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Prevalence of asymptomatic malaria at the communal level in Burkina Faso: an application of the small area estimation approach

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Abstract

Background In malaria-endemic countries, asymptomatic carriers of plasmodium represent an important reservoir for malaria transmission. Estimating the burden at a fine scale and identifying areas at high risk of asymptomatic carriage are important to guide malaria control strategies. This study aimed to estimate the prevalence of asymptomatic carriage at the communal level in Burkina Faso, the smallest geographical entity from which a local development policy can be driven.

Methods The data used in this study came from several open sources: the 2018 Multiple Indicator Cluster Survey on Malaria and the 2019 general census of the population data and environmental. The analysis involved a total of 5489 children under 5 from the malaria survey and 293,715 children under 5 from the census. The Elbers Langjouw and Langjouw (ELL) approach is used to estimate the prevalence. This approach consists of including data from several sources (mainly census and survey data) in a statistical model to obtain predictive indicators at a sub-geographical level, which are not measured in the population census. The method achieves this by finding correlations between common census variables and survey data.

Findings The findings suggest that the spatial distribution of the prevalence of asymptomatic carriage is very heterogeneous across the communes. It varies from a minimum of 5.1% (95% CI 3.6–6.5) in the commune of Bobo-Dioulasso to a maximum of 41.4% (95% CI 33.5–49.4) in the commune of Djigoué. Of the 341 communes, 208 (61%) had prevalences above the national average of 20.3% (95% CI 18.8–21.2).

Contributions This analysis provided commune-level estimates of the prevalence of asymptomatic carriage of plasmodium in Burkina Faso. The results of this analysis should help to improve planning of malaria control at the communal level in Burkina Faso.

Keywords Small area estimates, Communes, Malaria, Spatial analysis, Burkina Faso

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Introduction

Numerous efforts have been made worldwide to fight malaria. These efforts have led to a significant reduction in malaria-related morbidity and mortality, especially among children under 5. However, morbidity and mortality remain below expectations. Indeed, severe malaria remains one of the main causes of mortality, contributing to 6% of malaria deaths in sub-Saharan Africa (SSA) [1].

In 2022, the West African sub-region had approximately 121 million estimated cases and approximately 324,000 estimated deaths: an increase of 2% and a decrease of 15% respectively compared to 2010 [2]. Five countries accounted for more than 80% of the estimated cases, including Burkina Faso with 7% of cases [2]. Globally, Burkina Faso is among the ten countries most affected by malaria (3.4% of cases and 3.2% of deaths worldwide in 2020) [3]. In Burkina Faso, several initiatives such as the distribution of long-acting insecticide-treated mosquito nets (LLINs), seasonal malaria chemoprevention (SMC), indoor residual spraying (IRS) and the use of artemisinin-based combination therapies (ACTs) have been implemented to reduce the incidence and mortality of malaria. However, as in other SSA countries, malaria remains a major public health problem in the country. In 2017, Ministry of Health statistics show that malaria was the main reason for consultations (53%), hospitalization (48%) and 66% of deaths of children under 5 in hospitals and health facilities [4].

In view of the persistence of high morbidity and mortality due to malaria, several studies have focused on different aspects of the malaria disease process [1, 4–9] including factors associated with transmission and spatio-temporal inequalities in morbidity. Most of this research is based on survey or routine data, sometimes geographically targeted [5, 10] giving rise to only a partial analysis of the national situation or to an analysis on a relatively large geographical scale [1, 4–6] or unstructured [7]. For example, Ouédraogo and al. [4] using data from the baseline survey on "Assessing the impact of results-based financing in Burkina Faso", identified districts at higher risk of asymptomatic malaria infection in children in 24 districts of Burkina Faso. Along the same line, Rouamba and al. [5] used a hierarchical Bayesian spatio-temporal modeling to explore spatio-temporal patterns to identify health districts with probably of severe malaria incidence during pregnancy and high rates of mortality from routine data between 2013 and 2018.

Current guidelines on malaria elimination are based on the principle of "High burden to high impact: A targeted malaria response". In other words, interventions should target localities or entire towns where the incidence of malaria is higher, until only individual episodes of malaria remain. [10]. To contribute to optimize the elimination/control program by targeting the high risk area, the aim of this study was therefore to estimate malaria prevalence at commune level, using survey data designed to be representative at regional level.

Materials and methods

Study setting

A landlocked country of 274,200 km^2, Burkina Faso is located in the heart of West Africa. The country shares borders with Côte d'Ivoire, Ghana, Togo and Benin to the south, Mali to the north and Niger to the northwest. Its total population is estimated at 20 million (RGPH 2019). Burkina Faso has a dry, tropical climate of the Sudano-Sahelian type, characterized by highly variable rainfall ranging from 350 mm in the northern part of the country to over 1000 mm in its southwestern part [11]. There are two very distinct seasons. The first, the rainy season, lasts around 5 months (generally between mid-May and September), with a relatively shorter duration in the north of the country. The second season, the dry season, is the longest and is characterized by the Harmattan, a hot, dry, dust-laden wind from the Sahara desert. Based on rainfall and temperature, there are three main climatic bands in Burkina Faso [12]. Firstly, there's the Sahelian strip, which covers the north of the country, with its highly capricious rainfall of less than 600 mm per year and its extreme thermal oscillations (15 to 45 degrees). Then we have the Sudano-Sahelian band, a median zone for temperatures and rainfall that covers the central strip of the country. Finally, we have the Sudanian band covering the southern part of the country, the wettest with over 900 mm of rain per year and relatively low average temperatures. Rainfall thus decreases from the south-west to the north of the country.

This research complements these numerous studies to propose estimates of malaria infection at the scale of the three hundred and forty-two (342) communes covered by the census in 2019. The last administrative entity in the country, after the region and the province, the commune is a grouping of localities that are geographically close, often with cultural and economic ties. It is the only administrative entity managed by an elected official, the mayor. The management of communes is partly the responsibility of the local population, who contribute to their management through the payment of communal taxes. The commune is therefore the smallest geographical administrative entity from which a local development policy can be driven and coordinated by the community, under the watchful eye of the central administration. The choice of the commune is also justified by the fact that spatial disparities become more pronounced as the scale of analysis moves down to a finer level [13, 14]. This choice is also in line with one of the recommendations of the Sustainable Development Goals (SDGs), which call for the results of sustainable development actions to be assessed at finer geographical scales for greater effectiveness. [15, 16].

Sources of data

Three main data sources were used in this study: the general population and housing census (RGPH) carried out in 2019, the Malaria indicator survey carried out in 2018 and environmental data downloaded from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) website and the MOD11C3.006 module [17].

The RGPH is a complex operation carried out in 2019 that involved enumerating the Burkinabe population and its characteristics using a digitized questionnaire. It began on November 15, 2019 and officially ended on December 31, 2019. This nationwide operation was carried out against a backdrop of security crisis that led to partial coverage of the national territory. Of the country's 351 communes, 52 were only partially covered, and nine (9) were not covered at all. [18]. Estimates will therefore not include the nine (9) communes not covered by the census.

DHS program malaria indicator survey is a household survey based on a stratified 2-stage random sample selection. The primary sampling unit is the Enumeration Area (EA). Each area was subdivided into urban and rural parts to build the sampling strata, and the sample was drawn independently in each stratum. Overall, twenty-six strata were created. In the first stage, 252 EAs were drawn (52 in urban areas and 200 in rural areas)[1] with probability proportional to size. In the second stratum, 26 households were systematically selected with equal probability from each of the EA drawn in the first stratum. In all, 6552 households were selected, including 1352 in urban areas and 5500 in rural areas. This survey, unlike the census, was conducted on paper and took place between November 2017 and March 2018. The Survey involved a representative sample of 6500 households and 7600 women aged 15–49. Blood samples were taken from 50% of selected households, for malaria screening. All children aged 6–59 months living in these households were eligible for malaria screening. Parental or guardian consent was required for their children's participation.

The Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature/Emissivity Monthly (MOD11C3) Version 6.1 product provides monthly Land Surface Temperature and Emissivity (LST&E) values in a 0.05 degree (5600 m at the equator) latitude/longitude Climate Modeling Grid (CMG). A CMG granule is a geographic grid with 7200 columns and 3600 rows representing the entire globe. Climate Hazards Group In-fraRed Precipitation with Station data (CHIRPS) is a 35+ year quasi-global rainfall data set. Span-ning 50°S–50°N (and all longitudes) and ranging from 1981 to near-present, CHIRPS incorporates our in-house climatology, CHPclim, 0.05° resolution satellite imagery, and in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring.

For the purposes of our analysis, precipitation and temperature were used. Monthly data for each geographical entity in 2019 were downloaded and then aggregated into annual values.

Study population

Target population study is children under five. The study population is represented by 5482 children from DHS program malaria survey in 2018 and 293,715 children from a random sample 10% Census (2019) database.

Variables of interest

Outcome variable

Response or the main outcome variable in this study was asymptomatic malaria infection (asymptomatic carriage) in children under 5 detected by rapid diagnostic test (RDT) during the survey. Malaria was diagnosed using serological biomarkers, SD Bioline *Pan/Pf* which is based on the detection of the *HRP-2* antigen and specific *pLDH* for the five species of *Plasmodium*. The antibodies directed against *Plasmodium* antigens are sensitive biomarkers of malaria exposure to detect malaria in the community and to monitor variations over time or the impact of interventions, and to confirm malaria elimination. RDT requires 5 µL of blood drawn using a loop from the same finger prick taken for the hemoglobin test. The lancets included in the SD Bioline Pan/Pf kit have not been used and have been destroyed with other biohazardous waste.

Interpretation test is done after 15 min and the result and its interpretation have been communicated to the parents/adults responsible for the children who have taken the test.

Independent variables

The choice of variables is based on a review of the literature which highlighted factors associated with the prevalence of malaria in SSA. Commonly cited factors include:

Socio-demographic and residential factors: child's age, gender (male/female), household standard of living (very poor, poor, average, rich, very rich), mother's education, measured here as the proportion of educated women

[1] ZDs were allocated to strata in proportion to the number of ZDs in each stratum.

aged 15–49 in the region (for the survey) and in the commune (for the census), head of household's gender (male/female), head of household's age (15–34, 35–49, 50–64, 65 and over), religion of head of household (Muslim, Christian, Traditional), place of residence (Urban/Rural), region of residence (Boucle du Mouhoun, Cascades, Centre, Centre Est, Centre Nord, Centre Ouest, Centre Sud, Est, Hauts-Bassins, Nord, Plateau Central, Sahel, Sud-Ouest) and climatic factors such as temperature and rainfall [4, 7, 13, 14, 19].

Factors related to malaria control interventions: possession of LLINs (LLINs) (Yes/No), use of LLINs (Yes/No).

Environmental factors: cumulative monthly rainfall by commune and average monthly temperatures by commune for 2019.

Data processing and analysis

For the covariates retained in the two databases, the names and coding were harmonized before the two databases were assembled. Since differences in the distribution of the variables retained in the two databases could be a source of estimation bias, a consistency analysis was carried out (see Appendix A) to exclude variables with large distribution deviations. In addition, we ensured that the co-variables in the two data sources were comparable by examining the data collection methods and the definitions of the various concepts.

Ultimately, the variables retained at individual level are region and area of residence, age and sex of the head of household, age and sex of the child and household standard of living. At communal level, the proportion of educated women aged 15–49, annual rainfall and annual temperature were used in this secondary analysis. The distribution of these variables is shown in Appendix A.

Modeling approach

The estimation approach is that proposes by Elbers Langjouw and Langjouw (ELL),[2] which consists of combining data from several sources in an econometric model. In this study, we assembled data from the census and the malaria survey [13]. The variable of interest (here RDT positivity) was present only for survey participants. We conducted a binary logistic regression and estimated the regression coefficients from the survey data, then predicted the value of the variable of interest using the census data. Confidence intervals are calculated using the Delta method.[3] The procedure is described as follows.

A logistic regression model was used to predict the probability of child i testing positive for asymptomatic malaria infection using data from the malaria survey. The logistic regression model is expressed as follows:

$$y_i \sim Bernoulli(p_i)$$

$$log\left[\frac{p_i}{1-p_i}\right] = \beta_0 + \sum_{p=1}^{P} \beta_p x_{pi}(1) \tag{1}$$

where p_i is the probability that a child i has asymptomatic malaria infection. x_{pi} are the predictors variables included in the model. The coefficients β_p are the coefficients of each of the predictor variables included in the model. β_0 is the intercept.

The probability of a child under 5 years of age testing positive for asymptomatic malaria is defined as follows:

$$p_i = \frac{e^{\left(\beta_0 + \sum_{p=1}^{P} \beta_p x_{pi}\right)}}{1 + e^{\left(\beta_0 + \sum_{p=1}^{P} \beta_p x_{pi}\right)}} \tag{2}$$

A stepwise regression was applied and Akaike's information criterion (AIC) [20] was used to select the best model to explain asymptomatic malaria infection in children under 5. Thus, the model with the lowest AIC was selected. We also used the ROC (Receiver Operating Characteristic) curve to assess model quality. This assessment is based on the predictive power of the model. The ROC curve is recognized as one of the best tools for evaluating the predictive power of a logistic model [21].

In addition to these econometric evaluations, we compared direct estimates of the prevalence of asymptomatic malaria infection from the survey with predicted estimates at regional level. Furthermore, to refine the t-model, we ensured that a replication of the estimates from the census co-variates offered relevant results. This check on the model's consistency and relevance is carried out at regional level, where the actual values from the officially published survey report are available [22].

For the model selected, coefficients are applied to the same covariates in the census data to predict the probabilities of a child under 5 testing positive for asymptomatic malaria infection. These individual probabilities are then aggregated to obtain estimates of the prevalence of asymptomatic malaria at communal, regional and national levels (Appendix D). After estimation at different geographical levels, an important challenge is to assess the uncertainty associated with the estimates. As these estimates are averages of predictions, confidence intervals can be estimated using the Delta [23, 24]. In this study, we used the STATA post estimation "margins" which produce both the average of the predictive margins

[2] See Appendix A2 for more details.

[3] In probability and statistics, the delta method is a method for approximating the asymptotic distribution of the transform of an asymptotically normal random variable.

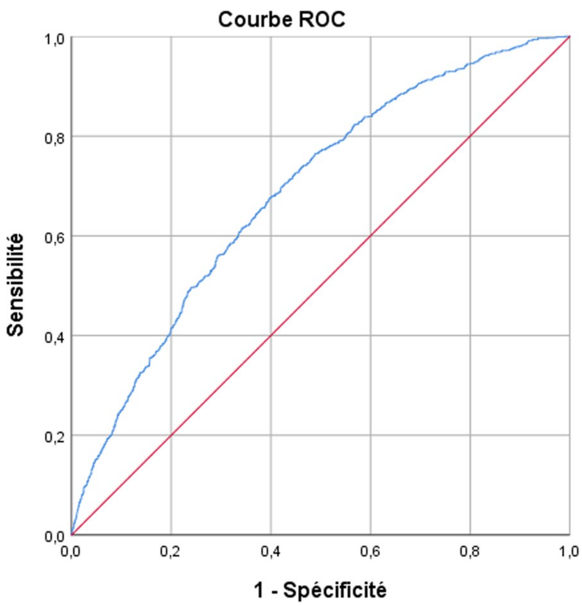

Fig. 1 The ROC curve: overall assessment of model performance by plotting sensitivity against specificity 1

[25] and calculate the associated standard errors by the Delta method.

Results

Analysis of the consistency of the results

Evaluation of the final model gives the Area Under the ROC curve (AUC) of 69.0% (Fig. 1). This value shows that the model provides non-random estimates.

Estimation of the prevalence of asymptomatic malaria in children under 5 years of age at regional level, using data from the malaria survey, provides estimates that are more or less equal to those observed, i.e. those derived from the survey analysis report [22]. In fact, for all 13 administrative regions of Burkina Faso, the confidence intervals derived from estimates based on survey data contain the prevalence of asymptomatic malaria observed in each region (cf. Table 1 and Fig. 2).

Verification of the consistency of estimates derived from census data also attests to better regional estimates. Indeed, cross-analysis of the confidence intervals of regional estimates from the two sources (Table 1) shows that estimates of asymptomatic malaria prevalence from census data are significantly the same as those observed and those derived from the survey.

Results description: exploring geographical heterogeneity

Figure 3 shows the spatial distribution of the prevalence of asymptomatic malaria in children under 5. It shows that the prevalence of asymptomatic malaria infection in children is similar across regions, whatever the data source considered. The regions with the highest prevalences were Centre-Ouest (33.4; 95% CI [29.5; 37.3]) and Sud-Ouest (32.6 with 95% CI [26.3; 38.8]), while Centre (15.2 with 95% CI [11.0; 19.4]), Hauts-Bassins (11.2 with 95% CI [8.9; 13.5]) and Plateau-central (11.4 with 95% CI [7.2; 15.5]) have the lowest levels of prevalence of asymptomatic malaria infection.

The consistency of estimates at regional level supports the idea that the model is suitable for predicting reliable estimates at communal level, as communal and regional results are the result of aggregating individual malaria infection probabilities.

Table 1 Regional prediction of malaria prevalence and values observed in the survey report

Region	Observed 2018	Malaria survey 2018	Census data 2019
Boucle du Mouhoun	25.0	22.3 (18.7, 26.0)	22.5 (18.8, 26.1)
Cascades	13.9	14.7 (10.3, 19.2)	18.6 (13.1, 24.0)
Centre	13.2	14.8 (10.8, 18.7)	15.2 (11.0, 19.4)
Centre Est	18.8	20.9 (16.8, 25.0)	22.0 (17.7, 26.4)
Centre Nord	19.8	22.7 (18.2, 27.1)	25.0 (20.1, 29.8)
Centre Ouest	34.7	34.7 (30.8, 38.6)	33.4 (29.5, 37.3)
Centre Sud	23.3	23.3 (17.1, 29.6)	23.1 (16.8, 29.4)
Est	19.7	19.7 (16.4, 22.9)	19.3 (16.1, 22.5)
Hauts-Bassins	13.5	11.4 (9.1, 13.6)	11.2 (8.9, 13.5)
Nord	16.6	16.7 (13.3, 20.1)	15.8 (12.5, 19.2)
Plateau Central	13.3	11.5 (7.3, 15.6)	11.4 (7.2, 15.5)
Sahel	19.2	19.1 (14.8, 23.3)	18.4 (14.3, 22.6)
Sud-Ouest	32.4	32.9 (26.7, 39.1)	32.6 (26.3, 38.8)
Total (National average)	20.02	20.02 (19.1, 21.3)	20.03 (18.8, 21.2)

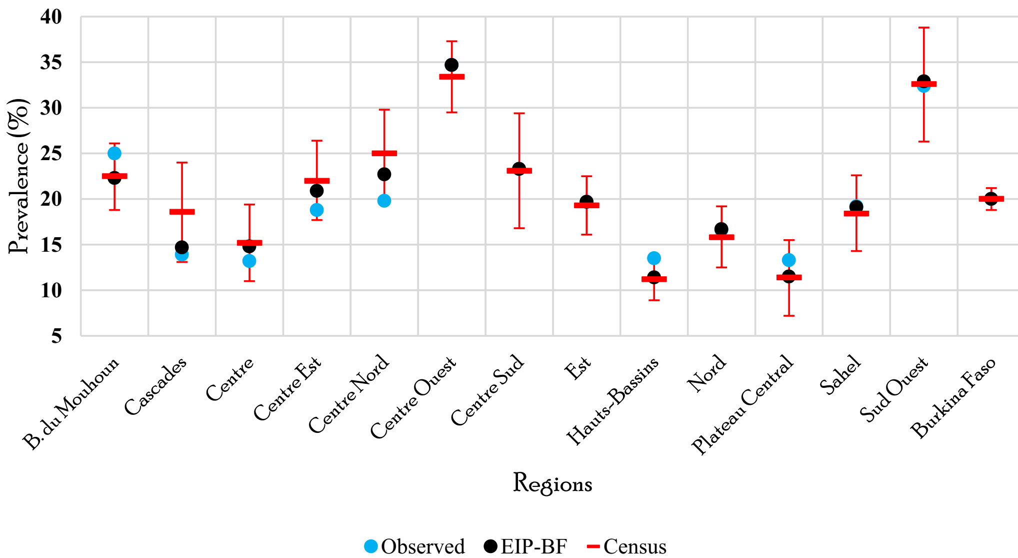

Fig. 2 Regional predictions of malaria prevalence from the two sources and values observed in the survey report

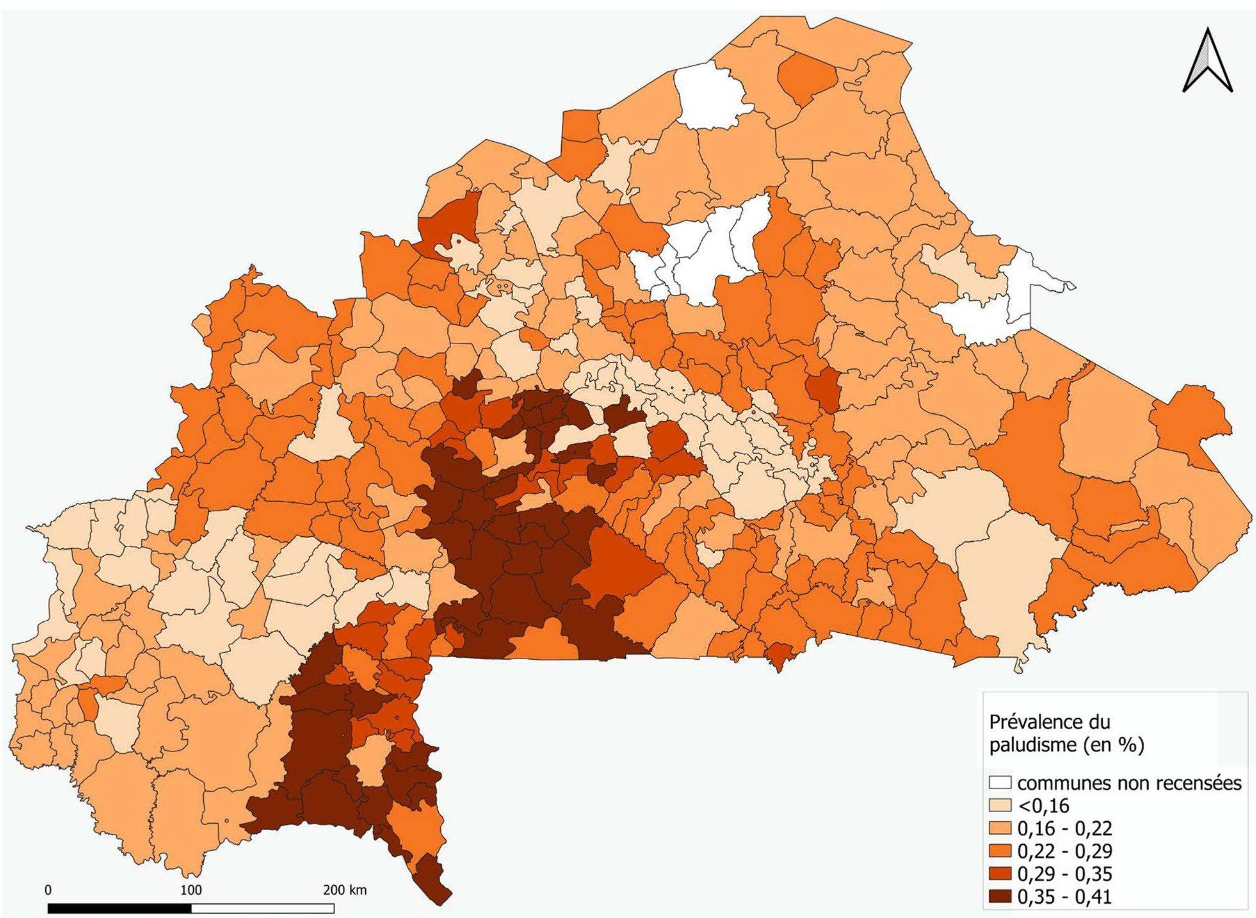

Fig. 3 Mapping of prevalence predictions for asymptomatic malaria in children under 5 at the communal level. *Source of the data*: Map created by Bassinga et al. (2024)

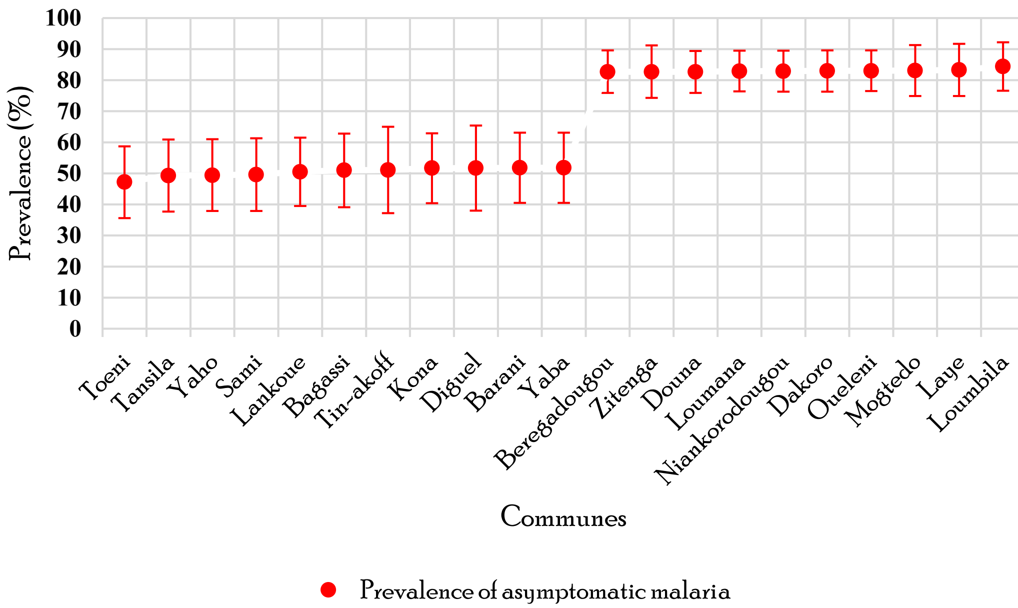

Fig. 4 Malaria prevalence in the ten communes with the highest and ten with the lowest indicator values

Thus, analysis of estimates at commune level reveals heterogeneity in the prevalence of asymptomatic malaria in children between these entities (Fig. 3).

Of the 341 communes in which estimates were made, 208 had prevalences higher than the national average of 20.3% (95% CI [18.8; 21.2]). The ten communes (Fig. 4) with the highest prevalences were Djigoué (41.4% with 95% CI [33.5; 49.4]), Périgban (40.9% with 95% CI [33; 48.8]), Bougnounou (40.1% with 95% CI [35.5; 44.8]), Loropéni (39.9% with 95% CI [32.3; 47.5]), Siglé (39.7% with 95% CI [35.2; 44.2]), Kpuéré (39.7% with 95% CI [32.2; 47.2]), Zamo (39% with 95% CI [34.5; 43.4]), Nébiélianayou (38.7% with 95% CI [34.2; 43.1]), Silly (38.7% with 95% CI [34.3; 43.0]), and Zawara (38.6% with 95% CI [34.3; 42.9]). At the other end of the scale in terms of prevalence of asymptomatCI malaria, the communes of Bobo-Dioulasso (5.1% with 95% CI [3.6; 6.5]), Houndé (8.4% with 95% CI [6.4; 10.4]), Ziniaré (8.7% with 95% CI [5.4; 11.9]), Zorgho (8.9% with 95% CI [5.5; 12.3]), Oula, Ouagadougou, Boussé, Orodara, Djibo and Pouytenga are the ten communes where malaria prevalence is relatively low.

When we look at heterogeneity within regions, we generally find that rural communes have the highest prevalence of asymptomatic malaria infection, compared to the urban communes. For instance, in the Centre region, the regional level prevalence of asymptomatic malaria is 15.3%, while this varies considerably between the urban commune of Ouagadougou (9,7%) and the region's rural communes of Komki-Ipala (36.1%), Komsilga (31.5%), Koubri (34.9%), Pabré (35.4%), Saaba (30.7%) and Tanghuin-Dassouri (34.6%), with an average malaria prevalence of 33%. The same is true for the Haut-Bassins region (11.2%), where the urban communes of Bobo-Dioulasso (5.1%), Houndé (8.2%) and Orodara (10.0%) have the lowest levels of malaria infection in children under five, compared with the other communes in the region, where prevalence varies from 14.0 to 19.0%. In the Centre-West and South-West regions, where levels of the indicator are the highest in the country, there are also strong communal disparities in malaria infection.

Discussion

Geographical identification of health problems is an important element of efforts control as it facilitates better allocation of the limited resources, improved health management and better targeting of interventions to maximize risk reduction [8, 23, 26, 27]. Analysis of the geographical distribution of the prevalence of asymptomatic malaria infection across the communes of Burkina Faso has highlighted sub-regional inequalities or heterogeneity that are often overlooked and difficult to highlight using survey data. The most perceptible communal differences are found between urban and rural communes within the same region, which is in itself a very useful result.

Geostatistical modeling of malaria risk among children in Burkina Faso using 2010 DHS data showed that low-risk areas were mainly concentrated in large urban centers such Ouagadougou the capital city [8]. This variation in malaria relative risk between localities in endemic regions is not surprising. It has always been recognized in other contexts [28, 29]. Differences between communes may be the result of heterogeneous ecological conditions that sustain larval breeding sites and thus facilitate the proliferation of mosquitoes, the vectors of malaria [30]. These vectors mainly determine the distribution and intensity of the disease [30]. In Kenya, for example, researchers noted that exposure to malaria could not be homogeneous, as malaria incidence did not follow a Poisson distribution, a phenomenon they described as over-dispersion [28]. Hence, the heterogeneity of malaria distribution at commune level could be explained mainly by socio-economic, health, hygiene and sanitation inequalities between communes, inequalities that are more prevalent between urban and rural communes [23]. These factors generally depend on the level of development of the various localities, since malaria and poverty are closely linked [30].

As Zhang et al. (2020) have already done in Nepal [16], we have succeeded in showing how the ELL small-area estimation model can be used to combine high-resolution census data with household survey data to produce more detailed and useful estimates. Compared with other small area estimation approaches (Bayesian models in particular), this one is relatively simple to implement and provides reasonably accurate results, provided certain precautions are taken to ensure data consistency and relevance. The steps required to implement the ELL method appear to be less complex, which represents a good opportunity to produce indicators at finer scales and adapt them to the needs of development policies, as recommended by the MDGs [18]. One of the prerequisites for this estimation approach is that the two operations (survey and census) are carried out at similar times, to avoid any major change in population and household structure. The data used in this analysis are collected at 1-year intervals, which is a major strength of this approach.

However, as is common knowledge, statistical estimates are sometimes subject to errors related to the estimation or sampling model. It is therefore important to assess the extent of these errors. In this study, the ROC curve reveals that the final model does not fully explain malaria prevalence, no doubt due to the failure to account for important and necessary variables. However, the robustness of the survey and census data helps to improve the accuracy of the estimates.

Another important fact to note, and one that remains a limitation of this study, is the failure to consider spatial autocorrelation. In fact, in the geographical analysis of a phenomenon measured in several places, it is generally observed that there is a relationship between the values of areas that are relatively close to each other [31]. As a result, other approaches to accounting for this spatial autocorrelation as a random effect in the analysis may be important. Such approaches may help to explain unmodeled variability more effectively, and would probably present a better picture of the spatial distribution of these data, albeit at the cost of reduced precision of the estimates [16].

Conclusions

The geographical inequalities in malaria prevalence highlighted among children under five suggest significant disparities between communes. Within the same region, this disparity is particularly marked between urban and rural communes. This highlights a pattern of dichotomy between urban and rural communities within the same region. Children in urban communes are relatively less exposed to malaria than those in rural communes. This situation seems to depend on the level of development of the targeted communes, especially since the factors associated with malaria prevalence easily demonstrate this.

This analysis shows that, while malaria control measures for children under 5 years of age need to be strengthened, regardless of their place of residence, rural communes need to be given greater attention in order to achieve greater gains in reducing malaria morbidity and mortality. Given the government's efforts to combat malaria, it's undeniable that we need to take account of the specific features of rural areas, where sanitation levels are sometimes poor.

Appendix

Appendix A: frequency and mean distributions of variables

Variables	Malaria survey 2018		Census 2019	
	Number	N %	Number	N %
Region of residence				
Boucle du Mouhoun	558	10.2	28,898	9.8
Cascades	255	4.6	13,344	4.5
Centre	313	5.7	36,483	12.4
Centre Est	441	8.0	24,757	8.4
Centre Nord	526	9.6	25,222	8.6
Centre Ouest	553	10.1	24,082	8.2
Centre Sud	167	3.1	10,807	3.7
Est	566	10.3	30,141	10.3
Hauts-Bassins	762	13.9	31,065	10.6
Nord	466	8.5	26,762	9.1
Plateau Central	255	4.6	14,931	5.1

Variables	Malaria survey 2018		Census 2019	
	Number	N %	Number	N %
Sahel	406	7.4	14,341	4.9
Sud-Ouest	214	3.9	12,882	4.4
Place of residence				
Urban	878	16.0	64,487	22.0
Rural	4604	84.0	229,228	78.0
Child's gender				
Male	2800	51.1	147,362	50.2
Female	2682	48.9	146,353	49.8
Child's age				
0 an	605	11.0	51,963	17.7
1 an	1098	20.0	53,276	18.1
2 ans	1206	22.0	64,018	21.8
3 ans	1326	24.2	62,399	21.2
4 ans	1247	22.8	62,059	21.1
Gender of head of household				
Male	5175	94.4	264,041	89.9
Female	307	5.6	29,674	10.1
Age of head of household				
15–34 ans	1652	30.1	110,538	37.6
35–49 ans	2345	42.8	122,721	41.8
50–64 ans	1079	19.7	45,204	15.4
65 ans ou+	406	7.4	15,252	5.2
Wealth index				
Poorest	1148	20.9	63,950	21.8
Poorer	1147	20.9	65,420	22.3
Middle	1129	20.6	64,658	22.0
Richer	1102	20.1	57,306	19.5
Richest	956	17.4	42,174	14.4

Other variables	Malaria survey 2018	Census 2019
	Mean	Mean
Proportion of women aged 15–49 with education	42.5	56.4
Net usage rate	55.2	89.4
Annual rainfall	928.8	907.6
Annual temperatures	35.9	35.9

Appendix B: ELL method

It consists in building an econometric model linking the malaria infection status of each child to a set of explanatory variables common to both the IBHS and the RGPH. The coefficients of the model's exogenous variables obtained from the survey data are fed into the census database to generate a prevalence of malaria infection per census child. Finally, the malaria prevalence is constructed for different geographical groups. The process thus comprises three stages.

First step: we begin by identifying a set of explanatory variables present in both databases that meet certain comparability criteria. We check that the wording of the questions and answers is the same in both questionnaires. From the selected questions, we then construct a series of variables whose comparability we test.

Second step: the per capita malaria prevalence model is estimated using the survey data. To maximize accuracy, the model is estimated at the lowest geographical level for which the survey remains representative. This level is usually the sampling strata. In this analysis, the geographical level considered is the region.

Third step: to complete the map, we associate the parameters estimated in the second step with the characteristics of each child in the census, to predict per capita prevalence. Individual prevalences are then aggregated at the regional and commune levels.

Appendix C: logistic regression result of the final model

Predictor	Odds ratio (95% CI)
Regions	
Boucle du Mouhoun	0.713 (0.474, 1.074)
Cascades	0.461 (0.281, 0.756)
Centre	1.324 (0.781, 2.244)
Centre Est	0.747 (0.484, 1.152)
Centre Nord	0.927 (0.572, 1.503)
Centre Ouest	1.262 (0.873, 1.824)
Centre Sud	0.673 (0.412, 1.099)
Est	0.555 (0.363, 0.849)
Hauts-Bassins	0.348 (0.236, 0.513)
Nord	0.494 (0.322, 0.758)
Plateau Central	0.336 (0.191, 0.592)
Sahel	0.634 (0.369, 1.090)
Sud-Ouest	1
Place of residence	
Rural	3.331 (2.289, 4.845)
Urban	1
Child's age	
0 year	1
1 year	1.764 (1.259, 2.473)
2 years	2.282 (1.646, 3.164)
3 years	2.624 (1.904, 3.616)
4 ans	3.312 (2.404, 4.564)
Age of head of household	
15–34 ans	0.747 (0.625, 0.892)
35–49 ans	0.945 (0.765, 1.169)
50–64 ans	1.230 (0.929, 1.629)
65 ans et+	1
Wealth index	

Predictor	Odds ratio (95% CI)
Poorest	1
Poorer	0.882 (0.708, 1.097)
Middle	0.624 (0.494, 0.786)
Richer	0.757 (0.601, 0.954)
Richest	0.443 (0.311, 0.631)
Temperature	
Mean	0.854 (0.766, 0.952)

Appendix D: results from estimation at commune level using census and survey data

Region	Province	Commune	Prevalence (95% CI)
Boucle du mouhoun	Bale	Bagassi	25.1 (20.8, 29.4)
Boucle du mouhoun	Bale	Bana	24.4 (20.2, 28.7)
Boucle du mouhoun	Bale	Boromo	17.6 (14.0, 21.2)
Boucle du mouhoun	Bale	Fara	20.7 (17.0, 24.4)
Boucle du mouhoun	Bale	Oury	23.6 (19.6, 27.6)
Boucle du mouhoun	Bale	Pa	25.8 (21.2, 30.3)
Boucle du mouhoun	Bale	Pompoi	24.6 (20.4, 28.7)
Boucle du mouhoun	Bale	Poura	19.6 (16.0, 23.2)
Boucle du mouhoun	Bale	Siby	25.1 (20.6, 29.6)
Boucle du mouhoun	Bale	Yaho	26.1 (21.7, 30.5)
Boucle du mouhoun	Banwa	Balave	22.1 (18.4, 25.8)
Boucle du mouhoun	Banwa	Kouka	24.7 (20.3, 29.1)
Boucle du mouhoun	Banwa	Sami	26.5 (22.0, 30.9)
Boucle du mouhoun	Banwa	Sanaba	24.0 (20.1, 28.0)
Boucle du mouhoun	Banwa	Solenzo	23.1 (19.2, 27.0)
Boucle du mouhoun	Banwa	Tansila	24.8 (20.7, 28.9)
Boucle du mouhoun	Kossi	Barani	24.7 (20.5, 28.9)
Boucle du mouhoun	Kossi	Bomborokuy	21.2 (16.8, 25.6)
Boucle du mouhoun	Kossi	Bourasso	22.6 (18.6, 26.5)
Boucle du mouhoun	Kossi	Djibasso	23.8 (19.8, 27.8)

Region	Province	Commune	Prevalence (95% CI)
Boucle du mouhoun	Kossi	Dokuy	23.7 (19.7, 27.7)
Boucle du mouhoun	Kossi	Doumbala	23.1 (19.1, 27.1)
Boucle du mouhoun	Kossi	Kombori	22.9 (18.9, 26.9)
Boucle du mouhoun	Kossi	Madouba	21.6 (17.9, 25.3)
Boucle du mouhoun	Kossi	Nouna	17.2 (13.9, 20.6)
Boucle du mouhoun	Kossi	Sono	25.0 (20.1, 30.0)
Boucle du mouhoun	Mouhoun	Bondokuy	25.4 (21.1, 29.6)
Boucle du mouhoun	Mouhoun	Dedougou	14.5 (11.7, 17.2)
Boucle du mouhoun	Mouhoun	Douroula	22.3 (18.6, 26.1)
Boucle du mouhoun	Mouhoun	Kona	23.5 (19.6, 27.4)
Boucle du mouhoun	Mouhoun	Ouarkoye	24.6 (20.6, 28.7)
Boucle du mouhoun	Mouhoun	Safane	23.0 (19.2, 26.8)
Boucle du mouhoun	Mouhoun	Tcheriba	25.0 (20.9, 29.1)
Boucle du mouhoun	Nayala	Gassan	19.7 (16.0, 23.5)
Boucle du mouhoun	Nayala	Gossina	24.5 (20.5, 28.5)
Boucle du mouhoun	Nayala	Kougny	20.7 (16.7, 24.6)
Boucle du mouhoun	Nayala	Toma	18.0 (14.7, 21.3)
Boucle du mouhoun	Nayala	Yaba	24.2 (20.1, 28.3)
Boucle du mouhoun	Nayala	Ye	22.8 (19.0, 26.7)
Boucle du mouhoun	Sourou	Di	24.2 (19.9, 28.4)
Boucle du mouhoun	Sourou	Gomboro	23.2 (19.3, 27.1)
Boucle du mouhoun	Sourou	Kassoum	21.5 (17.3, 25.6)
Boucle du mouhoun	Sourou	Kiembara	24.4 (20.3, 28.4)
Boucle du mouhoun	Sourou	Lanfiera	22.5 (18.7, 26.2)
Boucle du mouhoun	Sourou	Lankoue	24.5 (20.4, 28.6)
Boucle du mouhoun	Sourou	Toeni	25.0 (20.5, 29.5)
Boucle du mouhoun	Sourou	Tougan	20.5 (16.9, 24.1)
Cascades	Comoe	Banfora	10.3 (6.9, 13.6)
Cascades	Comoe	Beregadougou	20.6 (14.3, 26.9)
Cascades	Comoe	Mangodara	20.8 (14.7, 26.9)

Region	Province	Commune	Prevalence (95% CI)
Cascades	Comoe	Moussodougou	22.9 (15.9, 29.9)
Cascades	Comoe	Niangoloko	17.7 (12.4, 23.0)
Cascades	Comoe	Ouo	21.3 (15.1, 27.6)
Cascades	Comoe	Sideradougou	20.5 (14.5, 26.5)
Cascades	Comoe	Soubakaniedougou	19.6 (13.7, 25.4)
Cascades	Comoe	Tiefora	20.8 (14.7, 27.0)
Cascades	Leraba	Dakoro	19.7 (13.8, 25.6)
Cascades	Leraba	Douna	20.9 (14.6, 27.1)
Cascades	Leraba	Kankalaba	20.7 (14.6, 26.9)
Cascades	Leraba	Loumana	19.8 (13.9, 25.6)
Cascades	Leraba	Niankorodougou	18.7 (13.0, 24.4)
Cascades	Leraba	Oueleni	21.7 (15.3, 28.2)
Cascades	Leraba	Sindou	17.1 (12.0, 22.2)
Cascades	Leraba	Wolonkoto	22.8 (16.0, 29.6)
Centre	Kadiogo	Komki-Ipala	36.1 (27.0, 45.3)
Centre	Kadiogo	Komsilga	31.5 (23.0, 40.0)
Centre	Kadiogo	Koubri	34.9 (26.1, 43.8)
Centre	Kadiogo	Ouagadougou	9.7 (6.3, 13.1)
Centre	Kadiogo	Pabre	35.4 (26.5, 44.4)
Centre	Kadiogo	Saaba	30.7 (22.3, 39.1)
Centre	Kadiogo	Tanghin Dassouri	34.6 (25.7, 43.5)
Centre est	Boulgou	Bagre	28.2 (22.5, 33.9)
Centre est	Boulgou	Bane	28.4 (22.6, 34.1)
Centre est	Boulgou	Beguedo	23.3 (18.3, 28.2)
Centre est	Boulgou	Bissiga	26.2 (21.1, 31.3)
Centre est	Boulgou	Bittou	22.5 (18.0, 27.0)
Centre est	Boulgou	Boussouma	27.0 (21.2, 32.8)
Centre est	Boulgou	Boussouma	26.2 (21.1, 31.3)
Centre est	Boulgou	Garango	17.5 (13.7, 21.2)
Centre est	Boulgou	Komtoega	22.4 (17.8, 27.1)
Centre est	Boulgou	Niaogho	26.9 (21.5, 32.4)
Centre est	Boulgou	Tenkodogo	18.0 (14.3, 21.6)
Centre est	Boulgou	Zabre	24.7 (19.8, 29.6)
Centre est	Boulgou	Zoaga	29.6 (23.8, 35.4)
Centre est	Boulgou	Zonse	23.1 (18.4, 27.8)
Centre est	Koulpelogo	Comin-Yanga	23.5 (18.7, 28.4)
Centre est	Koulpelogo	Dourtenga	23.5 (18.7, 28.2)
Centre est	Koulpelogo	Lalgaye	27.5 (21.9, 33.1)
Centre est	Koulpelogo	Ouargaye	21.2 (17.0, 25.4)
Centre est	Koulpelogo	Sanga	26.7 (21.5, 31.9)
Centre est	Koulpelogo	Soudougui	26.5 (21.4, 31.6)
Centre est	Koulpelogo	Yargatenga	24.0 (19.2, 28.8)
Centre est	Koulpelogo	Yonde	24.6 (19.8, 29.4)
Centre est	Kouritenga	Andemtenga	24.2 (19.4, 29.0)
Centre est	Kouritenga	Baskoure	25.4 (20.3, 30.4)
Centre est	Kouritenga	Dialgaye	23.1 (18.4, 27.8)
Centre est	Kouritenga	Gounghin	24.4 (19.6, 29.3)
Centre est	Kouritenga	Kando	24.2 (19.4, 29.0)

Region	Province	Commune	Prevalence (95% CI)
Centre est	Kouritenga	Koupela	15.2 (11.8, 18.5)
Centre est	Kouritenga	Pouytenga	10.3 (7.4, 13.2)
Centre est	Kouritenga	Tensobentenga	23.6 (18.9, 28.3)
Centre est	Kouritenga	Yargo	23.9 (19.1, 28.7)
Centre nord	Bam	Bourzanga	27.3 (22.0, 32.7)
Centre nord	Bam	Guibare	26.8 (21.5, 32.1)
Centre nord	Bam	Kongoussi	20.8 (16.4, 25.2)
Centre nord	Bam	Rollo	27.1 (21.8, 32.5)
Centre nord	Bam	Rouko	27.9 (22.5, 33.3)
Centre nord	Bam	Sabce	28.2 (22.5, 33.9)
Centre nord	Bam	Tikare	26.1 (21.1, 31.2)
Centre nord	Namentenga	Boala	27.1 (21.7, 32.4)
Centre nord	Namentenga	Boulsa	25.5 (20.5, 30.5)
Centre nord	Namentenga	Bouroum	26.2 (20.9, 31.6)
Centre nord	Namentenga	Dargo	29.4 (23.6, 35.2)
Centre nord	Namentenga	Nagbingou	26.2 (20.9, 31.5)
Centre nord	Namentenga	Tougouri	25.3 (19.9, 30.7)
Centre nord	Namentenga	Yalgo	24.7 (19.7, 29.7)
Centre nord	Namentenga	Zeguedeguin	26.6 (21.2, 32.1)
Centre nord	Sanmatenga	Kaya	16.5 (12.9, 20.1)
Centre nord	Sanmatenga	Korsimoro	23.7 (18.8, 28.6)
Centre nord	Sanmatenga	Mane	27.3 (22.0, 32.6)
Centre nord	Sanmatenga	Pibaore	28.5 (23.0, 33.9)
Centre nord	Sanmatenga	Pissila	27.4 (22.0, 32.7)
Centre nord	Sanmatenga	Ziga	27.5 (22.3, 32.8)
Centre ouest	Boulkiemde	Bingo	35.7 (31.4, 40.0)
Centre ouest	Boulkiemde	Imasgho	36.5 (32.2, 40.9)
Centre ouest	Boulkiemde	Kindi	37.5 (33.0, 42.0)
Centre ouest	Boulkiemde	Kokoloko	34.7 (30.7, 38.8)
Centre ouest	Boulkiemde	Koudougou	18.6 (15.3, 21.8)
Centre ouest	Boulkiemde	Nandiala	35.1 (30.6, 39.6)
Centre ouest	Boulkiemde	Nanoro	35.7 (31.4, 40.0)
Centre ouest	Boulkiemde	Pella	35.7 (31.4, 40.1)
Centre ouest	Boulkiemde	Poa	33.1 (28.9, 37.3)
Centre ouest	Boulkiemde	Ramongo	38.3 (34.0, 42.6)
Centre ouest	Boulkiemde	Sabou	33.8 (29.4, 38.2)
Centre ouest	Boulkiemde	Sigle	39.7 (35.2, 44.2)
Centre ouest	Boulkiemde	Soaw	36.5 (32.0, 41.0)
Centre ouest	Boulkiemde	Sourgou	35.6 (31.5, 39.7)
Centre ouest	Boulkiemde	Thyou	33.8 (29.6, 37.9)
Centre ouest	Sanguie	Dassa	33.7 (29.4, 37.9)
Centre ouest	Sanguie	Didyr	34.3 (29.6, 39.0)
Centre ouest	Sanguie	Godyr	35.4 (30.6, 40.2)
Centre ouest	Sanguie	Kordie	34.8 (29.9, 39.7)
Centre ouest	Sanguie	Kyon	34.9 (30.0, 39.7)
Centre ouest	Sanguie	Pouni	35.4 (30.8, 40.0)
Centre ouest	Sanguie	Reo	24.7 (20.8, 28.5)
Centre ouest	Sanguie	Tenado	37.1 (32.7, 41.5)
Centre ouest	Sanguie	Zamo	39.0 (34.5, 43.4)
Centre ouest	Sanguie	Zawara	38.6 (34.3, 42.9)

Region	Province	Commune	Prevalence (95% CI)
Centre ouest	Sissili	Bieha	37.4 (33.1, 41.7)
Centre ouest	Sissili	Boura	38.0 (33.7, 42.2)
Centre ouest	Sissili	Leo	22.2 (18.7, 25.7)
Centre ouest	Sissili	Nebielianayou	38.7 (34.2, 43.1)
Centre ouest	Sissili	Niabouri	37.4 (33.1, 41.7)
Centre ouest	Sissili	Silly	38.7 (34.3, 43.0)
Centre ouest	Sissili	To	36.5 (32.3, 40.6)
Centre ouest	Ziro	Bakata	38.5 (34.0, 42.9)
Centre ouest	Ziro	Bougnounou	40.1 (35.5, 44.8)
Centre ouest	Ziro	Cassou	38.4 (34.1, 42.8)
Centre ouest	Ziro	Dalo	38.2 (33.7, 42.7)
Centre ouest	Ziro	Gao	36.8 (32.6, 41.0)
Centre ouest	Ziro	Sapouy	33.5 (29.4, 37.5)
Centre sud	Bazega	Doulougou	24.7 (18.0, 31.5)
Centre sud	Bazega	Gaongo	21.5 (15.1, 27.9)
Centre sud	Bazega	Ipelce	23.5 (16.9, 30.0)
Centre sud	Bazega	Kayao	25.5 (18.7, 32.4)
Centre sud	Bazega	Kombissiri	17.3 (12.3, 22.3)
Centre sud	Bazega	Sapone	23.6 (17.1, 30.0)
Centre sud	Bazega	Toece	24.1 (17.5, 30.6)
Centre sud	Nahouri	Guiaro	26.3 (19.2, 33.3)
Centre sud	Nahouri	Pô	19.4 (13.9, 25.0)
Centre sud	Nahouri	Tiebele	25.7 (18.9, 32.5)
Centre sud	Nahouri	Zecco	23.0 (16.6, 29.4)
Centre sud	Nahouri	Ziou	25.5 (18.7, 32.4)
Centre sud	Zoundweogo	Bere	22.8 (16.4, 29.1)
Centre sud	Zoundweogo	Binde	21.4 (15.1, 27.6)
Centre sud	Zoundweogo	Gogo	26.9 (19.7, 34.1)
Centre sud	Zoundweogo	Gomboussou-gou	27.6 (19.7, 35.6)
Centre sud	Zoundweogo	Guiba	24.0 (17.4, 30.6)
Centre sud	Zoundweogo	Manga	11.6 (7.8, 15.3)
Centre sud	Zoundweogo	Nobere	24.4 (17.7, 31.1)
Est	Gnagna	Bilanga	19.6 (16.2, 23.0)
Est	Gnagna	Bogande	17.3 (14.1, 20.4)
Est	Gnagna	Coalla	16.1 (12.8, 19.3)
Est	Gnagna	Liptougou	18.4 (15.0, 21.9)
Est	Gnagna	Mani	16.9 (13.4, 20.3)
Est	Gnagna	Piela	19.3 (16.0, 22.5)
Est	Gnagna	Thion	18.0 (14.3, 21.7)
Est	Gourma	Diabo	19.2 (15.8, 22.6)
Est	Gourma	Diapangou	20.6 (17.0, 24.2)
Est	Gourma	Fada N'Gourma	13.6 (11.2, 16.0)
Est	Gourma	Matiacoali	22.6 (18.7, 26.5)
Est	Gourma	Tibga	19.4 (16.2, 22.7)
Est	Gourma	Yamba	19.6 (16.3, 22.9)
Est	Komandjoari	Bartibougou	20.5 (17.0, 24.1)
Est	Komandjoari	Foutouri	19.7 (16.4, 23.0)
Est	Komandjoari	Gayeri	17.6 (14.4, 20.8)
Est	Kompienga	Kompienga	25.1 (19.4, 30.9)

Region	Province	Commune	Prevalence (95% CI)
Est	Kompienga	Madjoari	26.7 (21.3, 32.1)
Est	Kompienga	Pama	15.2 (12.6, 17.9)
Est	Tapoa	Botou	22.8 (18.8, 26.8)
Est	Tapoa	Diapaga	19.0 (15.8, 22.3)
Est	Tapoa	Kantchari	22.1 (18.3, 25.8)
Est	Tapoa	Logobou	24.0 (19.6, 28.4)
Est	Tapoa	Namounou	20.4 (17.0, 23.8)
Est	Tapoa	Partiaga	22.8 (18.9, 26.7)
Est	Tapoa	Tambaga	23.9 (19.5, 28.4)
Est	Tapoa	Tansarga	21.6 (18.0, 25.1)
Hauts-bassins	Houet	Bama	16.0 (12.8, 19.2)
Hauts-bassins	Houet	Bobo-Dioulasso	5.1 (3.6, 6.5)
Hauts-bassins	Houet	Dande	16.8 (13.4, 20.2)
Hauts-bassins	Houet	Faramana	15.8 (12.4, 19.2)
Hauts-bassins	Houet	Fo	15.2 (12.1, 18.4)
Hauts-bassins	Houet	Karankasso Sambla	16.9 (13.2, 20.5)
Hauts-bassins	Houet	Karankasso-Vigue	15.0 (11.9, 18.1)
Hauts-bassins	Houet	Koundougou	16.3 (12.9, 19.6)
Hauts-bassins	Houet	Lena	17.6 (14.1, 21.2)
Hauts-bassins	Houet	Padema	14.6 (11.5, 17.7)
Hauts-bassins	Houet	Peni	16.8 (13.4, 20.3)
Hauts-bassins	Houet	Satiri	16.4 (13.1, 19.7)
Hauts-bassins	Houet	Toussiana	17.6 (13.5, 21.7)
Hauts-bassins	Kenedougou	Banzon	16.9 (13.1, 20.8)
Hauts-bassins	Kenedougou	Djigouera	17.4 (13.5, 21.3)
Hauts-bassins	Kenedougou	Kangala	19.0 (14.1, 23.9)
Hauts-bassins	Kenedougou	Kayan	15.0 (11.9, 18.2)
Hauts-bassins	Kenedougou	Koloko	16.2 (12.6, 19.9)
Hauts-bassins	Kenedougou	Kourignon	18.7 (14.0, 23.3)
Hauts-bassins	Kenedougou	Kourouma	15.5 (12.4, 18.7)
Hauts-bassins	Kenedougou	Morolaba	14.2 (11.0, 17.3)
Hauts-bassins	Kenedougou	N'Dorola	14.6 (11.5, 17.7)
Hauts-bassins	Kenedougou	Orodara	10.0 (7.0, 13.1)
Hauts-bassins	Kenedougou	Samogohiri	19.0 (14.2, 23.8)
Hauts-bassins	Kenedougou	Samorogouan	14.7 (11.7, 17.8)
Hauts-bassins	Kenedougou	Sindo	14.0 (10.9, 17.1)
Hauts-bassins	Tuy	Bekuy	16.3 (13.0, 19.7)
Hauts-bassins	Tuy	Bereba	16.0 (12.7, 19.2)
Hauts-bassins	Tuy	Bony	14.7 (11.1, 18.3)
Hauts-bassins	Tuy	Founzan	14.3 (10.9, 17.6)
Hauts-bassins	Tuy	Hounde	8.4 (6.4, 10.4)
Hauts-bassins	Tuy	Koti	14.4 (11.0, 17.8)
Hauts-bassins	Tuy	Koumbia	15.1 (12.0, 18.2)
Nord	Loroum	Banh	18.7 (14.7, 22.7)
Nord	Loroum	Ouindigui	17.9 (14.1, 21.7)
Nord	Loroum	Solle	19.5 (15.3, 23.6)
Nord	Loroum	Titao	12.2 (9.4, 15.0)
Nord	Passore	Arbole	17.9 (14.2, 21.6)
Nord	Passore	Bagare	19.5 (15.5, 23.5)

Region	Province	Commune	Prevalence (95% CI)
Nord	Passore	Bokin	17.9 (14.2, 21.6)
Nord	Passore	Gomponsom	23.4 (17.6, 29.3)
Nord	Passore	Kirsi	16.0 (12.4, 19.6)
Nord	Passore	La-Todin	17.4 (13.7, 21.0)
Nord	Passore	Pilimpikou	17.8 (14.0, 21.5)
Nord	Passore	Samba	18.2 (14.4, 22.0)
Nord	Passore	Yako	14.5 (11.5, 17.6)
Nord	Yatenga	Barga	15.2 (11.5, 18.9)
Nord	Yatenga	Kain	18.3 (14.2, 22.4)
Nord	Yatenga	Kalsaka	18.0 (14.3, 21.7)
Nord	Yatenga	Kossouka	15.6 (12.1, 19.2)
Nord	Yatenga	Koumbri	16.4 (12.7, 20.1)
Nord	Yatenga	Ouahigouya	16.3 (12.7, 19.8)
Nord	Yatenga	Oula	9.7 (7.5, 11.9)
Nord	Yatenga	Rambo	15.8 (12.2, 19.4)
Nord	Yatenga	Seguenega	17.0 (13.5, 20.6)
Nord	Yatenga	Tangaye	16.0 (12.5, 19.5)
Nord	Yatenga	Thiou	16.9 (13.2, 20.7)
Nord	Yatenga	Zogore	18.7 (14.8, 22.5)
Nord	Zondoma	Bassi	15.7 (12.2, 19.3)
Nord	Zondoma	Boussou	19.8 (15.8, 23.8)
Nord	Zondoma	Gourcy	14.0 (11.0, 17.0)
Nord	Zondoma	Leba	17.4 (13.8, 21.0)
Nord	Zondoma	Tougo	17.7 (14.1, 21.4)
Plateau central	Ganzourgou	Boudry	11.5 (7.2, 15.7)
Plateau central	Ganzourgou	Kogho	14.1 (9.0, 19.3)
Plateau central	Ganzourgou	Meguet	11.4 (7.2, 15.6)
Plateau central	Ganzourgou	Mogtedo	10.4 (6.4, 14.3)
Plateau central	Ganzourgou	Salogo	13.1 (8.3, 17.9)
Plateau central	Ganzourgou	Zam	10.6 (6.5, 14.7)
Plateau central	Ganzourgou	Zorgho	8.9 (5.5, 12.3)
Plateau central	Ganzourgou	Zoungou	11.2 (7.0, 15.4)
Plateau central	Kourweogo	Bousse	10.0 (6.2, 13.8)
Plateau central	Kourweogo	Laye	13.8 (8.6, 19.1)
Plateau central	Kourweogo	Niou	13.0 (8.2, 17.7)
Plateau central	Kourweogo	Sourgoubila	14.9 (9.4, 20.4)
Plateau central	Kourweogo	Toeghin	12.9 (8.2, 17.6)
Plateau central	Oubritenga	Absouya	11.9 (7.5, 16.2)
Plateau central	Oubritenga	Dapelogo	13.0 (8.3, 17.8)
Plateau central	Oubritenga	Loumbila	12.4 (7.7, 17.1)
Plateau central	Oubritenga	Nagreongo	12.5 (7.9, 17.0)
Plateau central	Oubritenga	Ourgou-Manega	13.0 (8.3, 17.8)
Plateau central	Oubritenga	Ziniare	8.7 (5.4, 11.9)
Plateau central	Oubritenga	Zitenga	11.2 (6.9, 15.4)
Sahel	Oudalan	Deou	19.6 (15.1, 24.0)
Sahel	Oudalan	Gorom-Gorom	17.7 (13.6, 21.8)
Sahel	Oudalan	Markoye	17.7 (13.2, 22.1)
Sahel	Oudalan	Oursi	20.3 (15.7, 24.9)
Sahel	Oudalan	Tin-Akoff	19.4 (14.8, 23.9)
Sahel	Seno	Bani	19.7 (15.2, 24.1)
Sahel	Seno	Dori	17.6 (13.7, 21.6)
Sahel	Seno	Falagountou	18.9 (14.5, 23.3)
Sahel	Seno	Gorgadji	20.8 (16.1, 25.4)
Sahel	Seno	Sampelga	20.8 (16.2, 25.5)
Sahel	Seno	Seytenga	20.5 (15.9, 25.0)
Sahel	Soum	Arbinda	20.0 (15.5, 24.5)
Sahel	Soum	Baraboule	22.6 (17.5, 27.6)
Sahel	Soum	Diguel	23.4 (18.1, 28.7)
Sahel	Soum	Djibo	10.2 (7.3, 13.1)
Sahel	Soum	Kelbo	19.6 (14.9, 24.3)
Sahel	Soum	Nassoumbou	22.0 (17.1, 26.9)
Sahel	Soum	Pobe-Mengao	20.8 (15.6, 25.9)
Sahel	Soum	Tongomayel	21.8 (16.9, 26.7)
Sahel	Yagha	Sebba	15.6 (12.0, 19.2)
Sahel	Yagha	Solhan	20.6 (15.9, 25.2)
Sahel	Yagha	Tankougounadie	19.9 (15.4, 24.4)
Sahel	Yagha	Titabe	21.4 (16.7, 26.2)
Sud ouest	Bougouriba	Bondigui	35.5 (28.8, 42.3)
Sud ouest	Bougouriba	Diebougou	24.2 (18.9, 29.4)
Sud ouest	Bougouriba	Dolo	34.7 (28.0, 41.4)
Sud ouest	Bougouriba	Iolonioro	37.2 (30.2, 44.2)
Sud ouest	Bougouriba	Tiankoura	38.0 (31.0, 44.9)
Sud ouest	Ioba	Dano	23.7 (18.0, 29.4)
Sud ouest	Ioba	Dissin	30.7 (23.8, 37.5)
Sud ouest	Ioba	Gueguere	31.9 (25.1, 38.6)
Sud ouest	Ioba	Koper	32.0 (24.5, 39.4)
Sud ouest	Ioba	Niego	31.3 (23.6, 39.1)
Sud ouest	Ioba	Oronkua	32.1 (25.1, 39.1)
Sud ouest	Ioba	Ouessa	27.6 (20.2, 35.0)
Sud ouest	Ioba	Zambo	32.3 (25.3, 39.2)
Sud ouest	Noumbiel	Batie	27.7 (22.1, 33.4)
Sud ouest	Noumbiel	Boussoukoula	37.7 (30.7, 44.7)
Sud ouest	Noumbiel	Kpuere	39.7 (32.2, 47.2)
Sud ouest	Noumbiel	Legmoin	37.4 (30.5, 44.3)
Sud ouest	Noumbiel	Midebdo	38.0 (30.9, 45.2)
Sud ouest	Poni	Bouroum-Bouroum	34.8 (28.2, 41.5)
Sud ouest	Poni	Boussera	35.3 (28.0, 42.6)
Sud ouest	Poni	Djigoue	41.4 (33.5, 49.4)
Sud ouest	Poni	Gaoua	21.7 (16.9, 26.6)
Sud ouest	Poni	Gbomblora	36.7 (29.9, 43.5)
Sud ouest	Poni	Kampti	38.5 (31.1, 46.0)
Sud ouest	Poni	Loropeni	39.9 (32.3, 47.5)
Sud ouest	Poni	Malba	34.7 (27.6, 41.7)
Sud ouest	Poni	Nako	34.6 (27.7, 41.4)
Sud ouest	Poni	Perigban	40.9 (33.0, 48.8)

Abbreviations

AUC Area under the curve
CI Confidence interval

CMG Climate modeling grid
ELL Elbers Langjouw and Langjouw
INSD National Institute of Statistics and Demography
LST&E Land surface temperature and emissivity
ROC Receiver operating characteristic
SDGs Sustainable development goals
SSA Sub-Saharan Africa
WHO World Health Organization

Author contributions
Conceptualization: BH, MO, RT; methodology: BH, MO.; validation: MK, OM, formal analysis: BH, MO; data curation: BH, MOYP, OC, NA; writing—original draft: BH; writing—review and editing: BH, OM, OC, CK, RT; funding acquisition: this research received no external funding; project administration: BH.; supervision: MK. All authors read and approved the final manuscript.

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Availability of data and materials
Malaria Indicators Survey dataset is available on the dhs program (https://dhsprogram.com) website and the General Population and Housing Census dataset is available at the National Institute of Statistics and Demography (INSD) in Burkina Faso.

Declarations

Ethics approval
Permission to access the data was obtained from the measure DHS program (http://www.dhsprogram.com) via online request. The website and the data used were publicly available with no personal identifier. All methods were carried out in accordance with relevant guidelines and regulations.

Informed consent
Informed consent was obtained from all subjects involved in the study.

Competing interests
The authors declare that they have no competing interests. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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