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Reprint of "Modelling the influence of temperature and rainfall on malaria incidence in four endemic provinces of Zambia using *semiparametric Poisson regression*"☆

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A R T I C L E I N F O

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A B S T R A C T

Although malaria morbidity and mortality are greatly reduced globally owing to great control efforts, the disease remains the main contributor. In Zambia, all provinces are malaria endemic. However, the transmission intensities vary mainly depending on environmental factors as they interact with the vectors. Generally in Africa, possibly due to the varying perspectives and methods used, there is variation on the relative importance of malaria risk determinants. In Zambia, the role climatic factors play on malaria case rates has not been determined in combination of space and time using robust methods in modelling. This is critical considering the reversal in malaria reduction after the year 2010 and the variation by transmission zones. Using a geoadditive or structured additive *semiparametric Poisson regression* model, we determined the influence of climatic factors on malaria incidence in four endemic provinces of Zambia. We demonstrate a strong positive association between malaria incidence and precipitation as well as minimum temperature. The risk of malaria was 95% lower in Lusaka (ARR = 0.05, 95% CI = 0.04–0.06) and 68% lower in the Western Province (ARR = 0.31, 95% CI = 0.25–0.41) compared to Luapula Province. North-western Province did not vary from Luapula Province. The effects of geographical region are clearly demonstrated by the unique behaviour and effects of minimum and maximum temperatures in the four provinces. Environmental factors such as landscape in urbanised places may also be playing a role.

1. Introduction

The burden of malaria has greatly reduced globally (Moss et al., 2012) owing to great control efforts. However, the disease remains the main contributor to morbidity and mortality. Malaria was responsible for an estimated 214 million morbidity cases and 438,000 deaths worldwide in 2015, with 88% of the morbidity cases and 90% of the deaths occurring in Africa (World Health Organisation, 2015). Considering the estimated 262 million morbidity cases and 839,000 deaths recorded in 2000, the 2015 statistics represent a decline of 18% in the estimated malaria cases and of 48% in the number of deaths. Nevertheless, the decline in malaria burden has not been uniform among countries in the world as some countries experience resurgence (Moss et al., 2012).

Consistent with the global picture, Zambia reported a decline in malaria cases over the recent years (Masaninga et al., 2012). However,

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Abbreviations: R-INLA, R version of integrated Laplace; NDVI, normalised difference vegetation index; WHO, World Health Organisation; LS, Lusaka; LP, Luapula; NW, North-western; W, Western; CSO, Central Statistical Office; HMIS, Health Management Information System; MOH, Ministry of Health; LST, land surface temperature; MODIS, Moderate Resolution Imaging Spectroradiometer; USGS, U. S. Geological Survey; LP DAAC, Land Processes Distributed Active Archive Centre; CHIRPS, Climate Hazards Group InfraRed Precipitation with Station data; UCSB, University of California, Santa Barbara; DIC, Deviance Information Criterion; pD, effective number of parameters; Pop, total population; I, malaria incidence rate; M, new malaria cases; RW, random walk; RR, relative risk

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the burden of malaria continues to be high in the country (Chanda et al., 2012). An estimated four million suspected cases were reported in 2007 (Roll Back Malaria, 2011) increasing to an estimated 4,300,000 cases in 2010 (Government of the Republic of Zambia, 2013a). Within the country, all provinces are malaria endemic (Roll Back Malaria, 2011) although the transmission intensities vary mainly depending on environmental factors (Ghebreyesus et al., 1997; Lieshout et al., 2004) as they interact with the vectors. Following the break in interventions due to socio-economic problems in Zambia in 2009, the impact of malaria control efforts was reversed (Masaninga et al., 2012). Nonetheless, the reversal was not uniform across all provinces. The reversal in malaria reduction in Zambia observed during the 2009–2010 period was mainly attributed to decreased donor funding towards malaria control activities (Masaninga et al., 2012).

Malaria is a vector-borne disease and eco-environmental factors such as climate, landscape, housing structure (World Health Organisation, 2015) and proximity of households to vector breeding sites contribute to the burden in two major ways; either by affecting the vector and parasite development (Lieshout et al., 2004) or by facilitating exposure of community members to vectors (Lenntech, 2015). The larval development stage of mosquitoes occurs in various types of water bodies depending on their water-ecological requirements (World Health Organisation, 2001). In Africa, the *Anopheles gambiae* vector breeds in numerous small pools of water (Centre for Diseases Control and Prevention, 2016). The main sources of the water pools are rainfall (Centre for Diseases Control and Prevention, 2016), artificial means or even natural disasters (Lenntech, 2015). The occurrence of water pools has been shown to expose people to epidemics of flood-linked water borne diseases such as malaria (Lenntech, 2015).

With regards to climate, a number of studies have shown variations in climatic factors influencing malaria. Among them, some suggest minimum temperature only (Nkurunziza et al., 2010), others rainfall only (Huang et al., 2011) while others a combination of minimum, maximum temperature and rainfall (Mabaso et al., 2006). The variation in climatic factors influencing malaria in these studies could largely be due to the different regions experiencing varied intensity of prevailing eco-environmental factors. Eco-environmental factors relate to both the ecology of vector breeding sites as well as the environment including climate and housing structures where humans get exposed to vectors or favouring conditions.

The malaria control program in Zambia is one of the leading programs in Africa (Roll Back Malaria, 2011; Ashraf et al., 2010) although research in eco-environmental factors still has room for expansion. A number of studies have been conducted in Zambia to describe the epidemiology of malaria in the country (Masaninga et al., 2012; Chimumbwa, 2003). These studies have suggested that malaria is endemic throughout the country (Chimumbwa, 2003), varying in transmission intensity across three distinct transmission zones (Masaninga et al., 2012). Studies in Zambia have also indicated a marked change in sibling species composition over time, mainly due to change in ecology. The change in sibling species composition corresponds to malaria transmission rates in some places. Current findings suggest that the malaria vectors in Zambia consist of *An. gambiae ss*., *An. arabiensis*, and *An. funestus* (Chanda et al., 2012). Other studies conducted in Zambia have been focussed on land ecology as it relates to vector development (Ricotta et al., 2014; Clennon et al., 2010). One of such studies used an image processing software called ImageJ, to analyse Google Earth satellite imagery. This procedure was a way to evaluate and enumerate information on vegetation cover such as number of plants, total amount of vegetation and its percentage of the total area and in relation to malaria cases (Ricotta et al., 2014). The study obtained and modeled data to evaluate local vegetation as a risk factor and they obtained proper usable images in southern Zambia using the software (Ricotta et al., 2014). The landscape model was another tool developed for malaria control in Zambia. This tool was successful at ruling out potential locations of vector breeding sites although it was limited in predicting the type of vector species that inhabited the sites (Clennon et al., 2010). An early warning system which conformed to seasonal incidence patterns was also developed in Zambia although it required longer periods of surveillance data to perform better (Davis et al., 2011). Additionally, some climatic variables have also been demonstrated to be significantly related to malaria transmission based on geographic patterns of risk in Zambia, namely: low altitude, high normalised difference vegetation index (NDVI), and high day and night land surface temperatures (Riedel et al., 2010).

In a study by Martens et al. (1995), the authors conclude that future climate scenarios from models can be used to calculate the potential impact of climate change on malaria transmission. This conclusion was in consideration of the significantly differing estimates of future populations at risk of malaria between regions and between climate scenarios (Martens et al., 1995).

Generally in Africa, many perspectives and methods are used to study climate-malaria links (Bouma, 2003), and literature on the matter suggests variation in the relative importance of specific factors

with region (Teklehaimanot et al., 2004). For Zambia no current studies have demonstrated the relative importance of factors over space and time using robust methods in modelling. It is important for the country to undertake these studies considering the reversal in malaria reduction after the year 2010 (Masaninga et al., 2012) and the malaria burden variation by transmission zones.

Patz and Olson (2006) recommend cross-cutting research activities in fields of health, environment, sociology and economics if risk assessment and risk management of the synergistic processes of climate and land-use change are to be improved. (Patz and Olson, 2006). Therefore, this study sought to determine the influence of climatic factors on malaria incidence in four endemic provinces of Zambia.

2. Methods

2.1. Study area

Zambia is a landlocked country surrounded by eight countries (Africa-EU Energy Partnership, 2013). The country is located in southern Africa between latitudes −8° and −18° South and longitudes 22° and 34° East (Africa-EU Energy Partnership, 2013). It has a tropical climate with hot episodes at times. The climate in Zambia is generally made up of three seasons: a cool dry season with temperatures ranging from 25° to 30 °C in April to 29° to 33 °C in July, a hot dry season with temperatures ranging from 34° to 38 °C in August to 37° to 44 °C in October and a warm to hot wet season with temperatures ranging from 29° to 43 °C in November to 24° to 27 °C in March (Food and Agriculture Organisation, 2009). The climate is mainly affected by the movement of the inter-tropical convergence zone (ITCZ) and this varies throughout the year, lurking around the equator (Food and Agriculture Organisation, 2009). The direction of the ITCZ movement is mainly dictated by land temperatures, being drawn mostly by the warmest areas.

The rainfall pattern over the whole country is highest between November and April ranging from 70 mm to 320 mm per month compared to 0 to 54 mm per month between May and October (Food and Agriculture Organisation, 2009). In terms of regions and annual rainfall patterns, rainfall is highest in the north with estimates of 1, 250 mm or more per year. This decreases southwards to Lusaka and even further south of Lusaka (Food and Agriculture Organisation, 2009) Fig. 1. Average temperatures in Zambia are moderated by the height of the plateau. Maximum temperatures vary from 15 °C to 27 °C in the cool season and from 27 °C to 35 °C in dry season (Food and Agriculture Organisation, 2009).

The population in Zambia, according to Census of 2010, is estimated at 13 million people (Government of Zambia, 2010). The whole population is at risk of malaria (Zambia Malaria Operational Plan, 2014) as the disease is endemic in Zambia's all ten provinces (Chimumbwa,