ENVIROMENTAL PREDICTORS OF THE SEASONALITY OF MALARIA TRANSMISSION IN AFRICA: THE CHALLENGE

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Abstract. A description of malaria seasonality is important for planning and optimizing malaria control in both time and space, but adequate malariologic data are not available for many disease-endemic areas. We analyzed the relationship between seasonality in the entomologic inoculation rate (EIR) and environmental factors in sites across sub-Saharan Africa with the objective of predicting seasonality from environmental data. The degree of EIR seasonality in each site was quantified using an index previously used for rainfall. The results showed that seasonality of rainfall, minimum temperature, and irrigation are important determinants of seasonality in EIR. Model fit was poor in areas characterized by two rainfall peaks and irrigation activities. Two rainfall peaks probably dampen seasonality and irrigation creates perennial breeding habitats for vectors independent of rainfall. This complex interplay between the seasonal dynamics of environmental determinants and malaria pose a great challenge and highlights the need for improved models of malaria seasonality.

INTRODUCTION

Malaria is one of the most prevalent and devastating public health problems in sub-Saharan Africa.1 An important tool for optimizing malaria control over both time and geographic area is a map of malaria seasonality. Such a map would be valuable as a basis for mapping transmission intensity.2 It has long been suggested that assessing the relationship between malariometric indices and environmental factors may be the most effective way of predicting changes in malaria transmission dynamics and thus improve the impact of control efforts.3–5 A number of studies have analyzed this relationship using different approaches and indices in different parts of the continent.6–10 However, there is no convincing empirical model of the relationship between seasonality in environmental factors and seasonality in malariometric indices that could be used to map the pattern of seasonality across this continent.

The existing continental model of malaria seasonality is based on climate suitability for malaria transmission in a given month and shows the potential duration, start, and end of the malaria season.11 This model was validated against parasite prevalence data but these data are not ideal for describing malaria seasonality12,13 because at very high transmission levels malaria prevalence is not seasonal.14 Clinical malaria case data are more closely related to seasonality in transmission and thus to environmental proxies for malaria seasonality.12,15 Recently, an empirical seasonality model that incorporates a combination of clinical malaria data and environmental covariates was used to predict monthly variation in transmission in Zimbabwe.16 A seasonality concentration index previously used for rainfall was applied to the model estimates to quantify and map the seasonal risk patterns across the country.

The index quantifies the distribution of the malaria case load during the peak season in a given area and therefore has the potential to be applied to seasonal risk mapping. However, because of the scarcity of reliable clinical malaria case data in large parts of sub-Saharan Africa, the use of other malariometric indices sensitive to malaria seasonality is necessary.

The entomologic inoculation rate (EIR) is the definitive measure of malaria challenge and responds to seasonal changes in environmental factors.17 The EIR relates to both the human-biting activity of Anopheles vectors and the risk to humans of malaria infections.18

In this study, we use a seasonality concentration index to model the relationship between seasonality in EIR and environmental factors, to identify environmental predictors of malaria seasonality and evaluate the utility of the seasonality index in different sites across sub-Saharan Africa.

MATERIALS AND METHODS

Data. We compiled published and unpublished monthly EIR data from as many different sites across sub-Saharan Africa as we could find (Figure 1). The EIR is the number of infective mosquito bites per human per unit time.2,19 Studies included in the analysis were cross-sectional surveys conducted at least monthly throughout the year prior to the introduction of interventions or where no control methods were in place. These used standard mosquito sampling methods such as human landing catches, pyrethrum spray catches, or light traps for estimating biting rates, and included dissection or enzyme-linked immunosorbent assay for determining the presence of sporozoites and origin of blood meals.20 Annual and monthly inoculations were derived by multiplying the daily EIR (infective bites per human per night) by 365 and 30 days, respectively.

We used monthly minimum temperature, annual temperature range and rainfall data obtained from the Climate Research Unit, University of East Anglia (Norwich, United Kingdom) with a global grid of 0.5 spatial resolution.21 The annual temperature range (the difference between monthly minimum and maximum temperatures) was taken as a measure of seasonality. For EIR and rainfall, we applied Markham’s seasonality concentration index22 previously used to summarize the seasonal trend in malaria cases by displaying seasonal concentration of cases during the peak transmission season.16 The method is based on vector representation (i.e., both magnitude and direction) of mean
monthly values in a given year. The 12 monthly values are added up to give a vector total \( r_t \), i.e.,

\[
    r_t = \sqrt{\left( \sum r_i \sin \theta_i \right)^2 + \left( \sum r_i \cos \theta_i \right)^2} \tag{1}
\]

and

\[
    \theta_i = \tan^{-1} \left( \frac{\sum r_i \sin \theta_i}{\sum r_i \cos \theta_i} \right) \tag{1}
\]

and the seasonality concentration index \( C \) is given by \( C = r_t / \sum r_i \) expressed as a percentage, where \( r_i \) is the magnitude of the vectors and \( \theta_i \) is the direction that is the peak month expressed in units of arc. An index of 100% implies that value of interest is concentrated in one month and an index of zero percent means that it is equal in each month of the year.

The effect of anthropogenic environmental change, specifically the presence of irrigation activities in selected localities, was also taken into account in the analysis. All types of irrigated agriculture were recorded as either present or absent based on the information available from the literature used.

**Statistical analysis.** The analysis was carried out with Stata 8.0 software (Stata Corporation, College Station, TX). We used a probit transformation to convert the EIR seasonality concentration index into a variable with a normal distribution. A multiple stepwise linear regression analysis was used to describe and model the relationship between the probit-transformed EIR seasonality index and selected explanatory variables in each site (Figure 1), and variables with a \( P \) value > 0.2 were removed. Table 1 summarizes variables used in the analysis. These variables were used to see how well they predict seasonal concentration of EIR in the different sites. The performance of climatic predictors was further assessed by fitting the regression model in the presence or ab-

![Figure 1. Geographic location of entomologic inoculation rate study sites in Africa. Squares show locations with one rainfall peak in a given year, diamonds show locations with two rainfall peaks in a given year, and triangles show locations with irrigation schemes.](image-url)

**Table 1**

Mean (SD) of all variables used in the analysis from selected localities (n = 48) in sub-Saharan Africa*

<table>
<thead>
<tr>
<th>Variables</th>
<th>EIR Annual mean (SD)</th>
<th>C (%) mean (SD)</th>
<th>Rainfall (mm) Annual mean (SD)</th>
<th>C (%) mean (SD)</th>
<th>Minimum mean (SD)</th>
<th>Annual range† mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benin 1 (24)</td>
<td>4.09</td>
<td>56.45</td>
<td>13,536.33</td>
<td>26.65</td>
<td>22.20</td>
<td>3.40</td>
</tr>
<tr>
<td>Burkina Faso 3 (25–27)</td>
<td>80.15 (46.82)</td>
<td>62.79 (28.91)</td>
<td>11,281.50 (1,411.17)</td>
<td>73.52 (3.22)</td>
<td>16.20 (0.82)</td>
<td>7.67 (1.85)</td>
</tr>
<tr>
<td>Burundi 2 (28)</td>
<td>43.01 (53.27)</td>
<td>54.24 (0.02)</td>
<td>20,331.61 (3,296.17)</td>
<td>26.42 (8.89)</td>
<td>18.90 (0.85)</td>
<td>2.98 (0.76)</td>
</tr>
<tr>
<td>Gabon 3 (29,30)</td>
<td>60.549 (41.73)</td>
<td>32.83 (26.97)</td>
<td>10,702.63 (1,340.25)</td>
<td>18.83 (2.25)</td>
<td>13.50 (1.34)</td>
<td>1.86 (0.38)</td>
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</tr>
</tbody>
</table>

* Only sites with monthly entomologic inoculation rates (EIRs) values were included in the analysis. C is the seasonality concentration index expressed as a percentage.

† Annual range (difference between monthly minimum and maximum temperature) was used as a measure of seasonality in temperature.
sence of irrigation activities, and with or without sites from the tropical zone.

RESULTS

Table 1 shows that there is great variability in the annual EIR values and seasonality among the selected countries (n = 48 sites) and between-sites variation is masked by averaging by country. Only the rainfall seasonality concentration index, minimum temperature, and irrigation were selected as potential predictors of the seasonal concentration of EIR (Table 2). Rainfall seasonal concentration showed a positive association with seasonal concentration of EIR and both minimum temperature and irrigation showed a negative association. No evidence of an association was found between annual EIR and either annual rainfall or temperature range.

Model predictions were poor in sites situated in regions with two rainfall peaks (Figure 2). Most of these are in the tropical zone south of the equator (Figure 1) and show low EIR seasonality indices compared with the rest of the sites. However, we also observed poor model fit in a few sites with one rainfall season. EIR study sites located in the vicinity of irrigation schemes also had low seasonality indices compared with nearby non irrigated sites, for example in Mali with 40.1% (3 sites) and 88.3% (3 sites) and Tanzania with 26.8% (2 sites) and 91.2%, respectively.

Regardless of irrigation activities the seasonal concentration of rainfall remained a better predictor of EIR seasonality than minimum temperature. The predicted EIR seasonality index was higher when irrigated sites were excluded (Figure 3). Conversely, exclusion of study sites from the equatorial tropical zone did not have much effect on the model.

DISCUSSION

Our findings support the claim for a marked heterogeneity in the malaria transmission pattern across Africa. We further confirm that this variation reflects sub-regional ecologic heterogeneity, and is affected by anthropogenic activities such as irrigated agriculture. The analysis showed that rainfall seasonality, and to a lesser extent minimum temperature are important climatic determinants of the intensity of inoculation rate during the peak transmission season. Most of the selected EIR study sites are situated in tropical Africa where seasonality in rainfall drives the seasonal dynamics of malaria transmission. Minimum temperature probably plays little or no role in regulating malaria seasonality in these areas.

The results also showed that irrigation activities have a dampening effect on seasonality of malaria transmission. Elsewhere in Africa irrigation has been shown to alter the transmission pattern from seasonal to perennial especially during the dry season in areas of unstable transmission. The impact of irrigation on malaria seasonality can vary with the type of irrigation activity and according to the level of endemicity. Increases in the level of transmission in irrigated areas result in more rigorous control measures usually reflected in the low levels of malaria infection and morbidity. Rainfall seasonality still seems to operate in irrigated areas.

The two rainfall seasons in the equatorial tropical zone complement each other by intensifying and prolonging the transmission season. The seasonality index seems to work better in areas with unimodal seasonal pattern and this might have had an adverse effect in the analysis in areas with a bimodal seasonal pattern. Poor model fit in a few localities with one rainfall season may be due to the presence of two distinct common African malaria vectors, Anopheles funestus and An. gambiae sensu lato, which have been shown to sustain perennial parasite inoculation given suitable ecologic conditions. For example, in some parts of Africa, the two main vectors are seasonally replaced with high densities of An. gambiae and An. arabiensis after the rainy season, and An. funestus reaches its peak in the early dry season.

Urbanization may also be important because it has been shown to produce breeding habitats for malaria vectors by increasing the number of artificial water collection reservoirs. However, data used in this analysis was mainly from rural settings and therefore insufficient to explore the impact of urbanization on EIR seasonality. Some of the difficulties we face may be because of chaotic dynamics in the impacts of the environmental drivers of seasonality on the life histories of both parasite and vector.

We have successfully identified environmental predictors of malaria seasonality given the effect of irrigated agriculture across different sites in sub-Saharan Africa. However, we

Table 2

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficients</th>
<th>SE</th>
<th>P</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall seasonality index</td>
<td>0.011</td>
<td>0.004</td>
<td>0.006</td>
<td>0.003, 0.019</td>
</tr>
<tr>
<td>Minimum temperature (°C)</td>
<td>-0.057</td>
<td>0.033</td>
<td>0.090</td>
<td>-0.123, 0.009</td>
</tr>
<tr>
<td>Irrigation</td>
<td>-0.918</td>
<td>0.236</td>
<td>0.000</td>
<td>-1.393, -0.442</td>
</tr>
</tbody>
</table>

* EIR = entomologic inoculation rate; CI = confidence interval.
note that the global climate data used is rather coarse and may contain uncertainties that should be kept in mind when dealing with EIRs that vary over smaller spatial scales. We also acknowledge the need for a seasonality algorithm that captures other components of seasonal variation. Future work will explore the use of improved quantification and modeling of malaria seasonality.

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