Methodological framework for assessing malaria risk associated with climate change in Côte d'Ivoire

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Abstract

Malaria is the leading cause of morbidity among children under five years of age and pregnant women in Côte d'Ivoire. We assessed the geographical distribution of its risk in all climatic zones of the country based on the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) approach to climate risk analysis. This methodology considers three main driving components affecting the risk: *Hazard, exposure* and *vulnerability*. Considering the malaria impact chain, various variables were identified for each of the risk factors and for each variable, a measurable indicator was identified. These indicators were then standardized, weighted through a participatory approach based on expert judgement and finally aggregated to calculate current and future risk. With regard to the four climatic zones in the country: Attieen (sub-equatorial regime) in the South, Baouleen (humid tropical) in the centre, Sudanese or equatorial (tropical transition regime) in the North and the mountainous (humid) in the West. Malaria risk among pregnant women and children under 5 was found to be higher in the mountainous and the Baouleen climate, with the hazard highest in the mountainous climate and *Exposure* very high in the Attieen climate. The most vulnerable districts were those in Baouleen, Attieen and the mountainous climates. By 2050, the IPCC representative concentration pathway (RCP) 4.5 and 8.5 scenarios predict an increase in risk in almost all climatic zones, compared to current levels, with the former considering a moderate scenario, with an emissions peak around 2040 followed by a decline and RCP 8.5 giving the highest baseline emissions scenario, in which emissions continue to rise. It is expected that the AR5 approach to climate risk analysis will be increasingly used in climate risk assessment studies so that it can be better assessed at a variety of scales.

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Introduction

Climate change, including climate variability and its adverse effects on human health, is a global concern (Beaudoin & Gosselin, 2016; Romanello *et al.*, 2021; Watts *et al.*, 2021; Agache *et al.*, 2022; IPCC, 2023). The various climate change scenarios show the importance of the impact of these changes on diseases, particularly those linked to the environment (Cissé *et al.*, 2022). Many authors indicate that global warming and increased climate variability can increase malaria spread specifically in middle-income countries (Endo *et al.*, 2017; Shah *et al.*, 2019; Ogega & Alobo, 2021; Romanello *et al.*, 2021). It's known that the spatiotemporal distribution of vector-borne diseases is likely to expand as a result of more favourable temperatures, which would lead to changes in the dynamics of communicable diseases (Lowe, 2018; Fletcher *et al.*, 2022).

In West Africa, climate change in recent years contributed to increased malaria spread (Yamana *et al.*, 2016; Endo *et al.*, 2017; M'Bra *et al.*, 2018). Indeed, since the 1970s, West Africa has been subject to rising temperatures, falling average rainfall, shifting rainy seasons and often more heavy rainfall (Kouakou *et al.*, 2007; Kouassi *et al.*, 2010; Engelbrecht *et al.*, 2015; Nangombe *et al.*, 2019), thus contributing to the increased spread of vector-borne diseases. In Côte d'Ivoire, malaria, diarrheal diseases and acute respiratory infections (ARIs) have the highest impacts among children under 5 years of age (under-5) (MSHPCMU, 2021). However, with an impact of 173.43 cases per 1,000 in the general population, malaria is the leading cause of medical consultations in Côte d'Ivoire (MSHPCMU, 2021). Pregnant women and children under-5 are the groups most vulnerable to the disease (MSHPCMU, 2021). Moreover, the geographical distribution of malaria infection in the country is not homogeneous (Raso *et al.*, 2012). Azongnibo *et al.* (2023) note that the western zone had the highest impact rates, while Adja *et al.* (2022) observe high rates spreading in the northern, western and eastern regions, both in urban and rural areas, while Assouho *et al.* (2020) report persistence of high and heterogeneous malaria rates despite the distribution of long-lasting insecticidal nets (LLINs). Importantly, the spread of malaria is influenced by changes in weather conditions, which affect the life cycle of malaria vectors (Bhatt *et al.*, 2015; Khan, 2017; Segun *et al.*, 2020; Tiu *et al.*, 2021). There are considerable climatic changes along the south to north axis in Côte d'Ivoire, with three (3) different climatic regimes corresponding to different ecological zones (Kouassi *et al.*, 2010). Several authors have shown the influence of climatic conditions on malaria in various regions across the country (Patz & Olson, 2006; M'Bra *et al.*, 2018; Doumbia *et al.*, 2023). However, few projects have focused on the national scale. As pointed out by the German provider of international cooperation 'Deutsche Germam Gesellschaft für Internationale Zusammenarbeit' (GIZ), the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) is still not used systematically everywhere (GIZ, 2017; GIZ et al., 2018), the main aim of this study was to use the previous one, AR5, to measure the present and future risk of malaria in different agro-ecological zones along the equator.

Materials and Methods

Conceptual approach

The methodology focused on to the risk-centred assessment framework of IPCC (2014), in which risk is expressed as a function of three components: *Hazard*, *Exposure* and *Vulnerability*. Figure 1 shows the malaria impact chain (IC) approach (Schneiderbauer *et al.*, 2020; Zebisch *et al.*, 2021; Menk *et al.*, 2022; Zebisch *et al.*, 2022; Estoque *et al.*, 2022) that describes the stages from vector development to disease spread and risk. ICs are conceptual models used to capture this kind of factors illustrating how they lead to specific risks (Menk *et al.*, 2022). The IC method follows a general assessment framework consistent with the IPCC's AR5 concept on climate risk. *Hazard* refers to the potential occurrence of climate-related physical events that may cause damage and loss (represented here by rainfall and temperature); while *exposure* refers to the presence of people (pregnant women and children under-5 in this study) in locations that could be adversely affected, regard to potential harm, loss, or damage; and *vulnerability* refers to sensitivity or susceptibility and is a function of capacity to cope and adapt to harm (IPCC, 2014; GIZ, 2017; Estoque *et al.*, 2020). Based on this IC, various variables were identified for each of the risk factors and for each variable, a measurable indicator was identified. Table 1 lists all variables and measurable indicators for which data were collected.

Study area

Côte d'Ivoire is a coastal country located in the intertropical zone of West Africa. It is a malaria-endemic zone, with the climate determined by the position of the intertropical convergence zone (ITCZ), depending on the season resulting in four clearly marked climatic regimes (Figure 2). The transitional equatorial regime in the South called the Attiéen climate (zone I), has two dry and two wet seasons. The attenuated, humid tropical, transitional equatorial regime in the Centre called the Baouléen climate (zone II), has also four seasons: two dry seasons and two rainy seasons. The transitional tropical regime Sudanese or equtorial climate in the North (zone III), has two seasons: a long dry season and a short rainy season. Finally, the Mountain climate in the West (zone IV), has a long rainy season and a short dry season (Soro *et al.*, 2016).

Data collection

Data collection included secondary data concerning all the variables listed in Table 2 and they were obtained from available documents (INS, 2022; MICS, 2016; INS, 2015) and the web pages of some Institutions. Data on the malaria impact were obtained from the website of the University of Washington in the USA (https://vizhub.healthdata.org/lbd/) and covered the period from 2000 to 2019, which is the period of the current risk study. Precipitation and temperature data were taken from the World Bank's website (https://climateknowledgeportal.worldbank.org/download-data) covering the period 1991-2016. These data were downloaded for all weather stations covering the Ivorian territory.

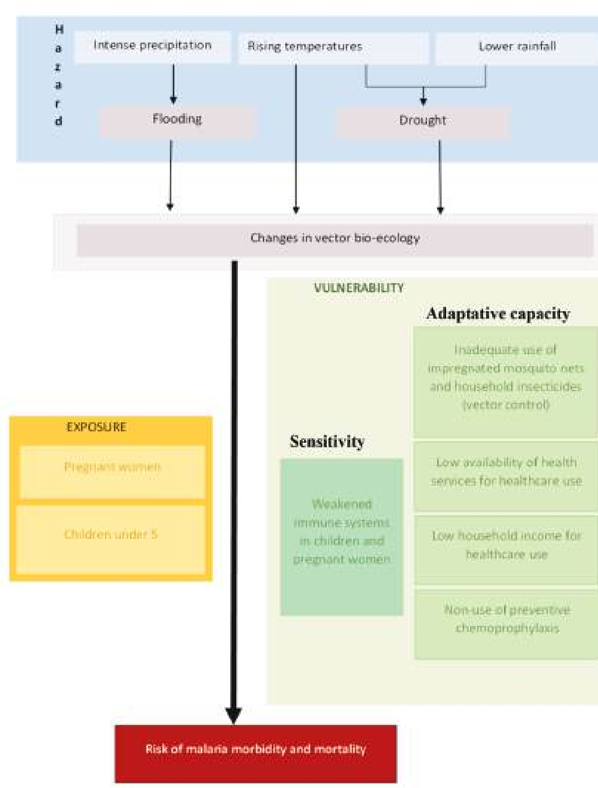

Figure 1. Impact chain of malaria-related morbidity and mortality risk.

As the health data obtained covered the period 2000-2019, the meteorological data were completed from 2016 to 2019 using linear regression based on data from the NASA website covering the period 1991-2020. Future risk was assessed at the 2050 horizon. Table 2 summarizes the measurable indicators for the selected variables. Thus, the *Hazard* and the *Exposure* risk components were assessed using two (02) indicators, while six (06) indicators were used for the *Vulnerability* one, including one (01) for *Sensitivity* and five (05) for *Adaptive Capacity*. These measurable indicators were standardized, weighted and aggregated to calculate current and future risks.

Standardizing the indicators

Standardization consisted of transposing the various indicator values into the same unit and scale of magnitude. This was done using the min-max method (GIZ, 2017). This method transforms all values into scores ranging from 0 (optimal situation) to 1 (critical situation), based on the following equation:

$$X_{i,0\ to\ 1} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \qquad \text{(Eq.1)}$$

where X_i represents the individual data point to be transformed; X_{min} the lowest value for this indicator; X_{max} the highest value for this indicator; and X_i, the new value between 0 and 1 we wished to calculate. The indicators were then weighted and aggregated.

Indicator weighting and aggregation

Weighting consists of assigning weights to the indicators. The participative approach was prioritized, and the experts' opinions

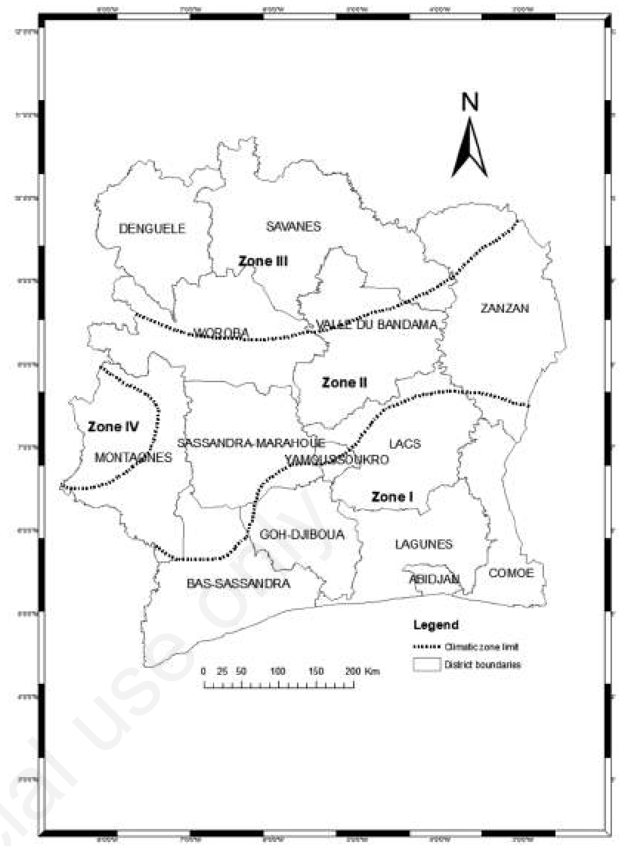

Figure 2. Districts and climatic zones of Côte d'Ivoire.

Table 1. Indicators used to calculate the malaria morbidity risk index.

Risk component		Variable	Indicator	Method	Scale	Data source
Hazard	Climate	Rainfall	Average rainfall (mm)	Min-max method	Synoptic stations	World Bank, year? GIZ, 2017
		Temperature	Average temperature (°C)	Min-max method	Synoptic stations	World Bank, year? GIZ, 2017
Vulnerability	Sensitivity	Possible low immunity in children and pregnant women	Population grouped by age and gender (%)	Min-max method	District	RASS, 2020, GIZ, 2017
	Adaptive capacity	Low availability of health services	Access to health care	Min-max method	District	MICS, 2016, GIZ, 2017
		Low household income available for health care	Average annual income of household head (FCFA)	Min-max method	District	MICS, 2016, GIZ, 2017
		Not using preventive chemo-prophylaxis	Proportion of households not using preventive prophylaxis (%)	Min-max method	District	MICS, 2025, 2016, RASS, 2020, ENVI, 2015 , GIZ, 2017
		Inadequate use of vector control (impregnated bed nets and insecticides)	Proportion of households misusing impregnated bed nets (%)	Min-max method	District	MICS, 2016, GIZ, 2017
		Selfmedication	Proportion of households practicing auto-medication (%)	Min-max method	District	MICS, 2016 , GIZ, 2017
Exposure	Exposure	Children under-5	Population grouped by age and gender (%)	Min-max method	District	INS, 2018, 2019-2021, GIZ, 2017
		Pregnant women	Proportion of pregnant women (%)	Min-max method	District	Population data, 2019-2021. , GIZ, 2017

FCFA, Central African CFA franc; RASS, The Annual Health situation Report; Multiple Indicator Cluster Survey; ENVI, Survey of household living standards in Côte d'Ivoire; INS, National Institute of Statistics.

prevailed. The experts assigned weights ranging from 1 to 5 with regard to the various indicators, according to their importance in terms of risk factors. As for the final risk calculation, weights were also assigned to the various risk factors. The composite indicator (CI) was then calculated for each risk factor according to equation 2 below:

$$CI = \frac{I_1 * w_1 + I_2 * w_2 + I_3 * w_3 \ldots\ldots I_n * w_n}{\sum_1^n w} \quad \text{(Eq.2)}$$

where I an individual indicator of a risk factor; and W the weight assigned to the indicator.

Final risk calculation

The current final risk was then evaluated according to the following formula:

$$Risk = \frac{(Hazard * W_H) + (Vulnerability * W_V) + (Exposure * W_E)}{W_H + W_V + W_E} \quad \text{(Eq.3)}$$

where W is the weighting of the risk factors assigned by the experts.

Future risk was assessed in the same way as current risk, but with climate parameters and population data projected to 2050. Other parameters, which could not be projected due to lack of data, were supposed to remain constant until 2050. Temperature and precipitation were projected by compiling data from a set of 14 climate models. The multi-model average (of this set) provided projected data closer to observed data. These models contain RCPs 4.5 and 8.5 climate forcing scenarios for the period 2006-2100, which were used as projection scenarios. RCP 4.5 is an optimistic scenario, while RCP 8.5 is a pessimistic one. As for population data, the projection was made by applying the growth rate to the population per administrative district. The risk values obtained (current and future risk) were ranked according to a nominal scale ranging from "very low" to "very high", as shown in Table 3.

Results

Weights assigned to the indicators

Table 4 shows the weights assigned to the indicators according to risk factor. For the *hazard* component, considering that mosquitoes develop more during the rainy season, the experts assigned a relatively higher weight to rainfall than to temperature. Regarding *exposure*, the experts considered that children under-5 were more exposed (weight of 2 out of 5) than pregnant women (1 out of 5). Considering the importance of the immune system in plasmodium spread, the experts assigned a weight of 4/5 to the sensitivity indicator of the *Vulnerability* component. In terms of adaptive capacity, the experts considered that inadequate use of insecticide-treated mosquito nets and intra-domestic insecticides, as well as the failure to use preventive chemoprophylaxis, would reduce adaptive capacity considerably. These two variables therefore play an important role for the adaptive capacity, hence the weight of 3 out of 5 was attributed to each of them. Self-medication and level of income for health care came just after the first two indicators, with a weighting of 2 out of 5, since the experts attached a greater importance to them than to accessibility to health services (1 out of 5).

Table 2. List of variables and indicatorsmeasured by risk component.

Component	Variable		Indicator
Hazard	Precipitation Temperature		Annual rainfall (mm) Average annual temperature (°C)
Exposure	Pregnant women Children under-5		Pregnant women (%) Children under-5 (%)
Vulnerability	Sensitivity	Possible low immunity in children and pregnant women	Population grouped by age and gender (%)
	Adaptive capacity	Inadequate use of vector control (impregnated bed nets and insecticides)	Use of impregnated bed nets
		Self-medication	Self-medication (%)
		Low household income	Household income allocated to health (%)
		Not using preventive chemoprophylaxis	Proportion of households not using preventive prophylaxis (%)
		Low availability of health services	Access to healthcare (%)

Table 3. Risk classification.

Risk value (0 to 1)	Description
00 - 0,2	Very low
0,2 – 0,4	Low
0,4 – 0,6	Intermediate
0,6 – 0,8	High
0,8 - 01	Very high

Malaria risk for pregnant women and children under-5

The analysis of Figure 3 shows that *hazard* due to the climate is high (between 0.6 and 0.8) in climate zone IV, intermediate in climate zones I and II in Goh Djiboua (Gagnoa) and Sassandra Marahoué (Daloa) Districts, and low (between 0.2 and 0.4) in climate zone III. In terms of *exposure*, pregnant women and children under-5 in Abidjan District in climate zone I were shown to have a very high level of *exposure* compared to those in the country's other districts. Pregnant women and children under-5 in climate zones II and III had a low level of *Exposure* (between 0.2 and 0.4) in districts, such as Zanzan (Bondoukou), Sassandra Marahoué (Daloa), Woroba (Séguéla) and Denguélé (Odienné). In terms of *vulnerability*, districts in all four climate zones had an intermediate level (between 0.4 and 0.6), except for Yamoussoukro and Zanzan in climate zone II and Denguélé in climate zone III, which had a low level (between 0.2 and 0.4). Ofthe three risk factors, the experts gave greater weight to vulnerability and exposure. The analysis of Figure 4, with Table 5 showing the weights assigned to the various risk factors, reveals that malaria risk among pregnant women and children under-5 was intermediate in the mountainous area, such as Abidjan and Sassandra Marahoué Districts. However, the Mountains District, with a score of 0.54, had the highest level of risk at the national level. All other districts showed a low risk.

The spatial distribution of malaria morbidity risk levels among pregnant women and children under-5 (Figure 5) showed that the three districts with intermediate risk levels are located in climate zones I, II and IV, with those in climate zone III being at low risk. Two of the three intermediate-risk districts were found to be located in the western part of the country.

Precipitation, temperature and population projections to 2050

Rainfall projections for 2050 under both scenarios (rcp 4.5 or rcp8.5) show an overall increase of over 200 mm in all climate zones. The highest rainfall amounts are still expected in the western part of the country, and the lowest in the North. It is estimated that temperatures will increase by approximately 1°C on average by 2050. Both scenarios predict rising temperatures in every district. The highest average temperatures will be seen in the Bas-Sassandra District (over 28°C). In the Lagunes, Abidjan, Lacs, Goh-djiboua and Comoe Districts, average temperatures should be

Table 4. Weights assigned by experts to risk component indicators.

Component	Indicator		Weight allocated
Hazard	Annua lrainfall (mm)		2
	Average annual temperature (°C)		1
Exposure	Pregnant women (%)		1
	Children under-5 (%)		2
Vulnerability	Sensitivity	Children under-5 and pregnant women (%)	4
	Adaptive capacity	Use of vector control (impregnated bed nets and insecticides) (%)	3
		Households using self-medication (%)	2
		Household income allocated to health (%)	2
		Households not using preventive prophylaxis (%)	3
		Access to healthcare (%)	1

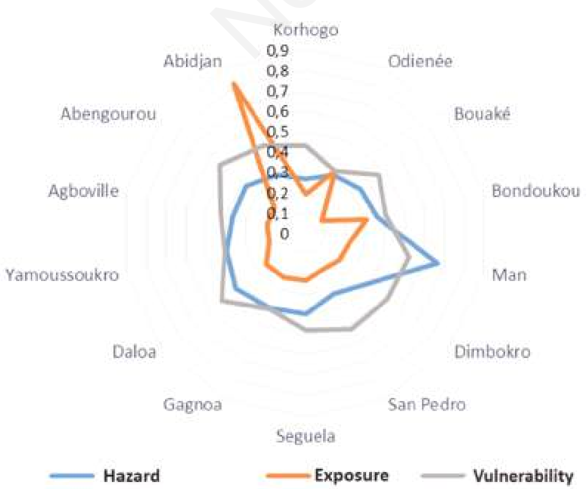

Figure 3. Current *hazard, exposure* and *vulnerability* levels of pregnant women and children under five to malaria by district.

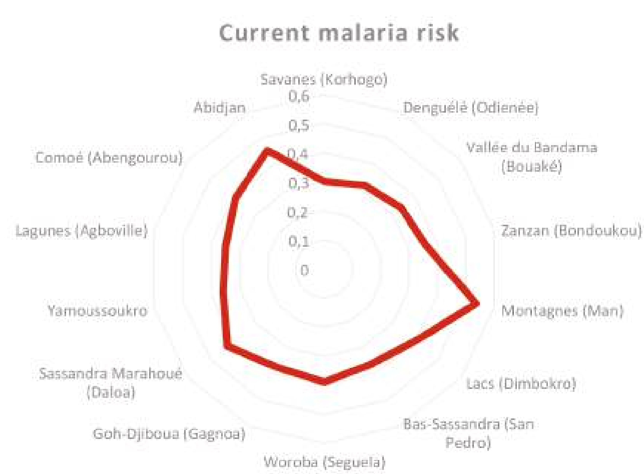

Figure 4. Level of malaria morbidity risk among pregnant women and children under.

between 26 and 27°C. Climate zone IV, situated within the Mountains District, is predicted to be the least affected, with temperatures expected to range between 25 and 26°C. The population projection to 2050 also shows population growth, with Abidjan in comparison to other districts continue to be very densely populated, followed by Savanes, Bas-Sassandra, Vallée du Bandama and Goh-Djiboua Districts.

Future malaria risk for pregnant women and children under-5

Analysis of Figure 6A and 6B shows a relatively similar evolution of *hazard, exposure* and *vulnerability* in the different districts by 2050, according to the two scenarios. Climate hazard is expected to be very high in climate zone IV in the Mountains District (Man), with a score of 1, and intermediate in climate zones II and III in the Sassandra Marahoué and Woroba Districts, respectively. The Bas-Sassandra, Zanzan and Savanes Districts, located in climate zones I, II and III, respectively, will have low hazard levels under both scenarios. In terms of exposure, the scenarios describe a situation almost identical to the current level of exposure. Pregnant women and children under five in the Abidjan District should remain highly exposed, with *vulnerability* remaining intermediate in all climatic zones. However, the districts of Sassandra Marahoué, Vallée du Bandama (in climate zone II), Bas-Sassandra and Comoé (in climate zone I) stand out, with significantly higher scores. Figure 7A and 7B show a similar evolution of the malaria up to 2050 under the two scenarios. The level of risk should be intermediate in climate zones I, II and IV in Abidjan, Sassandra Marahoué and the Mountains District, while climate zone III should have a low-risk level. Overall, the RCP 4.5 scenario may present a higher level of risk than RCP 8.5 by 2050 as presented in Figure 8. Only in Abidjan District in climate zone I should the risk level of RCP 8.5 be greater than that offered by RCP 4.5. The Mountains District, in climate zone IV, would have the highest malaria risk, while Zanzan and Denguélé Districts, in climate zones II and III respectively having the lowest.

Comparison of current and future malaria risk levels in pregnant women and children under-5

It is worth noting that the risk of future malaria morbidity in pregnant women and children under-5 may be greater than the current risk (Figure 9) under both scenarios. However, the RCP 4.5 scenario presents a slightly higher level of risk than the RCP 8.5 one.

Discussion

Impact chain and indicator weighting

The IC method (Estoque *et al.*, 2022) is consistent with the AR5 concept and a straightforward, practical and useful approach for gaining insight into climate-related impacts. As Zebisch *et al.*

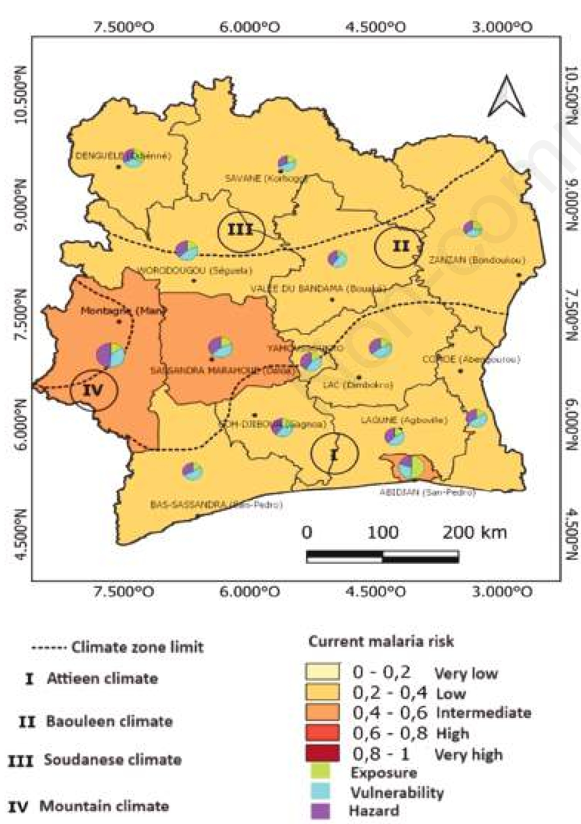

Figure 5. Spatial distribution of current malaria morbidity risk among pregnant women

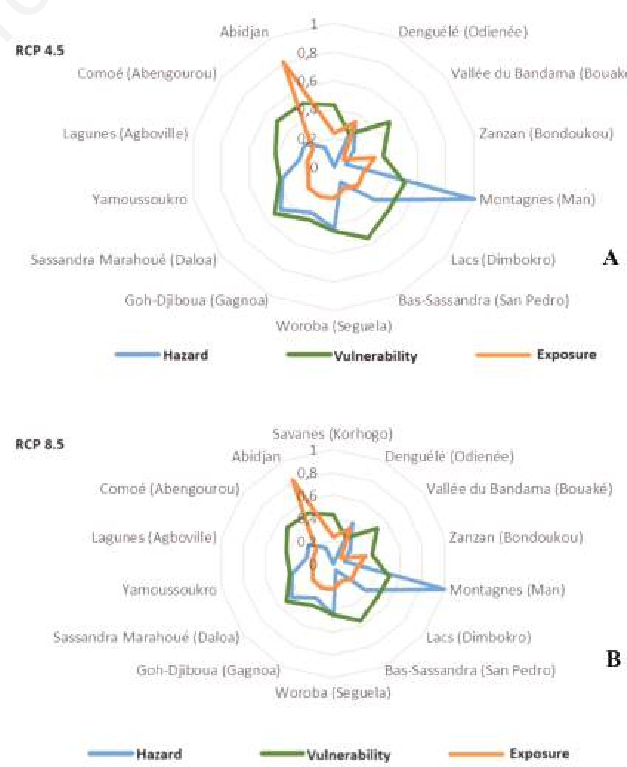

Figure 6. *Hazard, exposure* and *vulnerability* of pregnant women and children under five due to malaria by 2050. **A**) Under the RCP 4.5 scenario; **B**) and the RCP 8.5 scenario in Côte d'IvoireAnd children under five by administrative district.

Table 5. Weights for malaria risk assigned to risk components.

Component	Weight
Hazard	1
Exposure	2
Vulnerability	4

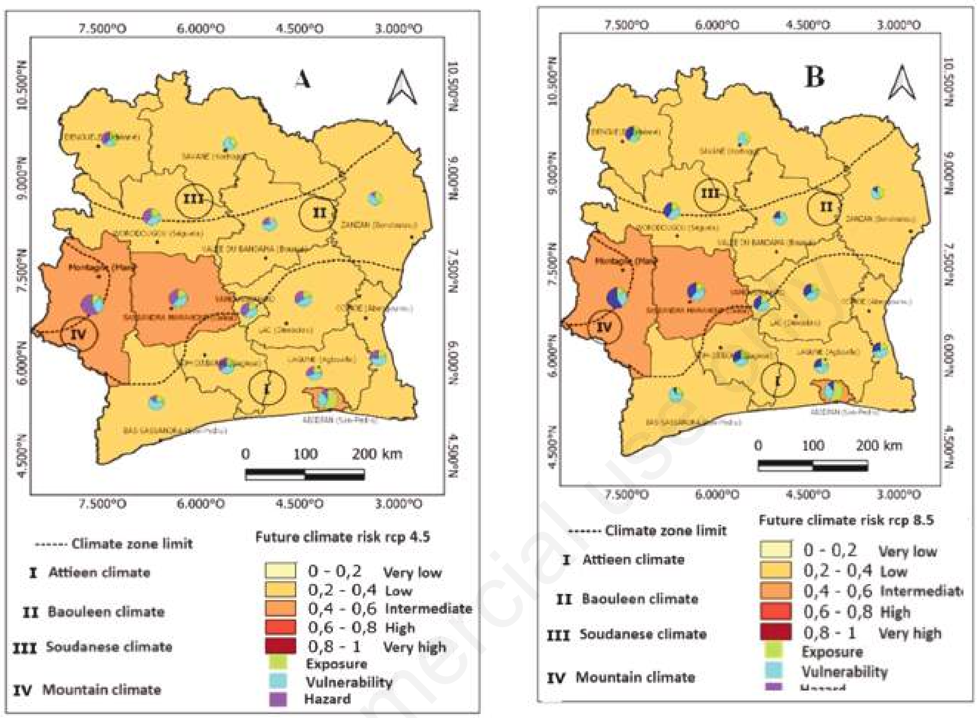

Figure 7. Spatial distribution of future malaria risk in pregnant women and children under five by 2050. A) Under the RCP 4.5 scenario; B) and the RCP 8.5 scenario in Côte d'Ivoire.

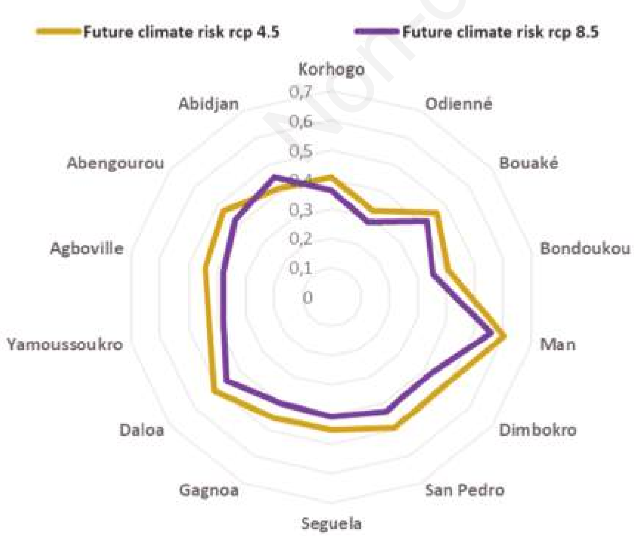

Figure 8. Future malaria risk in pregnant women and children under 5 by 2050 under the RCP 4.5 and RCP 8.5 scenarios in Côte d'Ivoire.

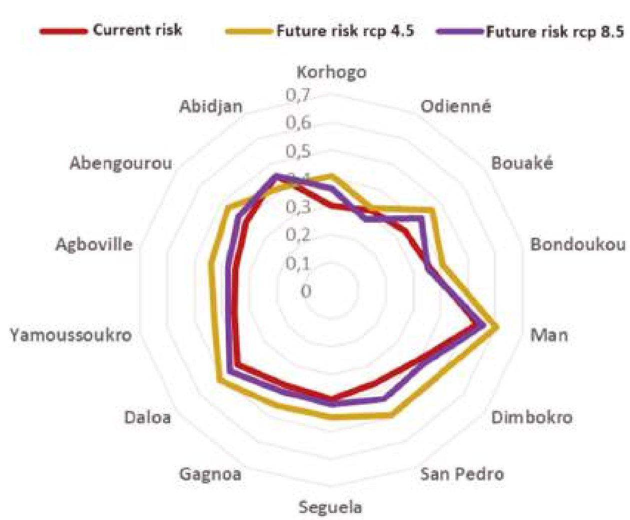

Figure 9. Comparative assessment of current and future malaria risk in pregnant women and children under 5 years.

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(2021) suggest, it serves the selection of appropriate indicators and guids a qualitative assessment based on expert opinion. This proved to be a valuable tool for weighting the indicators and determining the risk score as assessed by AR5. It is widely recognized that temperature and rainfall are the main environmental determinants of malaria. In this risk assessment, these variables represented the climatic hazard well. The indicators measured for these variables were the mean annual rainfall and the mean annual temperature. While both of these indicators are undoubtedly important in the impact chain (Tiu *et al.*, 2021; Yamba *et al.*, 2023), the experts felt that the former deserved a slightly higher weighting than the latter and should therefore be accepted as of slightly higher importance. Indeed, based on their experience and the literature, the experts believed that rain may play a role in the vector development process as it affects the development of larvae, particularly when rainfall is limited and the runoff not excessive. The rains may also increase the number of stagnant water points that are favourable for larval development. It is also worth noting that temperature can influence the intensity of spread through its effects on the growth of the mosquito vector population and the development of the pathogen in the vector (Johnson *et al.*, 2023). Moreover, several studies have indicated an increase in malaria-related morbidity during the rainy season in Côte d'Ivoire (Bassa *et al.*, 2016; Henry *et al.*, 2003; M'Bra *et al.*, 2018). For example, the work of M'Bra and colleagues (2018) indicate that a progressive increase of 10 mm in monthly rainfall in the Korhogo Region in northern Côte d'Ivoire is, on average, associated with a 1.2% increase in the number of clinical cases of malaria episodes one to two months later. It would appear that a 1°C increase in the mean monthly temperature is associated with a 3.5% decrease in malaria episodes, which makes it important to consider the weight of the mean annual rainfall in relation to the mean annual temperature. Our analysis of the *hazard* component of risk indicates that the current climatic hazard is relatively high in climate zone IV in the Mountains District (Man), intermediate in climatic zones II and I in Sassandra Marahoué (Daloa) and Goh Djiboua (Gagnoa) Districts and relatively low in climatic zone III. This change in climate appears to align with the spatial distribution of rainfall in the country. It would thus appear that the strength of the annual rainfall heights in Côte d'Ivoire is generally higher in the West of the country, the Mountains District, and progressively lower towards the Northeast in climate zone II in the Zanzan District as described by Soro et al. already in 2016.

Exposure of pregnant women and children under-5

The level of exposure to climatic hazards is highest in climate zone I in the Abidjan District. This high exposure could be explained by the high concentration of under-5children and pregnant women in this district. Indeed, the indicators considered for the *exposure* component are the percentage of these two groups. As Abidjan District, with a population of over 4.0 million, is home to a fifth (20.8%) of the country's total population (INS, 2021), it is thus obvious that there are more pregnant women and children in this District than in others. However, various authors have noted a significant increase in human exposure to vectors due to the growth in human and vector populations, globalization, population mobility and urbanization (UNEP, 2018; Rocklöv & Dubrow, 2020; Semenza, 2021), which could explain the importance of exposure in this district, which is also a highly urbanized. When calculating expected changes up to 2050, our results show no clear change with respect to *exposure*. These findings are in line with those of Winsemius *et al*. (2018), who found that exposure does not change significantly under future climate scenarios by analyzing household survey and hydrological data on river floods and droughts from 52 countries. However, the absolute number of people potentially exposed may increase or decrease significantly depending on the scenario and region (Winsemius *et al.*, 2018). It appears therefore important to make targeted investments (e.g., in early warning systems) to improve protection against such exposures in order to increase the resilience of vulnerable populations as proposed by Cissé and colleagues (2022).

Vulnerability of pregnant women and children under-5

As for *vulnerability*, the experts gave more weight to the sensitivity indicator than to adaptive capacity, which would mean that vulnerability here is more related to the sensitivity of pregnant women and children under-5. Indeed, according to several authors, pregnancy and maternal status increase vulnerability to heat, infectious diseases, food-borne infections and air pollution in pregnant women (Arroyo *et al.*, 2016; Ngo & Horton, 2016; Zhang *et al.*, 2017). However, children are particularly vulnerable to the impacts of climate change. Indeed, they often show unique pathways of exposure and sensitivity to climate risks, given their immature physiology and metabolism and their high consumption of air, food and water relative to body weight compared to adults (Kim, 2016). To this end, particular emphasis is placed on the sensitivity indicator compared to the adaptive capacity one in this study. Thus, districts in climate zone II (Sassandra Marahoué, Vallée du Bandama), zone I (Comoé) and zone IV (Mountains) had an intermediate level of vulnerability, while the other districts had a low level of vulnerability, particularly in climatic zone III. This change in *vulnerability* between districts and climatic zones could be linked to adaptive capacity in the different districts and, in particular, to indicators such as inadequate use of insecticide-treated mosquito nets and insecticides in the home and non-use of preventive chemoprophylaxis by pregnant women and children. Indeed, the experts considered that these two indicators further weaken the adaptive capacity of pregnant women and under-5 children, hence the importance of the weights of these two indicators. Indeed, Houngbedji *et al.* (2015) observed that the actual number of children regularly using mosquito nets is quite low in Côte d'Ivoire. These authors also noted a reduction in malaria prevalence from 43% to 33% between 2010 and 2014 in Côte d'Ivoire following the strengthening of the national malaria control policy, which resulted in the distribution of almost 30,000,000 insecticide-treated bed nets over the same period.

Malaria risk

In general, the current malaria risk is considered to be intermediate in climate zones I, II and IV. However, it is worth noting that Mountains District, situated in climate zone IV, had the highest level of risk at the national level. This could be linked to the magnitude of the *hazard* component, the low adaptive capacity, and also to the geographical location of this district. Of the 14 districts, this district has the most rugged terrain and the highest altitudes compared with the rest of the country. However, according to Midekisa *et al.* (2015) and Siraj *et al.* (2014) malaria has been observed to move to higher altitudes in the mountainous regions of Colombia and Ethiopia in warmer years. This indicates that, without intervention, malaria may potentially increase at higher altitudes as the climate warms. It is possible that the relatively minor change in risk factors by 2050 may be due to the fact that only the *hazard* and *exposure* components have been projected to rise, while other variables remain constant. A comparison between current and future risk levels suggests that the RCP 8.5 scenarios present a risk level very similar to the current. However, it is worth noting that the RCP 4.5 scenario presents a higher level of current risk than RCP 8.5. It is also worth noting that the RCP 8.5 scenario, which is arguably more pessimistic than the RCP 4.5 scenario, may not be as significant in this context. It may be due to the fact that the RCP 8.5 scenario predicts a greater temperature rise than RCP 4.5 does. It is possible that this increase could come at the expense of precipitation, *i.e.* a reduction in rainfall could potentially impact larval breeding sites. In addition, the relationship between malaria and temperature is not straightforward and projections of changes in risk under climate change can result in complex patterns (Ebi *et al.*, 2018). Some studies have indicated that an increase in monthly rainfall may lead to an increase in clinical malaria episodes (Han *et al.*, 2017; M'Bra *et al.*, 2018; Panda *et al.*, 2019). However, other studies have observed a pattern of reduced burden with increasing temperatures in West Africa (Yamana *et al.*, 2016; M'Bra *et al.*, 2018). Finally, some authors have even suggested that a warming climate does not necessarily lead to an increase in malaria spread in Africa (Murdock *et al.*, 2016; Tompkins & Caporaso, 2016).

Study limitations

The use of expert opinion was an important element in the methodological approach adopted. However, as observed by Hendrikx *et al.* (2001), the results obtained using this approach may vary from one group of experts to another. However, we made considerable efforts to address this limitation by basing our choices on literature-based justifications. Another limitation of this study is the lack of daily information, which could have provided more accurate data. It is worth noting that for diseases whose onset extends over fairly short periods, it can be challenging to fully appreciate the effect of climatic changes with annual data. It would be beneficial if countries could allocate resources to establish a health information and monitoring system acquiring daily data as that would allow for a more nuanced understanding of the nuances of change. Importantly, IPCC may have issued further clarification about the *Risk* concept in the AR6 after completion of this study that could better reflect its various uses and contexts, thereby clarifying issues leading to differing interpretations and applications across their Working Groups and in different reports.

Conclusions

This study has shown that the current and future malaria risk due to climate is greater in the Mountain District (Man) of Côte d'Ivoire. However, the city of Abidjan remains the most exposed to malaria risk. The level of vulnerability varies from district to district, depending on adaptive capacity and population practices. The IPCC AR5 framework is useful for understanding climate-related impacts, *exposure*, *vulnerability* and *risk* as this approach combines different indicators that are assessed on the same scale based on standardization. It can also integrate both quantitative and qualitative approaches to risk assessment that needs to be used more widely in a variety of studies and at different scales. In order to control the current and future risk of malaria in Côte d'Ivoire, it would be advisable to strengthen vector control measures in the various districts, particularly in the mountainous districts. Preventive measures such as early warning systems are also needed to strengthen the resilience of vulnerable populations.

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