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Risk Mapping and Determinants of the Potential Presence of Anopheles stephensi in Benin: A Geostatistical and Logistic Regression Approach

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Research Article

Keywords:

Posted Date: March 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8888663/v1

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Malaria Journal on September 19th, 2026. See the published version at https://doi.org/10.1186/s12936-026-06152-z.

Abstract

Background

Anopheles stephensi is an emerging malaria vector, historically confined to Asia but recently reported in several African countries. Its ability to adapt to urban environments represents a growing threat to vector control strategies. In Benin, the presence of environmental conditions conducive to its establishment suggests a potential risk of occurrence, although this has not yet been confirmed by comprehensive entomological data. This study aimed to identify determinants associated with the risk of potential presence of *Anopheles stephensi* and to map its probable spatial distribution at the national level.

Methods

An ecological study covering the 77 municipalities of Benin was conducted using agricultural, livestock, socioeconomic, demographic, and environmental data collected between March and May 2025. The dependent variable did not reflect observed vector presence but rather an indicator of the ecological suitability of larval habitats to support *Anopheles stephensi*. Multivariable logistic regression, followed by probabilistic spatial modeling, was used to estimate the likelihood of potential vector presence.

Results

Human population density ($p = 0.001$) and swine population size ($p < 0.001$) were positively associated with the risk of potential presence of *Anopheles stephensi*, whereas cattle, sheep, and goat populations showed significant negative associations. The maps produced represent probabilities of occurrence rather than confirmation of actual vector presence.

Conclusion

This study highlights areas of Benin with a high probability of potential presence of *Anopheles stephensi*. These findings provide decision-support tools to guide prioritized entomological surveillance and preventive interventions before confirmed establishment of the vector.

1. Introduction

Malaria, caused by parasites of the genus *Plasmodium* and transmitted by mosquitoes of the genus *Anopheles*, remains a major public health priority in Africa, with approximately 200 million cases reported annually (World Health Organization, 2020). A thorough understanding of the biology and ecology of *Anopheles* mosquitoes is essential for the development of effective malaria control and prevention strategies (Russell et al., 2014; Russell et al., 2015). Mosquitoes of the genus *Anopheles*, particularly *Anopheles gambiae*, *Anopheles funestus*, and *Anopheles stephensi*, which are primary malaria vectors, play a central role in disease transmission (Sinka et al., 2010; Coetzee et al., 2000; Balkew et al., 2021). *Anopheles stephensi* has attracted particular attention because of its capacity to adapt to diverse environments, including urban settings, thereby increasing the risk of transmission in densely populated areas (Sinka et al., 2020). In Benin, where malaria is endemic, the potential emergence of this vector would represent an additional public health threat, requiring a comprehensive understanding of its ecological and social determinants to inform control strategies.

The distribution of *Anopheles stephensi* is influenced by agricultural, livestock, socioeconomic, and demographic factors. Agricultural practices such as irrigation create suitable larval breeding habitats (Smith et al., 2020; Johnson & Brown, 2021), while livestock provide blood meal sources for mosquitoes (Williams et al., 2022; Davies et al., 2023). Urbanization and climate variability also play significant roles in shaping mosquito distribution (Dupont et al., 2020; Laurent et al., 2021). Moreau et al. (2022) and Petit et al. (2023) examined the role of water management and agricultural land use in the creation of mosquito habitats. Socioeconomic conditions influence mosquito prevention and exposure risk (Martinez et al., 2021; Garcia et al., 2022), and Rousseau et al. (2024) analyzed socioeconomic inequalities in vector-borne disease control. Demographic dynamics further affect the spread of vector-borne diseases (Lee et al., 2023; Chen et al., 2024), with Bernard et al. (2020) and Lefèvre et al. (2021) investigating demographic change and migration patterns in disease dissemination. Finally, Dubois et al. (2022), Lambert et al. (2023), Girard et al. (2020), and Lefort et al. (2021) contributed to understanding public health interventions and mosquito control strategies. Although these factors interact in complex ways, their specific role in the detection of *An. stephensi* in Benin remains insufficiently documented.

In Benin, agriculture and livestock production are central to the national economy; however, these activities may also create environments conducive to mosquito proliferation. For example, rice paddies and irrigated areas provide favorable breeding sites for *Anopheles stephensi* (Mutero et al., 2018). Socioeconomic factors, including educational attainment, income level, and access to health services, also play a critical role in malaria transmission dynamics. Disadvantaged populations, who often live in substandard housing and have limited access to insecticide-treated nets, are more exposed to mosquito bites (Tusting et al., 2016). In addition, demographic determinants such as population density and migratory movements may influence malaria distribution and transmission patterns (Sturrock et al., 2015).

Despite advances in malaria control, few studies have integrated agricultural, livestock, and socioeconomic determinants into a geospatial analysis of *An. stephensi* in West Africa. This gap limits the ability to design targeted interventions in settings such as Benin, where agriculture and animal husbandry dominate the economy. Geostatistical approaches, combined with robust statistical analyses, offer substantial potential for identifying high-risk areas and guiding public health policy.

This study aims to analyze factors associated with the detection of *Anopheles stephensi* in Benin, with particular emphasis on agricultural practices, livestock systems, socioeconomic conditions, and demographic characteristics. We hypothesize that population density and livestock population size are key drivers of its presence. By identifying these determinants, this research seeks to generate actionable evidence to support more targeted and effective control strategies, ultimately contributing to malaria reduction and improved public health outcomes. Furthermore, this work contributes to the scientific literature on malaria control by highlighting the complex interactions among environmental, socioeconomic, and demographic factors that shape the risk of malaria vector presence.

2. Materials and methods

2.1. Study Area

This study encompassed the 77 municipalities of Benin, including diverse rural and urban settings characterized by substantial socioeconomic, demographic, and environmental heterogeneity. The country has a tropical climate, with a subequatorial regime in the southern region and a Sudanian–Guinean regime in the northern region, both marked by pronounced seasonal variations in rainfall and temperature.

2.2. Data Collection

Data were collected between March and May 2025, with overall completeness exceeding 95%, as verified through cross-validation procedures. Data sources included:

- **Entomological data:** field surveys of potential breeding sites likely to support *Anopheles stephensi*;
- **Agricultural data:** distribution of agricultural households derived from national agricultural censuses conducted by the World Bank and the Ministry of Agriculture, Livestock and Fisheries (World Bank; MAEP);
- **Livestock data:** population sizes of cattle, sheep, goats, and swine (MAEP; INSAE);
- **Socioeconomic data:** the Human Poverty Index (HPI) and adult literacy rate, obtained from Human Development Reports of the Ministry of Planning and Development of Benin (Ministry of Planning, 2023);
- **Demographic data:** population density (INSAE);
- **Environmental data:** average rainfall and mean temperature.

It is important to emphasize that this study does not seek to demonstrate the confirmed presence of *Anopheles stephensi*, but rather to model its potential presence, defined as the probability of vector occurrence in areas exhibiting favorable ecological and anthropogenic conditions in the absence of direct entomological confirmation. Accordingly, the data describe a context of environmental and human suitability rather than confirmed vector detection.

2.3. Statistical Analysis

Within this predictive framework, a multivariable logistic regression analysis was conducted using R software (version 4.4.1) to identify factors associated with the risk of potential presence of *Anopheles stephensi*. The dependent variable corresponded to an indicator of the suitability of larval habitats to support *Anopheles stephensi*, dichotomized as a binary variable (GITES_BINARY). This variable does not represent observed vector presence but rather an ecological proxy based on local environmental favorability.

Explanatory variables included agricultural, livestock, socioeconomic, demographic, and environmental factors. The model was fitted using the glm() function with a binomial family. Statistical significance of associations was assessed using regression coefficients, 95% confidence intervals, and p-values.

2.4. Probabilistic Spatial Modeling of *Anopheles stephensi* presence

Variables identified as significant in the multivariable model were incorporated into a spatially explicit logistic regression to generate continuous probability surfaces of the potential presence of *Anopheles stephensi* across the national territory. Spatial predictions were derived from the estimated model coefficients and validated using a k-fold cross-validation procedure, with the area under the receiver operating characteristic curve (AUC) used as the performance metric. This approach enables the identification of priority areas for targeted entomological surveillance without assuming confirmed vector presence.

3. Results

3.1. Multivariable Logistic Regression Analysis

The multivariable logistic regression model identified several factors significantly associated with the probability of potential presence of *Anopheles stephensi* (dependent variable: GITES_BINARY). The model included 77 observations and yielded a pseudo R^2 of 0.2076, a log-likelihood of −41.669, and a likelihood ratio test p-value of 0.058, indicating an overall acceptable model fit (Table 1). Human population density was positively and significantly associated with an increased probability of potential presence of *An. stephensi* ($p = 0.001$). Similarly, swine population size showed a strong positive association ($p < 0.001$). In contrast, cattle, sheep, and goat populations were negatively and significantly associated with this probability ($p < 0.001$). Socioeconomic variables (adult literacy rate and Human Poverty Index), as well as climatic variables (monthly rainfall and temperature), were not significantly associated with potential vector presence in the multivariable model ($p > 0.05$). Overall, these findings suggest that the potential presence of *An. stephensi* is primarily associated with highly anthropized and densely populated environments, whereas areas dominated by extensive ruminant livestock systems appear less conducive to the establishment of suitable larval habitats.

Table 1. Multivariable logistic regression analysis of factors associated with the potential presence of *Anopheles stephensi* in Benin.

Variable	Coefficient (β)	OR (exp(β))	95 % CI	p-value
Constant	−1,8226	0,162	[0,09 – 0,29]	0,478
Human population density	0,0001	1,0001	[1,0000 – 1,0002]	0,001
Cattle	−0,0000	≈ 1,0000	[0,9999 – 1,0000]	< 0,001
Sheep	−0,0000	≈ 1,0000	[0,9999 – 1,0000]	< 0,001
Goats	−0,0000	≈ 1,0000	[0,9999 – 1,0000]	< 0,001
Pigs	0,0001	1,0001	[1,0000 – 1,0002]	< 0,001
Literacy rate	−0,0000	≈ 1,0000	[0,9999 – 1,0001]	0,999
Human poverty index (HPI)	0,0000	≈ 1,0000	[0,9999 – 1,0001]	0,999
Type of housing	−0,1132	0,893	[0,70 – 1,12]	0,311
Precipitation	−0,1519	0,859	[0,64 – 1,14]	0,285
Temperature	0,0576	1,059	[0,77 – 1,46]	0,720
Number of agricultural households	$3{,}64 \times 10^{-5}$	1,00004	[0,9999 – 1,0001]	0,604

3.2. Spatial Distribution of Socioeconomic Variables and Swine Populations

Spatial analysis revealed marked heterogeneity in the national distribution of socioeconomic indicators and swine populations. Several municipalities exhibited high levels of poverty and low literacy rates; however, these areas did not systematically coincide with zones of high predicted probability of potential presence of *Anopheles stephensi* (Figures 1a–h). In contrast, municipalities characterized by large swine populations, particularly Matéri, Toucountouna, and Abomey, largely overlapped with areas showing higher predicted probabilities of potential vector presence. This spatial concordance is consistent with the findings of the multivariable analysis and suggests that swine husbandry is frequently associated with peri-urban environments characterized by anthropogenic water storage structures, which may serve as suitable larval habitats for the development of *An. stephensi*.

3.3. Spatial Distribution of Ruminants and Human Population Density

High densities of cattle, sheep, and goats were predominantly concentrated in municipalities located in northern Benin. Although these areas may theoretically provide increased availability of animal blood meal sources, the multivariable analysis demonstrated a significant negative association between ruminant populations and the probability of potential presence of *Anopheles stephensi* (Figures 2a–d).

These findings suggest that the observed spatial patterns primarily reflect the distribution of traditional pastoral systems rather than ecological conditions conducive to the establishment of this species. Conversely, municipalities characterized by high human population density consistently overlapped with areas of elevated predicted probability, underscoring the central role of urbanization in shaping the spatial structure of the potential risk of *An. stephensi* presence.

3.4. Risk map of potential presence

The risk map (Figure 3) depicts the geographic distribution of the predicted probability of potential presence of *An. stephensi* in Benin. Areas classified as high risk correspond to municipalities characterized by substantial urbanization and high human population density, whereas low-risk areas are predominantly rural and minimally anthropized. This map should be interpreted as a predictive tool intended to guide entomological surveillance rather than as evidence of confirmed vector presence. High-risk areas included Banikoara, Parakou, Djougou, Malanville, Bohicon, Sô-Ava, Tchaourou, Cotonou, Ifangni, Aguégués, and Zagnanado, which exhibit environmental conditions favorable to the survival and reproduction of *Anopheles stephensi*. Moderate-risk areas, represented by shades of yellow or orange, included Kandi, Sinendé, Bembèrèkè, Savè, Kétou, and Dassa-Zoumè. These municipalities may be influenced by moderately suitable environmental conditions, including vegetation cover and land use patterns that provide partially favorable habitats, as well as intermediate population density levels. Finally, municipalities such as those in the Atacora region, Karimama, Toffo, Bonou, and Bantè appeared less conducive to the potential presence of this mosquito species and were classified as low-risk areas. Factors influencing this spatial distribution include climatic conditions, vegetation cover, the presence of standing water, and human population density.

4. Discussion

This study applied a combined approach integrating multivariable logistic regression and probabilistic spatial modeling to identify determinants associated with the potential presence of *Anopheles stephensi* in Benin and to map areas at risk. The findings highlight the central role of anthropogenic factors, particularly human population density and swine husbandry, in shaping the potential risk of presence of this emerging vector.

The positive and statistically significant association between human population density and the probability of potential presence of *An. stephensi* is consistent with the literature describing this species as highly adapted to urban and peri-urban environments (Sinka et al., 2020; Balkew et al., 2021). Unlike *An. gambiae* and *An. funestus*, which rely heavily on natural rainfall-dependent breeding sites, *An. stephensi* preferentially exploits anthropogenic habitats such as water storage tanks, cisterns, discarded tires, and poorly drained urban areas (Balkew et al., 2021).

The risk maps indicate that densely populated municipalities such as Cotonou, Parakou, and Bohicon are among the areas with the highest predicted probabilities, suggesting that rapid urbanization, combined with inadequate water management in some settings, may create favorable conditions for species

establishment. This finding supports the hypothesis that accelerated urban growth in West Africa may alter malaria transmission dynamics by favoring vectors better adapted to urban ecosystems (Dupont et al., 2020; Laurent et al., 2021).

The positive association between swine populations and the potential risk of *An. stephensi*, in contrast to the negative associations observed for cattle, sheep, and goats, suggests complex dynamics related to livestock management practices and spatial organization of human settlements. The frequent proximity of pig enclosures to human dwellings, particularly in municipalities such as Abomey and Toucountouna, may promote the formation of micro-larval habitats (e.g., puddles, poorly maintained troughs, wastewater accumulation), thereby explaining the observed positive association. These findings are consistent with previous work indicating that livestock can influence mosquito distribution by modifying blood meal availability and larval habitat characteristics (Bousema et al., 2016).

Conversely, the negative association with ruminants may reflect the predominance of these herds in more open, rural, and less urbanized areas, where permanent artificial breeding sites are less common. It is also possible that enclosure design and water point management in traditional pastoral systems limit the persistence of larval habitats suitable for *An. stephensi*. These hypotheses require confirmation through dedicated entomological and behavioral studies, particularly investigations of host-feeding preferences and anthropophily indices of *An. stephensi* in Benin.

In contrast to studies reporting associations between socioeconomic status and malaria risk (Tusting et al., 2016), no significant relationship was identified between the Human Poverty Index, literacy rate, and the potential presence of *An. stephensi*. This result may be explained by the aggregated nature of these indicators at the municipal level, which may be insufficiently sensitive to capture fine-scale variations in housing quality, domestic water management, or insecticide-treated net use. Additionally, nationwide distribution campaigns and awareness initiatives conducted by the National Malaria Control Program may mitigate certain socioeconomic disparities in prevention, thereby reducing their direct effect on vector-related risk.

The absence of a significant association with rainfall and temperature contrasts with previous research demonstrating a major influence of climatic factors on malaria vector distribution (Derua et al., 2019). This discrepancy may be attributable to the distinctive ecology of *An. stephensi*, which depends more on permanent artificial breeding sites than on seasonal rainfall. Furthermore, the use of monthly climatic data aggregated at the municipal level may have obscured important local variability. Future analyses incorporating high-resolution temporal (daily) and spatial (fine-grid) climate data would allow for more precise characterization of these relationships.

From an operational perspective, the results have important implications. Municipalities identified as high risk (Cotonou, Parakou, Bohicon, Banikoara, Djougou, Malanville, Sô-Ava, Tchaourou, Ifangni, Aguégués, and Zagnanado) should be prioritized for:

- Targeted entomological surveys (larval and adult surveillance for *An. stephensi*);

- Urban larval source management interventions (drainage, covering water storage containers, elimination of standing water);
- Community-based awareness campaigns focused on domestic water management;
- Enhanced monitoring of the effectiveness of insecticide-treated nets in these areas.

In rural zones characterized by intensive pastoral activity, an integrated strategy could include improved management of livestock water points and structural modifications of enclosures to minimize the formation of larval habitats.

This study represents the first nationwide analysis integrating agricultural, livestock, socioeconomic, and environmental determinants to model the potential presence of *An. stephensi* in Benin. The application of a geostatistical framework combined with cross-validation strengthens the robustness of the spatial predictions.

However, several limitations must be acknowledged:

1. **Absence of direct entomological confirmation:** the findings are based on modeling potential presence rather than confirmed vector detection.
2. **Spatial resolution of environmental data:** municipal-level aggregation may mask substantial local heterogeneity.
3. **Possible underreporting of livestock populations, particularly in rural settings.**

We recommend:

- Targeted entomological surveys in high-risk municipalities;
- Integration of high-resolution climatic datasets;
- Studies assessing host-feeding preferences and anthropophily indices of *An. stephensi* in Benin;
- Longitudinal analyses to monitor temporal changes in risk patterns.

5. Conclusions

This study examined factors influencing the risk of presence of *Anopheles stephensi* in Benin using geostatistical and statistical approaches. The findings underscore the complex interaction among human population density, agricultural practices, and livestock systems in significantly shaping the potential risk of presence of this mosquito species. Other variables, such as literacy rate, did not demonstrate a significant effect. Spatial analysis enabled the identification of both high- and low-risk areas. A proactive strategy integrating entomological surveillance, environmental management, and community engagement is essential to prevent escalation of malaria transmission in a context where *An. stephensi* represents an increasing public health concern.

Abbreviations

An : Anopheles

Declarations

Acknowledgments

We would like to thank the Entomological Research Center in Cotonou and its staff for their dedication and active participation in this study.

Funding

This study did not receive any external funding.

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Contribution

The study was designed and its protocol written by

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Ethical approval and consent to participate

This study used secondary ecological and administrative data at the commune level and did not involve direct human participants or animal experimentation. No personal identifiable data were collected or analyzed. The study was conducted in accordance with national data protection regulations in Benin. Ethical clearance was obtained from the **National Ethics Committee for Health Research of Benin (CNERS)**. Permission to use agricultural, livestock, demographic, and environmental data was granted by the relevant national institutions (INSAE, MAEP, Ministry of Environment, and Ministry of Planning).

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Figures

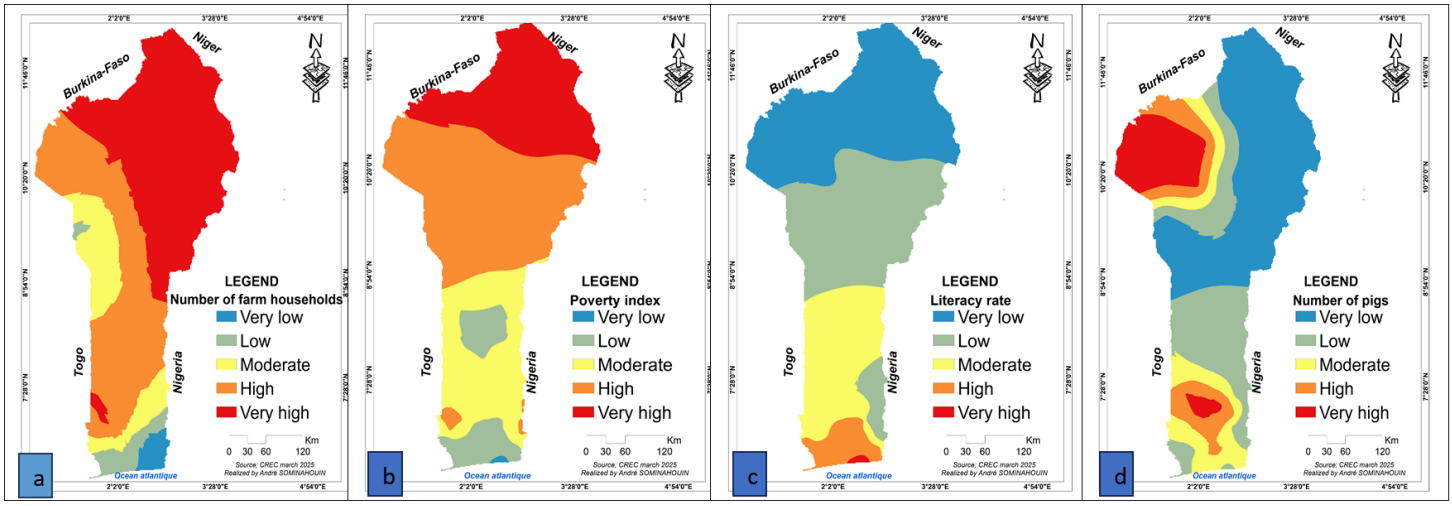


Figure 1

Map of Benin showing the spatial distribution of agricultural household numbers (a), poverty index (b), literacy rate (c), and pig numbers (d)

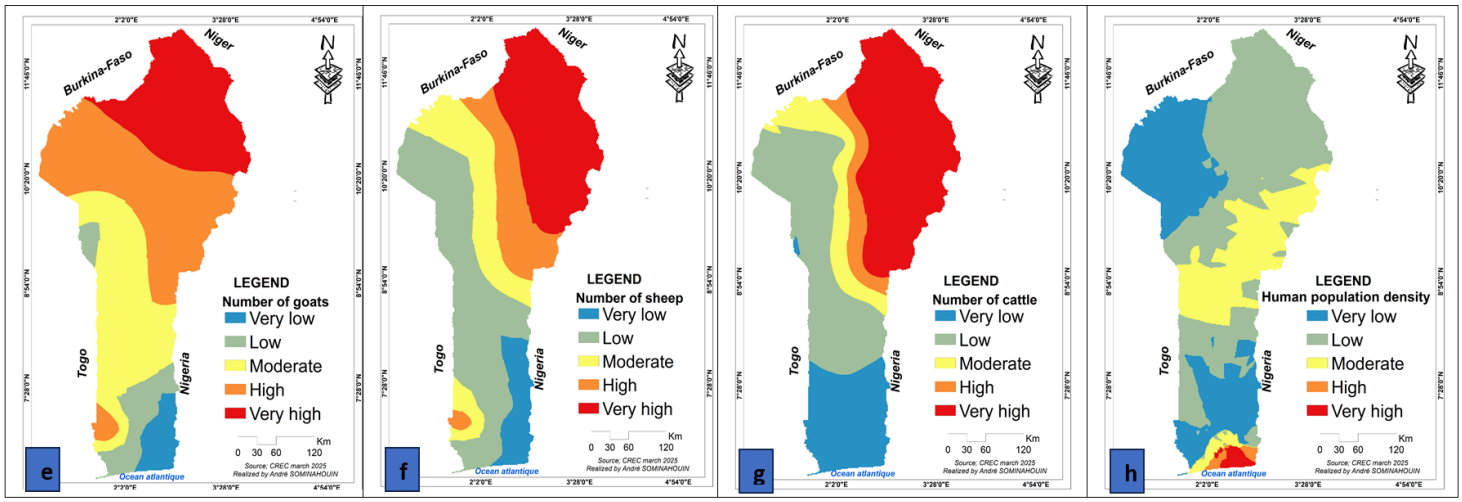


Figure 2

Map of Benin showing the spatial distribution of goat (a), sheep (b), and cattle (c) populations and human population density (d)

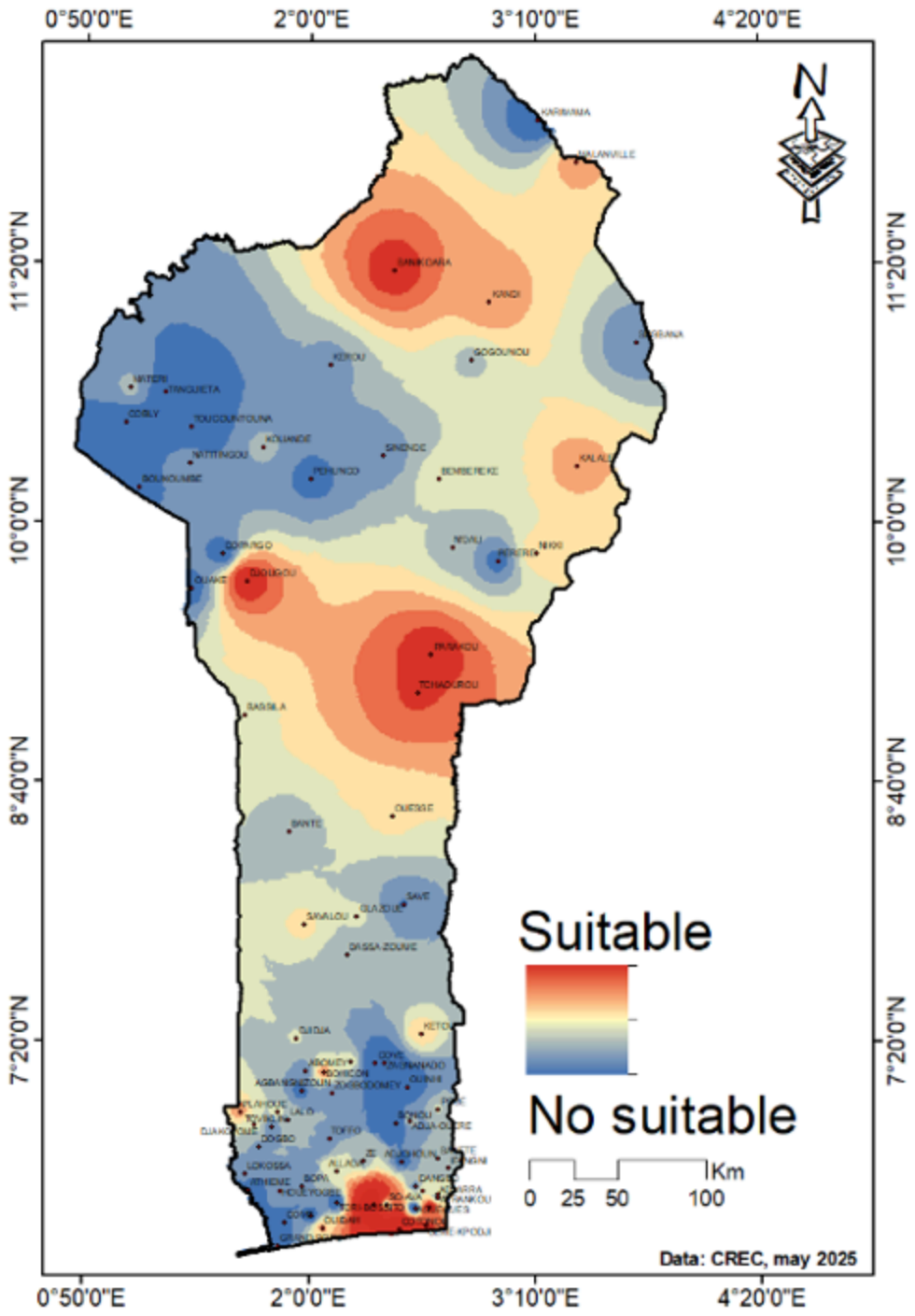


Figure 3

Risk map for *An. stephensi*