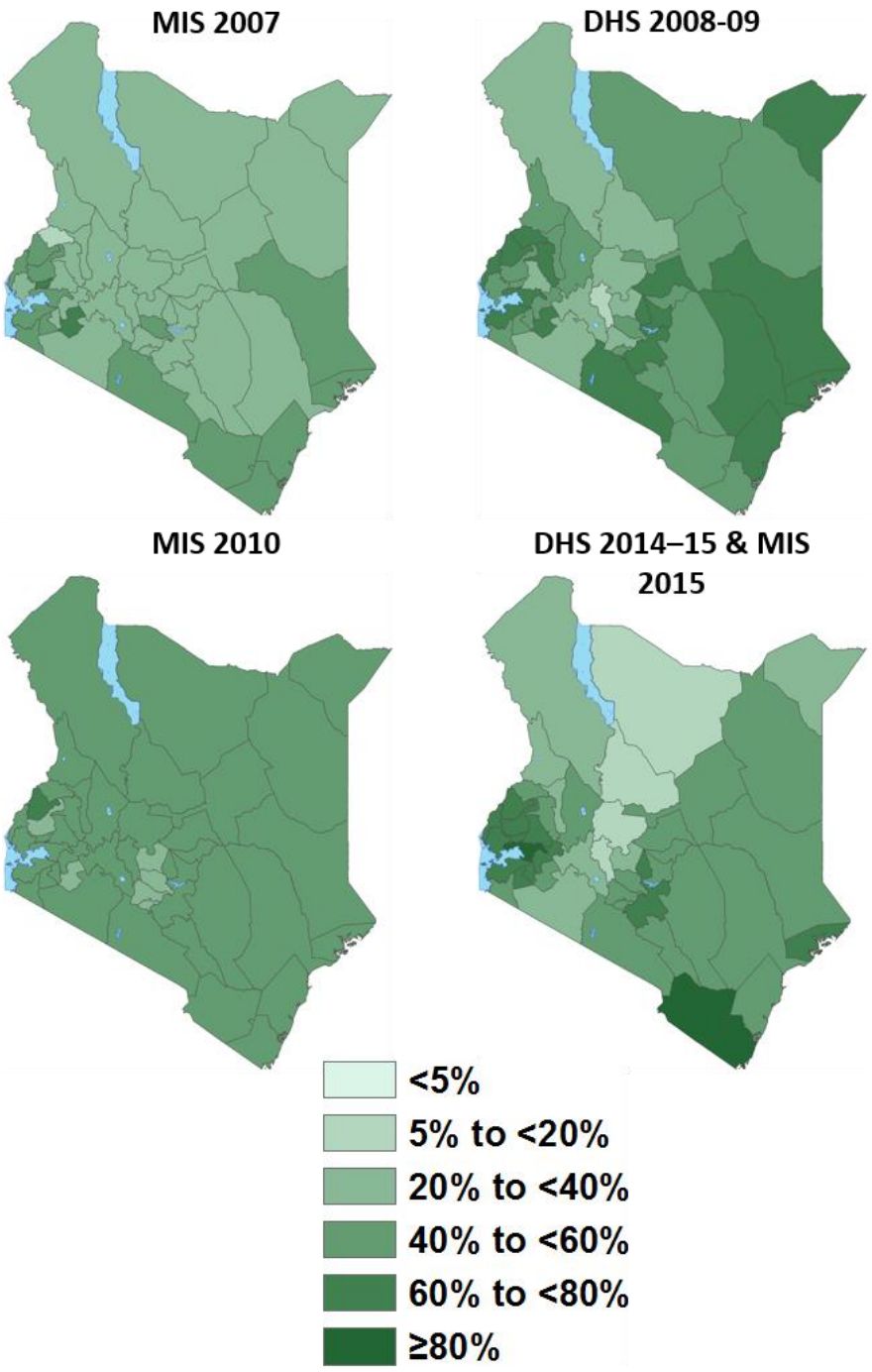
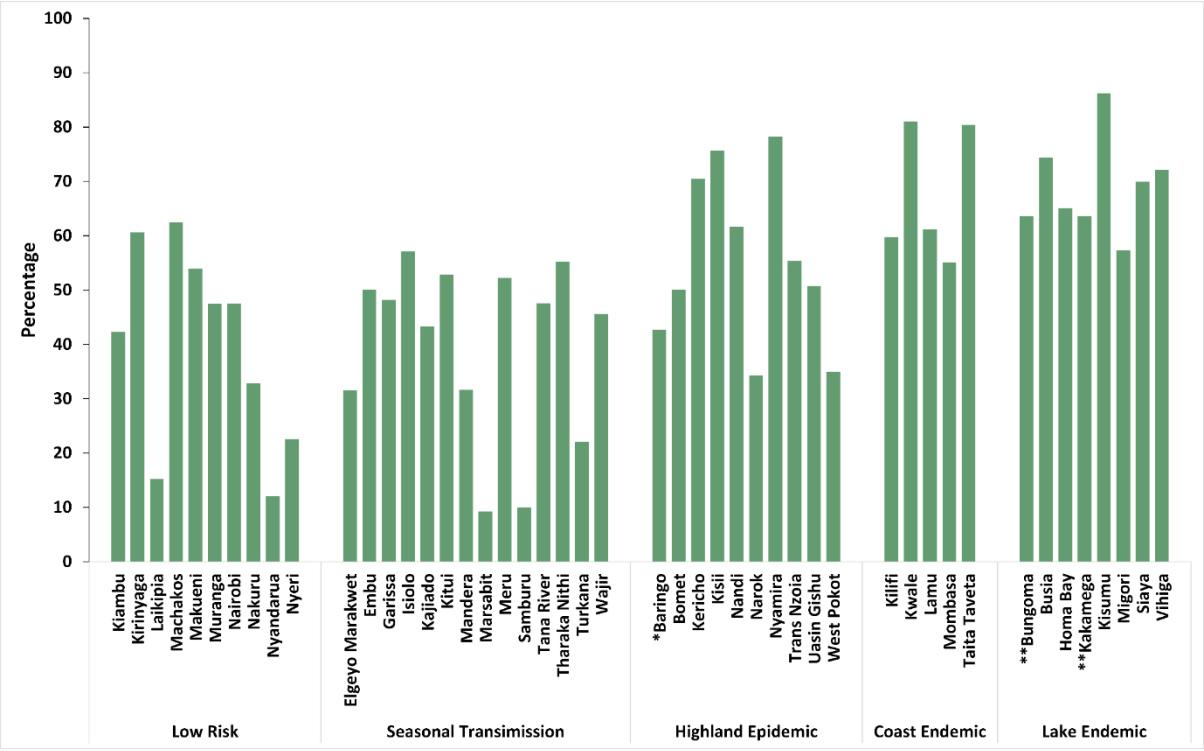


Figure 6.2 Percentage of currently pregnant women who slept under an ITN the night prior to survey by county in 2015. Estimated ITN use among pregnant women for 2015 was computed using the combined DHS 2014-2015 and MIS 2015. Reliable sub-county estimates were not possible for all surveys due to few observations at this level. Estimates related to pregnant women from household surveys are normally associated with higher margin of errors sub-nationally due to the small denominator of pregnant women.



*County is predominantly in the highland epidemic zone with few parts experiencing seasonal transmission. **County is predominantly in the lake endemic zone with few parts in the highland epidemic zone.

Figure 6.3 Percentage of women who received at least two doses of IPTp during a pregnancy within the last two years. Sample sizes were too small to analyse data by county using the MIS 2003. Reliable sub-county estimates were not possible for all the survey due to few observations at this level. Estimates related to pregnant women from household surveys are normally associated with higher margin of errors sub-nationally due to the small denominator of pregnant women.

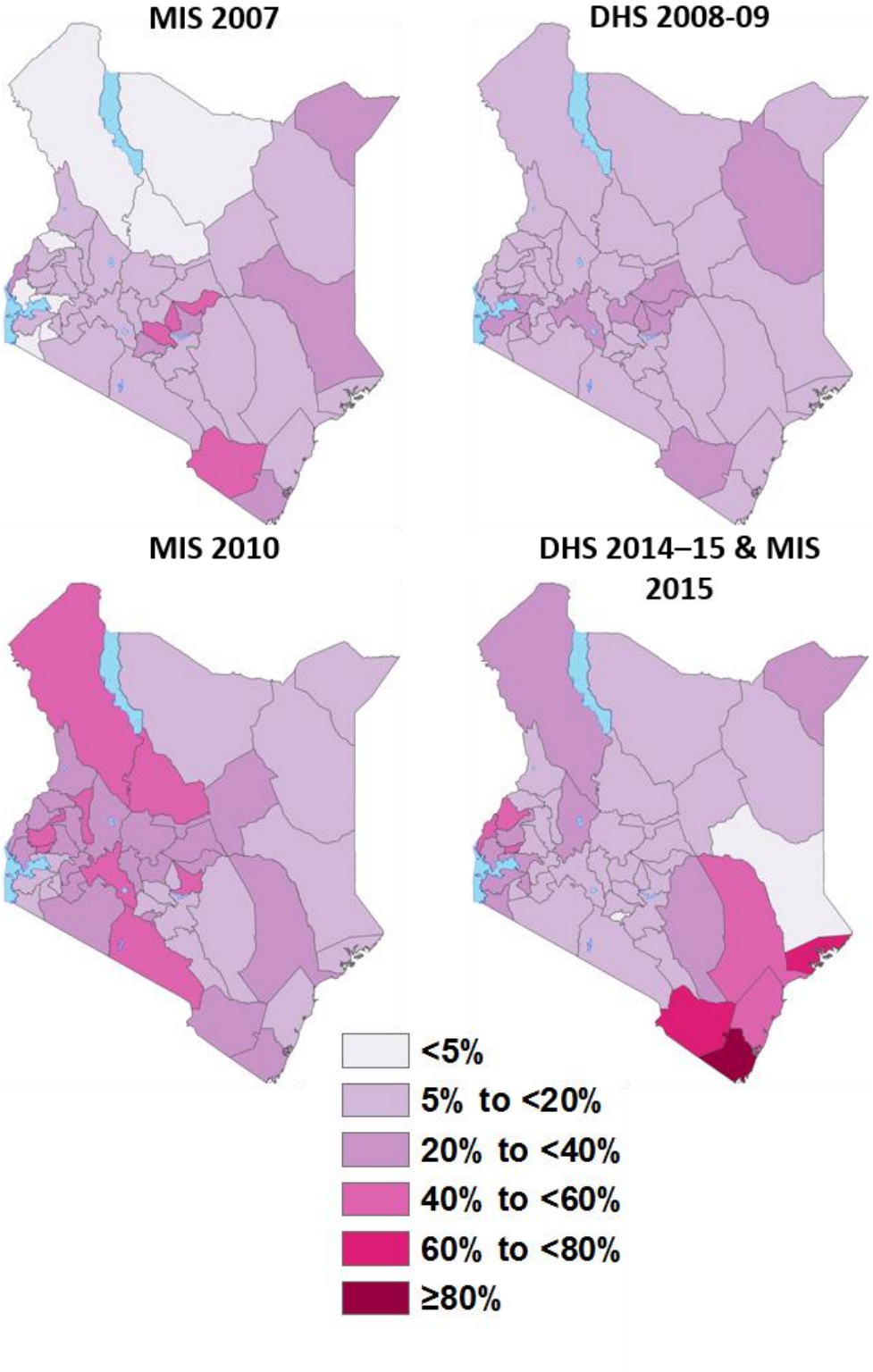
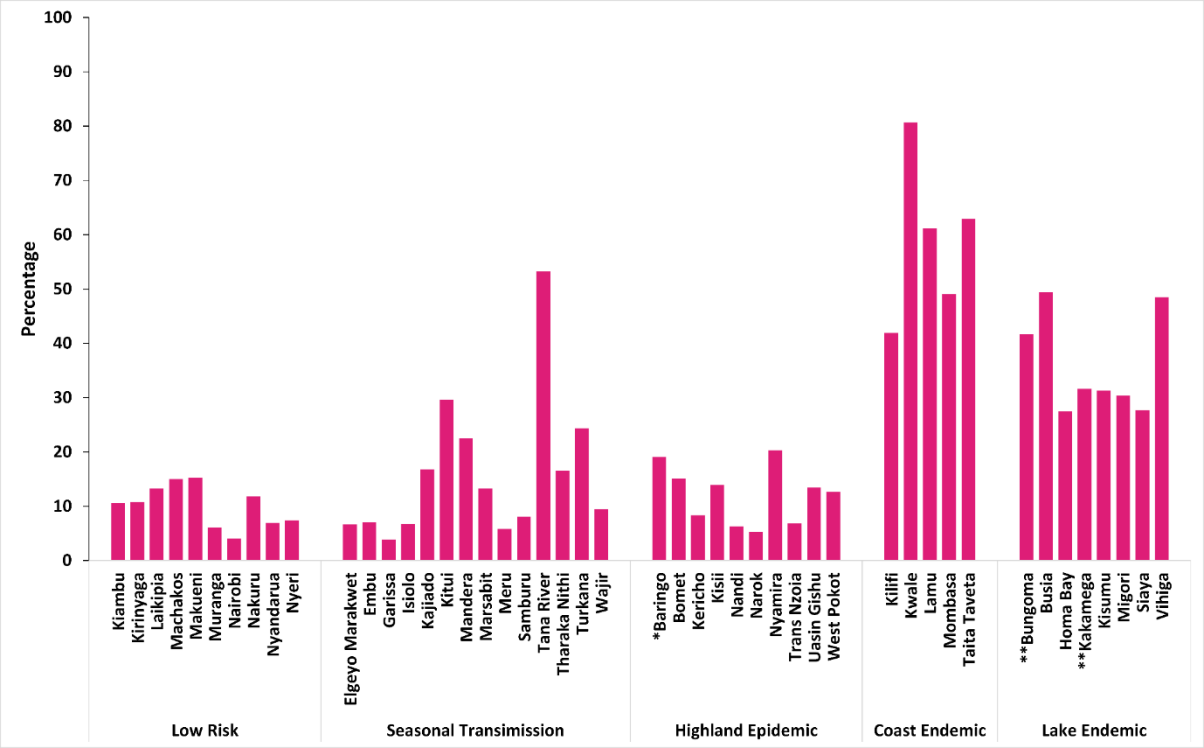


Figure 6.4 Percentage of women who received at least two doses of IPTp during a pregnancy within the last two years. Estimated IPTp use among pregnant women for 2015 was computed using the combined DHS 2014-15 and MIS 2015. Reliable sub-county estimates were not possible for all surveys due to few observations at this level. Estimates related to pregnant women from household surveys are normally associated with a higher margin of error sub-nationally due to the small denominator of pregnant women.



*County is predominantly in the highland epidemic zone with few parts experiencing seasonal transmission. **County is predominantly in the lake endemic zone with few parts in the highland epidemic zone.

7. Malaria case management

Following a massive therapeutic failure of chloroquine, SP was adopted as the first-line malaria treatment in 1998. By 2003, SP had also completely failed. In 2004, artemether lumefantrine (AL) was approved as the replacement for SP. The scale-up of AL however, only began in July 2006 (Amin et al., 2007). By 2012, RDTs were rolled out nationally and in 2013, the counties began taking over the responsibility for provision of primary health care.

Figure 7.1 Percentage of children under age five years with fever in the two weeks prior to survey who sought treatment at an appropriate source (public and private health facilities, pharmacies and drug stores) by county and survey year. For 2015, the data from the DHS 2014-15 and MIS 2015 were combined to produce both county and sub-county estimates.

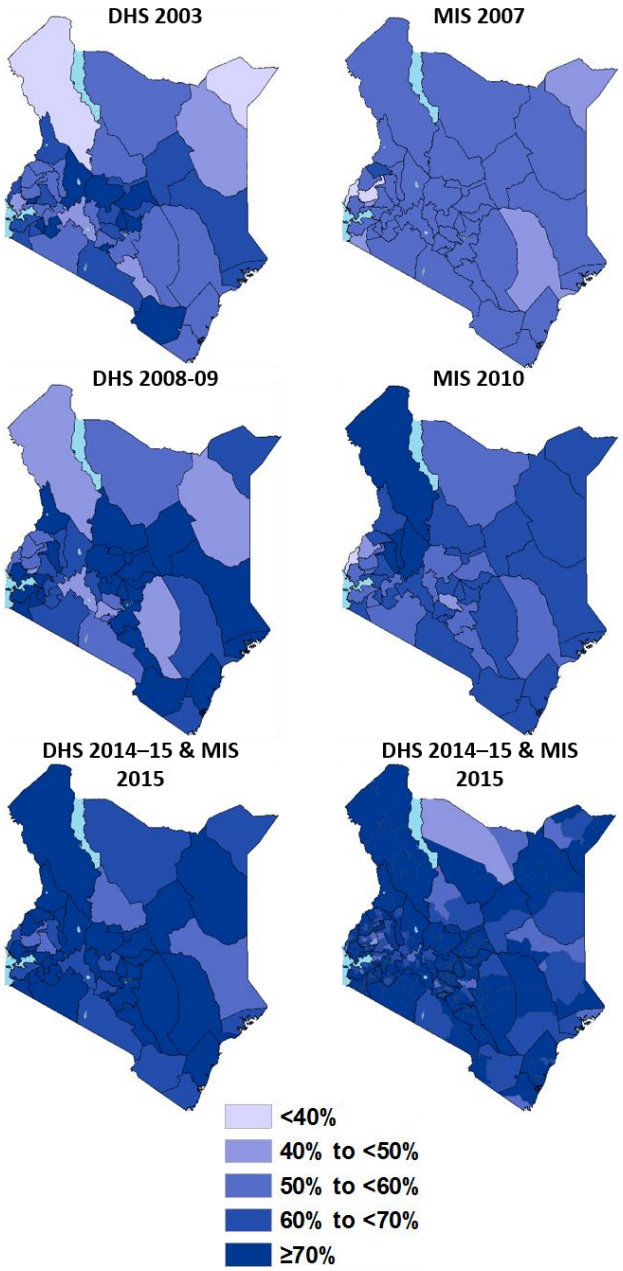
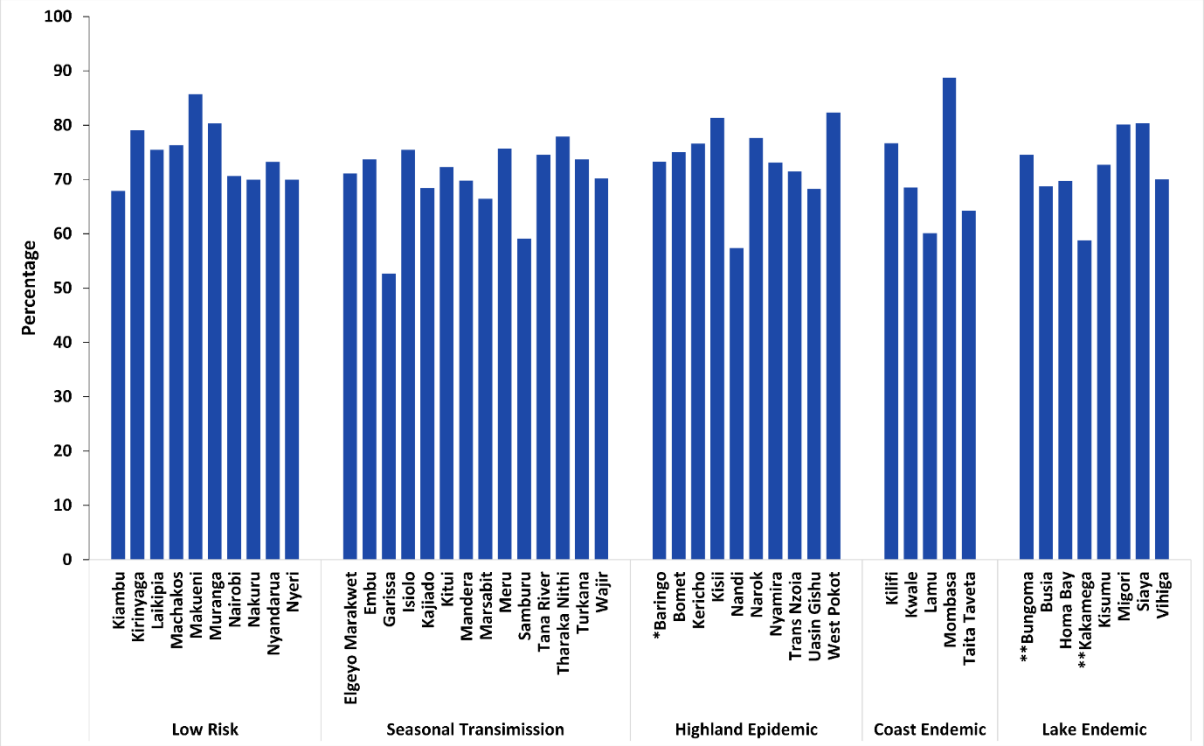


Figure 7.2 Percentage of children under age five years with fever in the two weeks prior to survey who were treated at an appropriate source (public and private health facilities, pharmacies and drug stores) in 2015 by county grouped according to malaria endemicity. The data from the DHS 2014-15 and MIS 2015 were combined to produce these estimates.



*County is predominantly in the highland epidemic zone with few parts experiencing seasonal transmission. **County is predominantly in the lake endemic zone with few parts in the highland epidemic zone.

Figure 7.3 Percentage of fevers among children age under five years treated with the recommended first line antimalarial drug among those treated for malaria by county and survey year. For 2015, the data from the DHS 2014-15 and MIS 2015 were combined to produce both county and sub-county estimates.

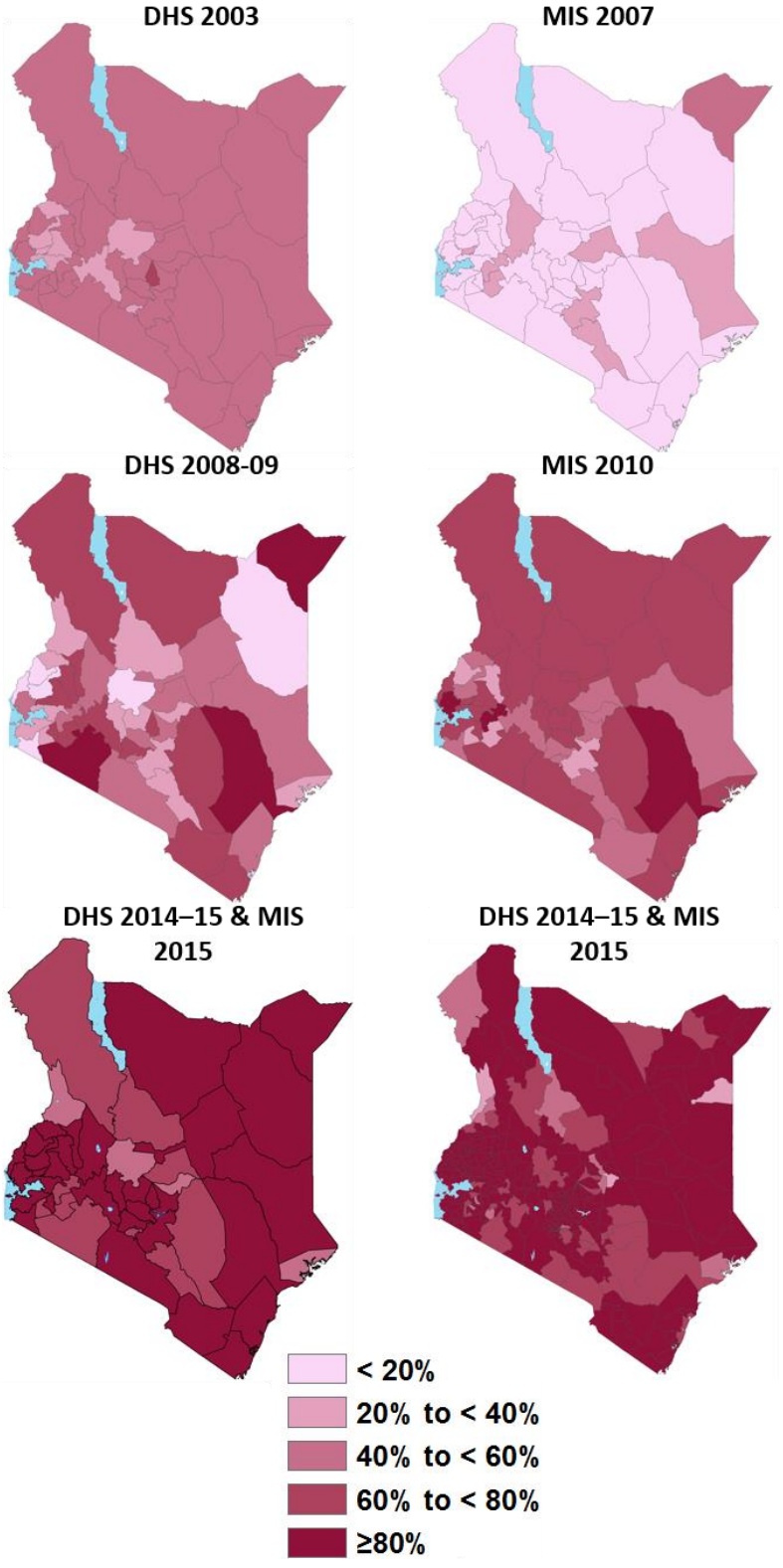
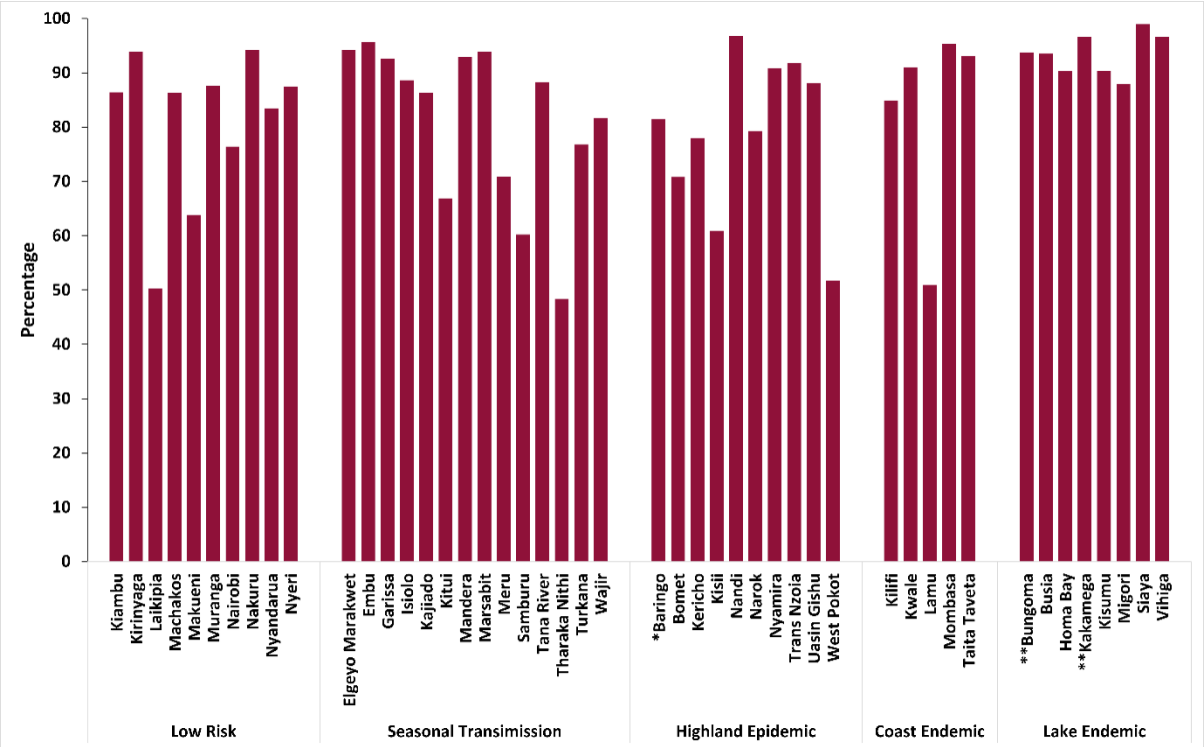


Figure 7.4 Percentage of fevers among children under the age of five years treated with the recommended first line antimalarial drug among those treated for malaria in 2015 by county grouped according to malaria endemicity. The data from the DHS 2014-15 and MIS 2015 were combined to produce these estimates.



*County is predominantly in the highland epidemic zone with few parts experiencing seasonal transmission. **County is predominantly in the lake endemic zone with few parts in the highland epidemic zone.

8. Key findings

8.1 Changing *P. falciparum* parasite prevalence

From a 2000 baseline, the estimated *P. falciparum* malaria infection prevalence in children aged two to below 10 years of age (*Pf*PR_{2-10}) has reduced substantially. In 2000, 13.2% of Kenya's population lived in areas where *Pf*PR_{2-10} was >50% and by 2015, on average, there were no areas of hyper or holo-endemic transmission (>50%*Pf*PR_{2-10}). In contrast, population in areas of *Pf*PR_{2-10} was <1% or malaria free increased from 35.1% in 2000 to 53.6% in 2015. Malaria-free areas were defined on the basis of temperature limits and therefore the proportion of population in this zone remained constant throughout. Not surprisingly, the largest absolute reductions in transmission were observed in the Lake endemic and Coastal regions, where malaria was naturally highest and where most intervention efforts were concentrated.

Despite these reductions, some of the gains made were undercut by the rapid increase in population. In addition, there were pockets within some counties where transmission increased. Equally important is that most of the reductions in transmission in the hyper and holoendemic areas appear to be in the period 2000-2005, suggesting a natural transition from peak transmission, although major gains were also made across the board between 2005-2010. The pace of reduction seems lower in the period 2010-2015, where declines in transmission were mainly in the Lake endemic zone. For detailed with county changes in reference should be made to the county profiles.

As transmission declines, community parasite prevalence data becomes a less sensitive indicator for measuring progress. Many areas in Kenya are now under very low transmission and efforts must now be concentrated in the assembly of high quality and timely routine data to track the trends and compare with the intermittent community parasite survey data.

8.2 Progress in vector control interventions

Since 2004, more than 50 million ITNs, of which nearly 49 million were of the LLIN variety, have been distributed in Kenya. Most of these distributions have occurred since 2011, following the change of LLIN strategy in 2009, whereby the free mass campaigns and routine distributions were targeted in malarious counties, instead of nationwide distributions. From the household survey data, household ownership of ITNs has risen considerably since 2003. Household ownership of one ITN by 2015 was above 70% in the majority of targeted counties. However, universal coverage (1 LLIN per 2 persons) was between 40% and 50% in most targeted counties. Use of bed nets by household members was between 40% and 70% in the Lake and Coastal endemic counties. Therefore, although access to LLINs has improved substantially, universal coverage and use of bed nets remain relatively moderate and further efforts are required to reach the 100% target.

Beginning 2013, all IRS activities ceased in Kenya, as the country was realigning the policy with the WHO policy guidelines on insecticides resistance management strategy where non-Pyrethroids were recommended in areas of high LLIN coverage. Kenya has limited non-pyrethroids registered for public health use. By 2014 Pirimaphos methyl, an organophosphate, was registered for use in IRS.

8.3 Prevention of malaria in pregnancy

There are uncertainties around the estimations of interventions targeted at pregnant women because the denominator recorded during surveys is often relatively small. Nonetheless, use of LLINs among pregnant women seems to have increased since the MIS of 2007, and was between 50% and 90% in 2015 in the Lake and Coastal endemic counties. Interestingly, the proportion of women receiving at least two doses of SP for IPTp was generally higher in the Coastal endemic counties, expect in Kilifi where it was below 50%, compared to the Lake endemic counties where it was between 30% and 50% across all counties. The policy recommendation to administer IPTp with each scheduled visit after quickening to ensure pregnant women receive a minimum of three doses was launched in 2016. Since then, there are no data to track the coverage of the revised indicator. However, given the relatively modest coverage of IPTp2, major efforts are required in reaching the target of universal coverage in the targeted counties.

8.4 Improvements in treatment-seeking and access to recommended treatment

Treatment-seeking for fever in the formal health sector has substantially increased since 2003 and by 2015 the majority of counties reported more than 60% of children seeking treatment in either a clinic, pharmacy or drug store. Among those who sought treatment and were treated for malaria, the majority also received the first-line recommended drug, AL. Only in Laikipia, Tharaka Nithi, Lamu and West Pokot was prescription of AL below 60%. It is unclear, however, what proportion of these febrile were confirmed to have malaria. In the MIS 2015, only 39% of children with fever in the last week had received a finger or heel prick (KMIS, 2015).

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Appendix A List of counties and sub-counties in Kenya

Country	County	Sub-county	Sub-county Code	Map Code
Kenya	Baringo	Baringo Central	KEN001	1
Kenya	Baringo	Baringo North	KEN002	2
Kenya	Baringo	Baringo South	KEN003	3
Kenya	Baringo	Eldama Ravine	KEN004	4
Kenya	Baringo	Mogotio	KEN005	5
Kenya	Baringo	Tiaty	KEN006	6
Kenya	Bomet	Bomet Central	KEN007	7
Kenya	Bomet	Bomet East	KEN008	8
Kenya	Bomet	Chepalungu	KEN009	9
Kenya	Bomet	Konoin	KEN010	10
Kenya	Bomet	Sotik	KEN011	11
Kenya	Bungoma	Bumula	KEN012	12
Kenya	Bungoma	Kabuchai	KEN013	13
Kenya	Bungoma	Kanduyi	KEN014	14
Kenya	Bungoma	Kimilili	KEN015	15
Kenya	Bungoma	Mt Elgon	KEN016	16
Kenya	Bungoma	Sirisia	KEN017	17
Kenya	Bungoma	Tongaren	KEN018	18
Kenya	Bungoma	Webuye East	KEN019	19
Kenya	Bungoma	Webuye West	KEN020	20
Kenya	Busia	Budalangi	KEN021	21
Kenya	Busia	Butula	KEN022	22
Kenya	Busia	Funyula	KEN023	23
Kenya	Busia	Matayos	KEN024	24
Kenya	Busia	Nambale	KEN025	25
Kenya	Busia	Teso North	KEN026	26
Kenya	Busia	Teso South	KEN027	27
Kenya	Elgeyo Marakwet	Keiyo North	KEN028	28
Kenya	Elgeyo Marakwet	Keiyo South	KEN029	29
Kenya	Elgeyo Marakwet	Marakwet East	KEN030	30
Kenya	Elgeyo Marakwet	Marakwet West	KEN031	31
Kenya	Embu	Manyatta	KEN032	32
Kenya	Embu	Mbeere North	KEN033	33
Kenya	Embu	Mbeere South	KEN034	34
Kenya	Embu	Runyenjes	KEN035	35
Kenya	Garissa	Balambala	KEN036	36
Kenya	Garissa	Dadaab	KEN037	37
Kenya	Garissa	Dujis	KEN038	38
Kenya	Garissa	Fafi	KEN039	39
Kenya	Garissa	Ijara	KEN040	40
Kenya	Garissa	Lagdera	KEN041	41
Kenya	Homa Bay	Homa Bay	KEN042	42
Kenya	Homa Bay	Kabondo Kasipul	KEN043	43
Kenya	Homa Bay	Karachuonyo	KEN044	44
Kenya	Homa Bay	Kasipul	KEN045	45
Kenya	Homa Bay	Mbita	KEN046	46
Kenya	Homa Bay	Ndhiwa	KEN047	47
Kenya	Homa Bay	Rangwe	KEN048	48
Kenya	Homa Bay	Suba	KEN049	49
Kenya	Isiolo	Garbatulla	KEN050	50
Kenya	Isiolo	Isiolo	KEN051	51
Kenya	Isiolo	Merti	KEN052	52
Kenya	Kajiado	Kajiado Central	KEN053	53
Kenya	Kajiado	Kajiado East	KEN054	54
Kenya	Kajiado	Kajiado North	KEN055	55
Kenya	Kajiado	Kajiado South	KEN056	56
Kenya	Kajiado	Kajiado West	KEN057	57
Kenya	Kakamega	Butere	KEN058	58
Kenya	Kakamega	Ikolomani	KEN059	59
Kenya	Kakamega	Khwisero	KEN060	60
Kenya	Kakamega	Likuyani	KEN061	61
Kenya	Kakamega	Lugari	KEN062	62
Kenya	Kakamega	Lurambi	KEN063	63
Kenya	Kakamega	Malava	KEN064	64
Kenya	Kakamega	Matungu	KEN065	65

Kenya	Kakamega	Mumias East	KEN066	66
Kenya	Kakamega	Mumias West	KEN067	67
Kenya	Kakamega	Navakholo	KEN068	68
Kenya	Kakamega	Shinyalu	KEN069	69
Kenya	Kericho	Buret	KEN070	70
Kenya	Kericho	Kericho East	KEN071	71
Kenya	Kericho	Kericho West	KEN072	72
Kenya	Kericho	Kipkelion East	KEN073	73
Kenya	Kericho	Kipkelion West	KEN074	74
Kenya	Kericho	Sigowet	KEN075	75
Kenya	Kiambu	Gatundu North	KEN076	76
Kenya	Kiambu	Gatundu South	KEN077	77
Kenya	Kiambu	Githunguri	KEN078	78
Kenya	Kiambu	Juja	KEN079	79
Kenya	Kiambu	Kabete	KEN080	80
Kenya	Kiambu	Kiambaa	KEN081	81
Kenya	Kiambu	Kiambu	KEN082	82
Kenya	Kiambu	Kikuyu	KEN083	83
Kenya	Kiambu	Lari	KEN084	84
Kenya	Kiambu	Limuru	KEN085	85
Kenya	Kiambu	Ruiru	KEN086	86
Kenya	Kiambu	Thika Town	KEN087	87
Kenya	Kilifi	Ganze	KEN088	88
Kenya	Kilifi	Kaloleni	KEN089	89
Kenya	Kilifi	Kilifi	KEN090	90
Kenya	Kilifi	Magarini	KEN091	91
Kenya	Kilifi	Malindi	KEN092	92
Kenya	Kilifi	Rabai	KEN093	93
Kenya	Kirinyaga	Gichugu	KEN094	94
Kenya	Kirinyaga	Kirinyaga Central	KEN095	95
Kenya	Kirinyaga	Mwea	KEN096	96
Kenya	Kirinyaga	Ndia	KEN097	97
Kenya	Kisii	Bobasi	KEN098	98
Kenya	Kisii	Bomachoge Borabu	KEN099	99
Kenya	Kisii	Bomachoge Chache	KEN100	100
Kenya	Kisii	Bonchari	KEN101	101
Kenya	Kisii	Kitutu Chache North	KEN102	102
Kenya	Kisii	Kitutu Chache South	KEN103	103
Kenya	Kisii	Nyaribari Chache	KEN104	104
Kenya	Kisii	Nyaribari Masaba	KEN105	105
Kenya	Kisii	South Mugirango	KEN106	106
Kenya	Kisumu	Kisumu Central	KEN107	107
Kenya	Kisumu	Kisumu East	KEN108	108
Kenya	Kisumu	Kisumu West	KEN109	109
Kenya	Kisumu	Muhoroni	KEN110	110
Kenya	Kisumu	Nyakach	KEN111	111
Kenya	Kisumu	Nyando	KEN112	112
Kenya	Kisumu	Seme	KEN113	113
Kenya	Kitui	Kitui Central	KEN114	114
Kenya	Kitui	Kitui East	KEN115	115
Kenya	Kitui	Kitui Rural	KEN116	116
Kenya	Kitui	Kitui South	KEN117	117
Kenya	Kitui	Kitui West	KEN118	118
Kenya	Kitui	Mwingi East	KEN119	119
Kenya	Kitui	Mwingi North	KEN120	120
Kenya	Kitui	Mwingi West	KEN121	121
Kenya	Kwale	Kinango	KEN122	122
Kenya	Kwale	Lunga Lunga	KEN123	123
Kenya	Kwale	Matuga	KEN124	124
Kenya	Kwale	Msambweni	KEN125	125
Kenya	Laikipia	Laikipia East	KEN126	126
Kenya	Laikipia	Laikipia North	KEN127	127
Kenya	Laikipia	Laikipia West	KEN128	128
Kenya	Lamu	Lamu East	KEN129	129
Kenya	Lamu	Lamu West	KEN130	130
Kenya	Machakos	Kangundo	KEN131	131
Kenya	Machakos	Kathiani	KEN132	132
Kenya	Machakos	Machakos Town	KEN133	133
Kenya	Machakos	Masinga	KEN134	134
Kenya	Machakos	Matungulu	KEN135	135

Kenya	Machakos	Mavoko	KEN136	136
Kenya	Machakos	Mwala	KEN137	137
Kenya	Machakos	Yatta	KEN138	138
Kenya	Makueni	Kaiti	KEN139	139
Kenya	Makueni	Kibwezi East	KEN140	140
Kenya	Makueni	Kibwezi West	KEN141	141
Kenya	Makueni	Kilome	KEN142	142
Kenya	Makueni	Makueni	KEN143	143
Kenya	Makueni	Mbooni	KEN144	144
Kenya	Mandera	Banissa	KEN145	145
Kenya	Mandera	Lafey	KEN146	146
Kenya	Mandera	Mandera East	KEN147	147
Kenya	Mandera	Mandera North	KEN148	148
Kenya	Mandera	Mandera South	KEN149	149
Kenya	Mandera	Mandera West	KEN150	150
Kenya	Marsabit	Laisamis	KEN151	151
Kenya	Marsabit	Moyale	KEN152	152
Kenya	Marsabit	North Horr	KEN153	153
Kenya	Marsabit	Saku	KEN154	154
Kenya	Meru	Buuri	KEN155	155
Kenya	Meru	Central Imenti	KEN156	156
Kenya	Meru	Igembe Central	KEN157	157
Kenya	Meru	Igembe North	KEN158	158
Kenya	Meru	Igembe South	KEN159	159
Kenya	Meru	North Imenti	KEN160	160
Kenya	Meru	South Imenti	KEN161	161
Kenya	Meru	Tigania East	KEN162	162
Kenya	Meru	Tigania West	KEN163	163
Kenya	Migori	Awendo	KEN164	164
Kenya	Migori	Kuria East	KEN165	165
Kenya	Migori	Kuria West	KEN166	166
Kenya	Migori	Nyatike	KEN167	167
Kenya	Migori	Rongo	KEN168	168
Kenya	Migori	Suna East	KEN169	169
Kenya	Migori	Suna West	KEN170	170
Kenya	Migori	Uriri	KEN171	171
Kenya	Mombasa	Changamwe	KEN172	172
Kenya	Mombasa	Jomvu	KEN173	173
Kenya	Mombasa	Kisauni	KEN174	174
Kenya	Mombasa	Likoni	KEN175	175
Kenya	Mombasa	Mvita	KEN176	176
Kenya	Mombasa	Nyali	KEN177	177
Kenya	Murang'a	Gatanga	KEN178	178
Kenya	Murang'a	Kahuro	KEN179	179
Kenya	Murang'a	Kandara	KEN180	180
Kenya	Murang'a	Kangema	KEN181	181
Kenya	Murang'a	Kigumo	KEN182	182
Kenya	Murang'a	Kiharu	KEN183	183
Kenya	Murang'a	Mathioya	KEN184	184
Kenya	Murang'a	Murang'a South	KEN185	185
Kenya	Nairobi	Dagoretti North	KEN186	186
Kenya	Nairobi	Dagoretti South	KEN187	187
Kenya	Nairobi	Embakasi Central	KEN188	188
Kenya	Nairobi	Embakasi East	KEN189	189
Kenya	Nairobi	Embakasi North	KEN190	190
Kenya	Nairobi	Embakasi South	KEN191	191
Kenya	Nairobi	Embakasi West	KEN192	192
Kenya	Nairobi	Kamukunji	KEN193	193
Kenya	Nairobi	Kasarani	KEN194	194
Kenya	Nairobi	Kibra	KEN195	195
Kenya	Nairobi	Langata	KEN196	196
Kenya	Nairobi	Makadara	KEN197	197
Kenya	Nairobi	Mathare	KEN198	198
Kenya	Nairobi	Roysambu	KEN199	199
Kenya	Nairobi	Ruaraka	KEN200	200
Kenya	Nairobi	Starehe	KEN201	201
Kenya	Nairobi	Westlands	KEN202	202
Kenya	Nakuru	Bahati	KEN203	203
Kenya	Nakuru	Gilgil	KEN204	204
Kenya	Nakuru	Kuresoi North	KEN205	205

Kenya	Nakuru	Kuresoi South	KEN206	206
Kenya	Nakuru	Molo	KEN207	207
Kenya	Nakuru	Naivasha	KEN208	208
Kenya	Nakuru	Nakuru Town East	KEN209	209
Kenya	Nakuru	Nakuru Town West	KEN210	210
Kenya	Nakuru	Njoro	KEN211	211
Kenya	Nakuru	Rongai	KEN212	212
Kenya	Nakuru	Subukia	KEN213	213
Kenya	Nandi	Aldai	KEN214	214
Kenya	Nandi	Chesumei	KEN215	215
Kenya	Nandi	Emgwen	KEN216	216
Kenya	Nandi	Mosop	KEN217	217
Kenya	Nandi	Nandi Hills	KEN218	218
Kenya	Nandi	Tinderet	KEN219	219
Kenya	Narok	Emurua Dikirr	KEN220	220
Kenya	Narok	Kilgoris	KEN221	221
Kenya	Narok	Narok East	KEN222	222
Kenya	Narok	Narok North	KEN223	223
Kenya	Narok	Narok South	KEN224	224
Kenya	Narok	Narok West	KEN225	225
Kenya	Nyamira	Borabu	KEN226	226
Kenya	Nyamira	Manga	KEN227	227
Kenya	Nyamira	Masaba North	KEN228	228
Kenya	Nyamira	Nyamira	KEN229	229
Kenya	Nyamira	Nyamira North	KEN230	230
Kenya	Nyandarua	Kinangop	KEN231	231
Kenya	Nyandarua	Kipipiri	KEN232	232
Kenya	Nyandarua	Ndaragwa	KEN233	233
Kenya	Nyandarua	Ol Jorok	KEN234	234
Kenya	Nyandarua	Ol Kalou	KEN235	235
Kenya	Nyeri	Kieni East	KEN236	236
Kenya	Nyeri	Kieni West	KEN237	237
Kenya	Nyeri	Mathira East	KEN238	238
Kenya	Nyeri	Mathira West	KEN239	239
Kenya	Nyeri	Mukurweini	KEN240	240
Kenya	Nyeri	Nyeri Town	KEN241	241
Kenya	Nyeri	Othaya	KEN242	242
Kenya	Nyeri	Tetu	KEN243	243
Kenya	Samburu	Samburu Central	KEN244	244
Kenya	Samburu	Samburu East	KEN245	245
Kenya	Samburu	Samburu North	KEN246	246
Kenya	Siaya	Alego Usonga	KEN247	247
Kenya	Siaya	Bondo	KEN248	248
Kenya	Siaya	Gem	KEN249	249
Kenya	Siaya	Rarieda	KEN250	250
Kenya	Siaya	Ugenya	KEN251	251
Kenya	Siaya	Ugunja	KEN252	252
Kenya	Taita Taveta	Mwatate	KEN253	253
Kenya	Taita Taveta	Taveta	KEN254	254
Kenya	Taita Taveta	Voi	KEN255	255
Kenya	Taita Taveta	Wundanyi	KEN256	256
Kenya	Tana River	Bura	KEN257	257
Kenya	Tana River	Galole	KEN258	258
Kenya	Tana River	Garsen	KEN259	259
Kenya	Tharaka Nithi	Maara	KEN260	260
Kenya	Tharaka Nithi	Meru South	KEN261	261
Kenya	Tharaka Nithi	Tharaka North	KEN262	262
Kenya	Tharaka Nithi	Tharaka South	KEN263	263
Kenya	Trans Nzoia	Cherangany	KEN264	264
Kenya	Trans Nzoia	Endebess	KEN265	265
Kenya	Trans Nzoia	Kiminini	KEN266	266
Kenya	Trans Nzoia	Kwanza	KEN267	267
Kenya	Trans Nzoia	Saboti	KEN268	268
Kenya	Turkana	Loima	KEN269	269
Kenya	Turkana	Turkana Central	KEN270	270
Kenya	Turkana	Turkana East	KEN271	271
Kenya	Turkana	Turkana North	KEN272	272
Kenya	Turkana	Turkana South	KEN273	273
Kenya	Turkana	Turkana West	KEN274	274
Kenya	Uasin Gishu	Ainabkoi	KEN275	275

Kenya	Uasin Gishu	Kapseret	KEN276	276
Kenya	Uasin Gishu	Kesses	KEN277	277
Kenya	Uasin Gishu	Moiben	KEN278	278
Kenya	Uasin Gishu	Soy	KEN279	279
Kenya	Uasin Gishu	Turbo	KEN280	280
Kenya	Vihiga	Emuhaya	KEN281	281
Kenya	Vihiga	Hamisi	KEN282	282
Kenya	Vihiga	Luanda	KEN283	283
Kenya	Vihiga	Sabatia	KEN284	284
Kenya	Vihiga	Vihiga	KEN285	285
Kenya	Wajir	Eldas	KEN286	286
Kenya	Wajir	Tarbaj	KEN287	287
Kenya	Wajir	Wajir East	KEN288	288
Kenya	Wajir	Wajir North	KEN289	289
Kenya	Wajir	Wajir South	KEN290	290
Kenya	Wajir	Wajir West	KEN291	291
Kenya	West Pokot	North Pokot	KEN292	292
Kenya	West Pokot	Pokot Central	KEN293	293
Kenya	West Pokot	Pokot South	KEN294	294
Kenya	West Pokot	West Pokot	KEN295	295

Appendix B Model-based geostatistical methods

B1. Covariate processing and selection

A set of four geographical covariates were examined; Precipitation, Enhanced Vegetation Index (EVI), Temperature Suitability Index (TSI) and Urbanisation. Precipitation and temperature rasters were derived from the monthly average rasters obtained from WorldClim website and were summarised to get the annual mean rainfall and annual mean temperature surfaces.[6] The EVI surface was derived from the MODerate-resolution Imaging Spectroradiometer (MODIS) sensor imagery[7] while the urbanisation surface was obtained from Global Rural Urban Mapping Project (GRUMP)[8]

The best generalised linear approach was used to generate minimum adequate set of covariates that have a significant effect on malaria to be used in geostatistical model. The function "bestglm" was used as implemented in R-Project version 3.0.1 package. This function selects the best subset of the input covariates for the GLM family.[9] Bayes Information Criterion (BIC) was used to select the significant covariates for the study because it has been shown that BIC often selects more parsimonious models than the AIC.[10] A uniform prior of the model of fixed size implemented in BIC_γ was used (see Equation B1 following):

$$BIC_\gamma = D + k\log(\mathrm{n}) + 2\gamma\log\binom{p}{k}$$

This is where γ is an adjustable parameter, p is the number of possible input covariates not counting the bias or intercept term and k is the number of the parameters in the model.[11]

6. Murtaugh PA (2009): Performance of several variable-selection methods applied to real ecological data. *Ecology Letters*, **12**(10):1061-1068.
7. Scharlemann JorP, Benz D, Hay SI, Purse BV, Tatem AJ, Wint GW, Rogers DJ (2009). Global data for ecology and epidemiology: a novel algorithm for temporal Fourier processing MODIS data. *PLoS One 2008*, **3**(1):e1408.
8. Schneider A, Friedl M, Potere D (2009): A new map of global urban extent from MODIS satellite data. *Environmental Research Letters*, **4**(4):044003.
9. McLeod A, Xu C bestglm (2010): Best Subset GLM. URL http://CRAN R-project org/package= bestglm.
10. Ibid.
11. Ibid.

B2. SI 2: Space-time Bayesian geostatistical model

Bayesian hierarchical space-time model was implemented through Stochastic Partial Differential Equations (SPDE) approach using Integrated Nested Laplace Approximations (INLA) in R-INLA library to produce continuous malaria risk maps at 1 km x 1 km spatial resolution and predicting to each year of study: 2000, 2005, 2010 and 2015 in Kenya.[12] This SPDE is formulated as a link between Gaussian random fields (GRFs) and the Gaussian Markov Random Fields (GMRFs).[13] The spatio-temporal covariance function and the dense covariance matrix of the Gaussian field are replaced by a neighbourhood structure and a sparse precision matrix respectively that together define a GMRF.[14] This finite-dimensional GMRF that substitutes infinite-dimensional GRF can be expressed as shown in Equation B2 following:

$$x(u) = \sum_{i=1}^{n} \psi_i(u) w_i$$

Here the $\{w_i\}$ represents the Gaussian distributed weights and Ψ_i are piece-wise linear basis functions defined on a triangulation of the domain with η nodes defined as mesh. The solution of a Gaussian random field SPDE with Matern covariance function is represented as in Equation B3 following:

$$(\mathrm{k}^2 - \Delta)^{\alpha/2} x(\mathrm{u}) = W(\mathrm{u}),\ u \in R^d,\ \alpha = v + d/2,\ k > 0,\ v > 0,$$

The innovation process W is the spatial Gaussian white noise and Δ is the Laplacian. Finite element method (FEM), a numerical technique for solving partial differential equation, has been successfully used in solving the SPDE of this type.[15] This SPDE-formulation is motivated by computational benefits and also introduces a new class of spatial models.[16] In this SPDE approach, a non-stationary model was used and achieved by modifying the SPDE to obtain the GRFs with defined dependence structure and is expressed in Equation B4 as:

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12. Rue Hav, Martino S, Chopin N (2009). Approximate Bayesian inference for latent Gaussian models by using integrated nested Laplace approximations. *Journal of the Royal Statistical Society: Series B* (statistical methodology), **71**(2):319-392.
13. Lindgren F, Rue H (2015). Bayesian Spatial and Spatio-temporal Modelling with R-INLA. *Journal of Statistical Software*, **63** (19).
14. Cameletti M, Lindgren F, Simpson D, Rue Hav (2013). Spatio-temporal modeling of particulate matter concentration through the SPDE approach. *AStA Advances in Statistical Analysis*:1-23.
15. Lindgren F, Rue H (2015). Op cit.
16. Ingebrigtsen R, Lindgren F, Steinsland I (2013). Spatial models with explanatory variables in the dependence structure. *Spatial Statistic,* **8**: 6.

$$(k(\mathrm{u})^2 - \Delta)(\tau(\mathrm{u})\,\mathrm{x}(\mathrm{u})) = \mathrm{w}(\mathrm{u}),\ u \in \Omega,$$

In the current version of the SPDE package[17] as implemented in (6), a non-stationary model defined via spatial varying $k(\mathrm{u})$ and $\tau(\mathrm{u})$ is available for the case $\alpha = 2$. The $\mathrm{logk(u)}$ and $\log \tau(\mathrm{u})$ are defined as linear combinations of basic functions in Equation B5:

$$\log(\tau(\mathrm{u})) = \mathrm{b}_0^{\tau}(\mathrm{u}) + \sum_{k=1}^{p} b_k^{\tau}(\mathrm{u})\theta_k,$$

$$\log(\mathrm{k}(\mathrm{u})) = \mathrm{b}_0^{k}(\mathrm{u}) + \sum_{k=1}^{p} b_k^{k}(\mathrm{u})\theta_k,$$

The precision matrix with parameter fields in the diagonal matrices is evaluated in a mesh in Equation B6 as:

$$T = diag(\tau(\mathrm{u}_i)),\ K = diag(\mathrm{k}(\mathrm{u}_i)),$$

$$Q = T(\mathrm{K}^2\mathrm{C}\mathrm{K}^2 + \mathrm{K}^2\mathrm{G}_1 + \mathrm{G}_1^T\mathrm{K}^2 + \mathrm{G}_2)\mathrm{T}$$

The space-time SPDE model used in this study is represented as show in Equation 7. This is by constructing Kronecker product model by first starting with the basis function represented as

where each basis function is computed as a product of a spatial and a temporal basis function, $\psi_i(\mathrm{u},\mathrm{t}) = \psi_i^u(\mathrm{u})\psi_j^t(\mathrm{t})$, thus the space-time SPDE.[18] The temporal aspect of the model is based on autoregressive (AR) second order process in Equation B7:

$$\frac{\partial}{\partial t}(\mathrm{k}(\mathrm{u})^2 - \Delta)^{\alpha/2}(\tau(\mathrm{u})\,\mathrm{x}(\mathrm{u},\mathrm{t})) = \mathrm{w}(\mathrm{u},\mathrm{t}),\ (\mathrm{u},\mathrm{t}) \in \Omega \times R$$

Therefore, the overall non-stationary hierarchical space-time binomial model of the prevalence of malaria was represented as the realization of a spatial-temporal process of malaria risk at the survey location, survey date, significant covariates at sampled locations and date, and the measurement error defined by the Gaussian white noise process. This can simply be denoted as in Equation B8:

$$y(u_i,t) = z(u_i,t)\beta + \xi(u_i,t) + \varepsilon(u_i,t)$$

17. Lindgren F, Rue H (2015). Op cit.
18. Lindgren F, Rue H (2015). Op cit

This equation defines a hierarchical model where $y(u_i, t)$ is a realization of a spatial-temporal process that represents risk of malaria at study location $i = 1 \ldots n$, and year $t \ldots, T$, $z(u_i, t_j) = (z_1(u_i, t_j), \ldots, z_p(u_i, t_j))$ denotes the vector of p covariates for cluster u_i at time t_j, $\beta = (\beta_1 \ldots, \beta_p)'$ is the coefficient vector, $\varepsilon(u_i, t_j) \sim N(0, \sigma_\varepsilon^2)$ is the measurement error defined by the Gaussian white noise process that is uncorrelated both over space and time.

B3. Validation

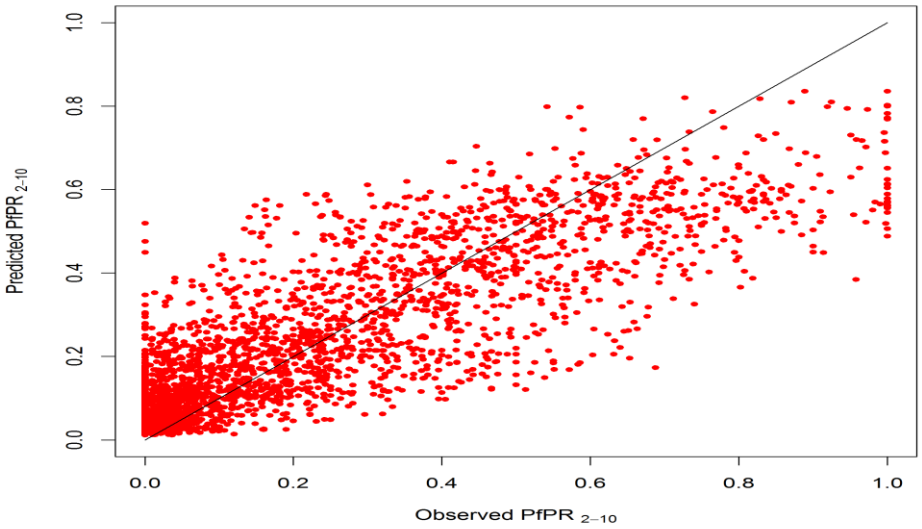
To assess the predictive performance of the model, the predicted prevalence of malaria in the surveyed locations was extracted and matched with the actual prevalence in surveyed data at the corresponding locations and time in a randomly sampled 10% holdout validation dataset using a sampling algorithm which de-clusters over space and time. Four performance indices were chosen to evaluate predictive performance and model fit: root-mean-square error (RMSE), mean prediction error (MPE), mean absolute prediction error (MAPE), and the correlation coefficient between the predicted and the observed values. The RMSE is simply the square-root of the mean of the squared difference between the posterior predicted mean and observed value and it is used to measure the accuracy of the model. The MPE provides a measure of the bias of the predictor, the MAPE provides a measure of the mean accuracy of individual predictions, and the correlation coefficient provides a measure of association between the observed data and prediction sets.[19] The correlation between the observed and predicted data was visualised in a scatter plot with a least-squares best fitting line.

19. Magalhaes RJS, Clements ACA (2011). Mapping the risk of anaemia in preschool-age children: The contribution of malnutrition, malaria, and helminth infections in West Africa. *PLoS Medicine*, **8**(6).

B4. Validation results

From the validation statistics, the RMSE was 0.177; MPE0.010; MAPE0.126 and the correlation coefficient 0.813. Maps of the posterior standard deviation from the mean can be found in Figure B1. The scatterplot for the observed and predicted prevalence is shown in Figure B1.

Figure B1. The correlation graph of observed PfPR2-10 and predicted PfPR2-10 for the 10% holdout dataset



Appendix C Small area estimation methods

Weighted probability estimates were modelled as binomial proportions, for each areal unit, where an underlying spatial correlation in the observations is assumed, and attributed to geographical adjacency between the areas of study. The spatially autocorrelated predictions are smoothened out by assigning an intrinsic conditional auto-regressive (CAR) prior to the spatially varying random effect in a Bayesian hierarchical modelling framework (Besag et al., 1991).

Let $y_i^*|p_i \sim Binomial(m_i^*, p_i)\ \ for\ i^{th}\ areal\ unit$, where $y_i^*$the true prevalence rates is.

The true value of y_i^*can be estimated by taking care of spatial autocorrelation, a normally distributed intercept and also including area-level spatially correlated covariates in such a model frame as below in Equation C1:

$$\hat{y}_{p,i} = \hat{\alpha} + \hat{\beta}\bar{x}_i + \hat{U}_i + \hat{V}_i$$

Where $\hat{\alpha}$, $\bar{x}_i$, $\hat{U}_i$, $\hat{V}_i$ are the intercept, spatially correlated covariate ,spatially structured random effect and non-spatially structure random effect- for each study district, respectively.

However, a simpler version of model (1) was adopted as in Equation C2:

$$\hat{y}_{p,i} = \hat{U}_i + \hat{V}_i + \ \varepsilon_i\ ,$$

The spatial autocorrelation was computed through a neighbourhood structure that is defined as a function of distance between centroids of study districts. However, the neighbourhood structure can similarly be based on shared boundaries between study regions.

C1. Random effects and model priors

To make the resulting posterior distributions amenable to analytical integration in INLA, the probabilities of intervention coverage were modelled on a logit or signal scale, then back-transformed to coverage scale or to observation scale which is originally binomial. Thus the sampling model was as in Equation C3:

$$logit(p_i) = \beta_0 + U_i + V_i$$

The spatially smooth random effects U_i , for area i, are assigned a conditional normal distribution with mean given as the average of its neighbours and conditional variance inversely proportional to the number of neighbours of that particular area. This representation is given below in Equation 4. For the non-spatially structured random effect V_i an independent normal distribution was assigned.

$$U_i|U_j, j \neq i \sim N(\frac{1}{k_i}\sum_{j\in\delta_i} U_i\ , \frac{\sigma_u^2}{k_i})$$
$$V_i \sim iid\ N(0, \sigma_V^2)$$

U_i, U_j are spatially smooth effect for the i^{th} *and* j^{th} neighbors while $\delta_i$is the set of neighbors of i. The set of spatially smooth random effects U_i are assigned a CAR prior, specifically in this case, a Besag prior (Besag et al., 1991; Mercer et al., 2014).

Required were priors for β_0 and random effect variances: σ_u^2 and σ_V^2. The $\beta_0,'s$ are given normal hyperprior and the latter are assigned gamma distributions (Gomez-Rubio et al., 2010).The parameters are then estimated using an approximate Bayesian framework, namely INLA; which relies on the Gaussian Markov Random Field as supported by Rue et al., 2009.

C2. Including sampling weights in the model

The sampling weights are required to adjust for biases due to complex surveys. A survey is complex in the context of choice of sampling scheme, rates of no-responses and objectivity introduced in the sample. For example, a multi-stage sampling framework each carried out in a strata may introduce non-response bias, non-coverage bias and variance.

While bias due to variance is taken care of by smoothing in hierarchical models, the other types of bias are countered by introducing weights in our model. However, non-response bias is explained by post-stratification which requires sampling population data (Cici et al 2014); this might not be available in some survey datasets. Weights can be incorporated in the model response in the two ways highlighted below. The first option was used in our analysis.

a) Direct standardisation of proportions using design weight

In the simplest form, weights w_{ij} adjusts true population mean $\hat{y}_{u,i}$ as in Equation C5 following:

$$\hat{y}_{u,i} = \frac{\sum_j w_{ij} y_{ij}}{\sum_j w_{ij}} = \bar{y}_i$$

$w_{ij} = \left({}^{Ni}/_{ni}\right)$; i, j indexes area and observation in an area, respectively

$var(\hat{y}_{u,i}) = \left(1 - \frac{n_i}{N_i}\right) s_i^2$; s_i^2 is sample variance.

This expression only reduces bias from non-coverage and confounding but not non-response.

b) Horwitz –Thompson estimator for Bayesian hierarchical model

The most commonly used direct unbiased estimator of the area proportion in complex surveys is the post-stratified Horwitz-Thompson estimator (Horvitz and Thompson, 1952; Sarndal et al., 1992). This weighting option is more robust in the sense that it takes care grouping variables that discriminate outcomes to subpopulations, for example, the age-gender structure of the population under study. (See Equation C6 following):

$$\hat{p}_i = \frac{\sum_{J=1}^{J} \sum_{K=1}^{Nij} R_{ijk}\, w_{ijk} y_{ijk}}{\sum_{j=1}^{J} \sum_{k=1}^{Nij} R_{ijk}\, w_{ijk}}$$

y_{ijk} is the observed response.

w_{ijk} is the sampling weights of kth person in area i and group j, a group could permutations of factor variables like age and gender etc

Using Horwitz-Thompson estimator, weights are often calculated as the products of the reciprocal of sampling probability for selection (design weight) and the post-stratification weights as in Equation C7 following:

$$w_{ijk} = \pi_{ijk}^{-1} \times \frac{N_j}{\widehat{N}_j} \text{ ;for k=1,...,} N_{ij}$$

Where $\widehat{N}_j = \sum_{i=1}^{I} \sum_{k=1}^{Nij} R_{ijk}\, \pi_{ijk}^{-1}$ so that $N_j = \sum_{i=1}^{I} \sum_{k=1}^{Nij} w_{ijk}$, the known group totals in the population.

Hence the design weight adjusts for systematic sampling used, while the post-stratification weights attempt to adjust for non-response, by rescaling each group j so that the estimated population total matches the known population total. The estimated variance for post-stratified mean is as in Equation C8 following:

$$var(\hat{p}_i) = \frac{1}{n_i(n_i-1)}\left(1 - \frac{n_i}{N_i}\right) \sum_{j=1}^{J} \sum_{k=1}^{Nij} R_{ijk}\, \rho_{ijk}^2 \text{; is sample variance.}$$

$$\rho_{ijk} = y_{ijk} - \hat{p}_{.j}$$

The effective number of cases is defined by as in Equation C9 following:

$$y^* = m_i^* \times \hat{p}_i$$

C3. Model selection

The best model was selected in terms of prediction of the values in the small areas using the DIC (Deviance Information Criterion) – a hierarchical modelling generalisation of the BIC-when all models are run on the same data. Model with the smallest DIC is picked for inference.

$$D(\theta) = -2log\big(p(y|\theta)\big) + C$$

$$DIC = D\big(\hat{\theta}\big) + 2P_D$$

$P_D = 0.5\widehat{var}(D(\theta))$, is the effective number of parameters (Gelman et al., 2004). The more the number of effective parameters, the bigger chances of over-fitting we have, so the DIC is penalised to avoid effects of over-fitting.

$p(y|\theta)$;is the likelihood function and C is a constant that cancels out in all calculations comparing different models.

C4. Extracting results

The main results to be extracted are the summary of predicted means and standard errors- for each study area as sampled from the predictive distribution. These results are merged with the boundary shape files and mapped accordingly.

Posterior distributions of spatially structured and unstructured random effects were also extracted, which are plotted and mapped. These help diagnose presence of multimodal distribution in spatial estimates, evaluate proportion of variance explained by spatially structured component etc.

Besides calculating and mapping the fitted values and spatial risk we can also manually use predictions to evaluate spatial exceedance for a relative risk of p say ($\Pr(p > 0.4)$).

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