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# Increased risk of malaria transmission with warming temperature in the Ethiopian Highlands

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## Abstract

The heavily populated highlands of Ethiopia are currently at low risk for malaria transmission, but global warming may change the risk level significantly. The inhabitants of the Ethiopian Highlands are highly vulnerable to this potential hazard due to their lack of immunity. Here, we identify hotspots within the Highlands where projected warming towards the end of the 21st century will increase the risk of malaria transmission significantly. Based on projected temperature changes, we conclude that about a third of the region's population and roughly 14% of its land area will become at high risk for malaria transmission within a century under the high-emissions-no-mitigation baseline scenario for future climate change. Our analysis combines dynamically down-scaled regional climate projections, high resolution satellite observations of temperature, and a village-scale malaria transmission model that was developed based on climatic, environmental, entomological, and medical data collected by our group in comprehensive multi-year field surveys of villages in this region. The projected impacts of global warming on malaria transmission in Africa have been controversial. We propose a framework that reconciles seemingly contradictory conclusions, and informs strategies for climate adaptation not only over the Ethiopian Highlands but broadly over Africa, where more than 90% of malaria deaths occur every year.

## Introduction

Pronounced increases in malaria have been reported widely over the East African Highlands in the late 20th century [1–4]. Malaria transmission in highland areas is generally limited by temperatures due to the thermal biology of malaria parasites and aquatic-stage vectors, but these limitations quickly diminish as temperature climbs [4–6]. The increased malaria transmission over the East African Highlands has been explained by observed warming [7–9], while other studies explain the surge of malaria by an increase in climate variability [10–12], or other factors such as drug resistance, land-use change, and population migration [13]. The role of climate change in recent epidemics of malaria in highland areas has been controversial. In comparison to the magnitude of the temperature increase in the recent decades (~0.5 °C from 1960 to 2000 [7, 8]), the projected temperature rise in the future (as high as 4 °C by 2100 [14]) leaves little room for disputing the potential impact of warming on malaria transmission in highland areas.

This study focuses on the Ethiopian Highlands (elevation above 1200 m above sea level)—one of the most heavily populated regions in Africa (supplementary figure 1 is available online at stacks.iop.org/ERL/15/054006/mmedia). Nearly 90% of population in Ethiopia live in less than 40% of the highland land area, where malaria is mostly hypo-endemic [15, 16]. While low temperature limits malaria transmission in the Highlands, so does the low population density in the lowlands. Malaria transmission in non-populous areas is less of a problem, and hard to quantify through observations. Therefore, analysis in this study was conducted for populous areas where population density is above $50/\text{km}^2$, which almost correspond to areas where elevation is above 1200 m (supplementary figure 1). Most of regions in the Highlands experience three seasons, called Kiremt, Belg, and Bega. The seasonality of temperature is shown in supplementary figure 6. The impact of spatial and temporal variability in rainfall was not considered in this analysis. Most of those populated areas in the Highlands receive more than 800 mm of rainfall annually (supplementary figure 1(b)), hence rainfall is not likely a limiting factor of malaria transmission [17]. With expected climate change, the Ethiopian Highlands are thus particularly vulnerable to potential impacts of warming on malaria transmission.

The potential enhancement of malaria transmission with warming in any region depends not only on the magnitude of temperature increase but also on the current intensity of malaria. High risk is associated with areas where malaria is currently absent but will become endemic in the future. In those areas, people are susceptible to malaria due to low immunity levels, and hence more likely to encounter epidemics. In contrast, people already living in malaria-endemic areas may not suffer severely under higher potential for malaria transmission driven by global warming, due to their high acquired immunity [4, 18, 19]. People in areas far too cold for malaria transmission are also unlikely to suffer, where global warming would not enhance temperatures enough to cause these areas to become malaria-endemic.

The most important metric in determining the potential of malaria endemicity is the basic reproduction number, $R_o$, which is defined as the number of infections expected to be generated by a single person in a totally susceptible population. Malaria is expected to spread when $R_o > 1$ or contract when $R_o < 1$. We define: *high-risk area* as the area currently $R_o < 1$ but $R_o > 1$ in the future; *low-risk area* as the area where $R_o$ currently is and continues to be below 1; and *endemic area* as the area where $R_o > 1$ both at present and in the future. Our goal is to simulate $R_o$ accurately over the Ethiopian Highlands in comparison to observational data, and then to identify the high-risk and low-risk malaria areas as a consequence of global warming.

## Methods

(Study approach) Our approach combines both detailed projection of local temperature conditions, and credible development of a malaria transmission model that translates local temperature conditions into reliable projections of disease prevalence at the local scale within the Highlands (figure 1(a) and Methods). Current (2006–2010) temperature distribution was estimated as mean air temperature using high-resolution satellite observations of surface temperature from MODIS-Aqua satellite [20–22]. Future (2070–2100) temperature distribution was obtained from a regional climate model, MIT Regional Climate Model (MRCM) [23], through regional dynamical downscaling over East Africa and rigorous selection of global circulation models (GCMs) [24]. The future GCMs climate is based on the RCP8.5, a high greenhouse gas (GHS) emissions, no mitigation baseline scenario, which projects that mean temperature over the Highlands would rise by around 3.9 °C by 2100 but that the change in precipitation would not be significant [24].

Current and future $R_o$ were estimated using a detailed field-tested mechanistic model of malaria transmission at the village scale, Hydrology Entomology and Malaria Transmission Simulator (HYDREMATS) [25, 26]. HYDREMATS was updated for the Highland conditions (supplementary figure 2) and calibrated extensively (supplementary figures 3–5) based on three years of monitoring campaigns at our field site in the Ethiopian Highlands, named Ejersa [26] (figures 1(b)–(f) and supplementary Methods). The weather during the monitoring campaigns was typical of the long-term trend. Values of $R_o$ were first simulated in HYDREMATS using series of temperature data from MRCM for 13 major cities in Ethiopia and Ejersa, and assigned values of mean annual temperatures (supplementary figure 6 and Methods). Values of $R_o$ were calculated for *Plasmodium falciparum (P.f.)* and *Plasmodium vivax (P.v.)*—the two major malaria parasites—malaria, and expressed as a function of annual temperature for the 14 patterns of temperature series (figure 2(a), supplementary figure 7). Then, $R_o$ values were estimated over the Ethiopian Highlands for current and future climates using both (1) observed time series of temperature data to identify the closest climate patterns among the 14 cities, and (2) annual temperatures in observed current and projected future climate (supplementary figure 8 and Methods). The pattern of the estimated $R_o$ for current *P.f.* malaria (figure 2(c)) compares well with that of *P.f.* parasite rate in children two to ten years old (figure 2(d)) [16] (supplementary Discussion), which lends credence to this approach.

(Field surveys in the Ethiopian Highland) Comprehensive multi-year field surveys were conducted at two villages in the Ethiopian Highlands; Ejersa (N8°27′; E39°04′) and Gudedo (N8°33′; E39°12′). Both villages are located approximately 80 km southwest of Addis Ababa. Here we focus on our main field site, Ejersa, where the assumption used in this study about abundant vector breeding sites (or, non-limiting rainfall conditions) is evident and confirmed through field surveys.

Ejersa (figure 1(b)) is located adjacent to the Koka Reservoir. Its elevation is around 1600 m, and its mean annual temperature is about 21 °C. Ejersa is a set of three small communities called *kebele*, and most of the field campaigns were conducted at the kebele located closest to the reservoir, Dungugi-Bekele kebele. This kebele had about 2800 inhabitants and 590 households in 2012 (personal correspondence with local administrator, 2012).

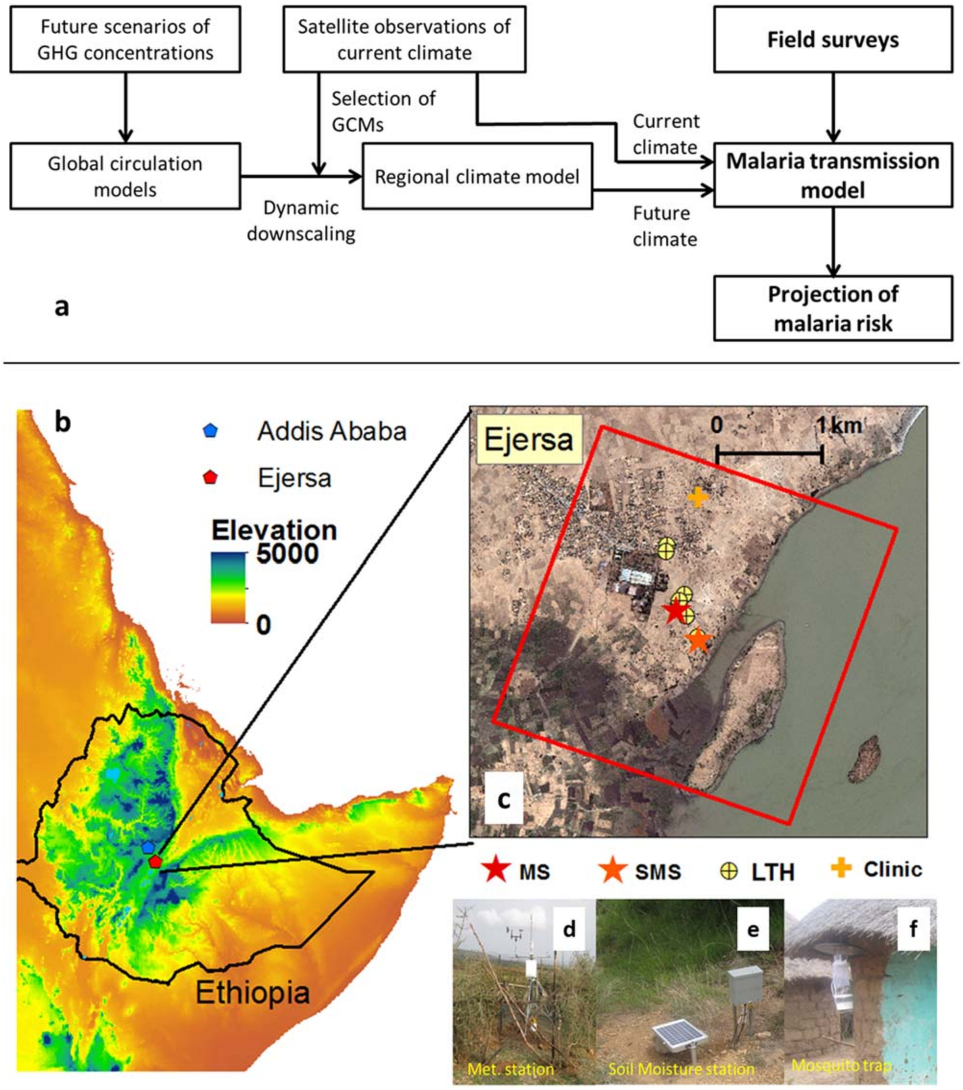

**Figure 1.** Approach and target of the study. Our study approach includes field surveys, development of malaria transmission model, and preparation of climate forcing data through dynamic downscaling of climate models (a). The location of our study site, Ejersa, (red) and of Ethiopia's capital, Addis Ababa, (blue) are presented in (b). Diverse topography over the Ethiopian Highlands (colored) is also found (b). The field setting in Ejersa are presented in (c). Monitoring campaigns were conducted with a meteorological station (MS) (red star; picture in (d)), a soil moisture station (SMS) (orange star; picture in (e)), groundwater-measuring pressure transducers, and six mosquito light traps (yellow circle with cross; picture in (f)). Malaria incidence data were collected from a local clinic (orange cross). The red rectangle indicates the 3 km-by-3 km simulation domain.

The field campaigns were conducted from July 2012 through April 2015. Meteorological and entomological data were collected during this period. Meteorological data collected include precipitation, temperature, relative humidity, incoming shortwave radiation, wind speed, and wind direction at 30 min resolution. Hydrological conditions such as soil moisture and groundwater table were also monitored every 30 min. Entomological data collected include adult mosquito abundance and aquatic-stage mosquito abundance. In addition, monthly malaria clinical data were obtained at the local clinic at the Dungugi-Bekele kebele. The daily water levels of the Koka Reservoir were provided by the Ethiopian Electric Power Corporation. Meteorological and environmental data are shown in supplementary figure 2. The data collected in our field surveys are used to develop and test a mechanistic model of malaria transmission.

(Malaria Transmission Model) We use a mechanistic model of malaria transmission at the village scale, Hydrology Entomology and Malaria Transmission Simulator (HYDREMATS) [25, 26]. HYDREMATS features one of the most detailed mechanistic structures, with coupled hydrology and entomology [25, 26]. HYDREMATS was updated for the Highland conditions (supplementary figure 2) based on three years of extensive monitoring campaigns at our field site in the Ethiopian Highlands, Ejersa (figure 1(b)) [26]. The simulation results of HYDREMATS compare well with hydrological observation data (supplementary figures 3 and 4), sampled *Anopheles* mosquito population data (supplementary figure 5(a)), and the

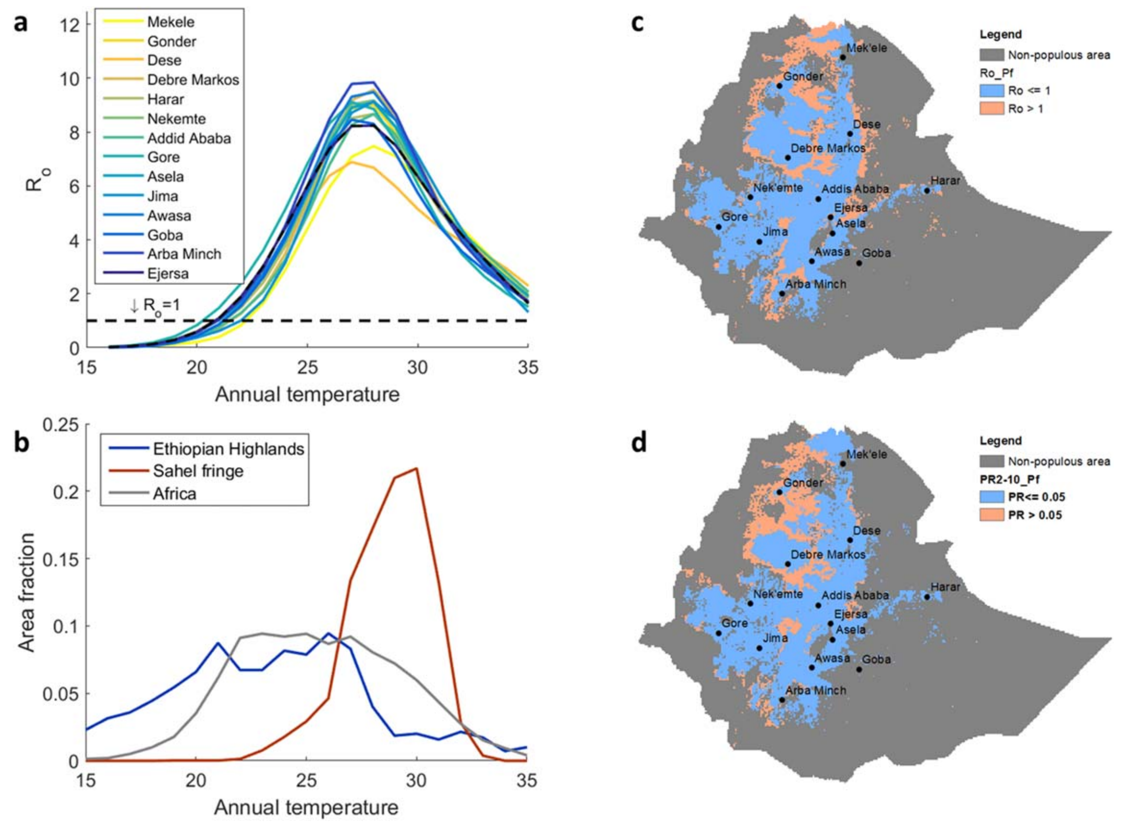

**Figure 2.** Estimation of $R_o$ and comparison with MAP estimates. (a) Estimated $R_o$values for *P.f.* malaria as a function of annual temperature for the 13 major cities in Ethiopia and Ejersa. (b) Area fraction of Africa (gray), Sahel fringe (N10°–N20°, W18°–E16°) (red), and the Ethiopian Highlands (blue) corresponding annual temperatures. For example, the area where annual temperature is [20–21) °C is 0.03 (3%) of the whole land area in Africa. (c) and (d) Estimated *current* (2006–2010) $R_o$for *P.f.* malaria (c) and estimates of *P.f.* parasite rate (PR) in 2–10-year-old children for the years 2000–2015 (d) for the Ethiopian Highlands. The non-populous areas where population density is less than 50/km$^2$ are shown in gray. Locations of the 13 major cities in Ethiopia and Ejersa are also marked. The estimates of PR data were obtained from the Malaria Atlas Project (MAP) [16], which provides modeled PR yet reflecting the most comprehensive PR survey results to date.

average seasonality of malaria infection (supplementary figure 5(b)).

(Basic Reproduction Rate ($R_o$)) The spatially-explicit approach of HYDREMATS allows for the estimation of $R_o$ accurately with minimal assumptions, which presents a significant advantage over the conventional Ross-MacDonald formula [6]. The basic reproduction number ($R_o$) is the most important and commonly used indicator of disease transmission potential; yet despite the importance and the popularity of this metric, accurate estimation of $R_o$ for malaria transmission has not been easy. The conventional Ross-MacDonald formula assumes static conditions; however, malaria transmission is highly dynamic, responding to non-static climate, especially in unstable transmission conditions. On the other hand, the mechanistic structure of HYDREMATS allows to estimate $R_o$ under dynamic conditions, following the exact definition of $R_o$—the number of infections expected to be generated by a single person in a totally susceptible population, without making assumptions. HYDREMATS can simulate the status of each human, as well as each mosquito, and tracks infections (e.g. which human infects which mosquito, and which mosquito infects which human; hence it can calculate how many people were infected from an infectious person). In this way, HYDREMATS can calculate $R_o$ for any dynamic environmental conditions and mosquito populations.

The values of $R_o$were estimated through the HYDREMATS-based long-term average of $R_o$ (hereafter $\widehat{R_o}$):

$$\widehat{R_o} = \sum_{i=1}^{N_{inf}} R_o^i / N_{inf},$$

where $N_{inf}$ is the number of infectious people simulated over the simulation period of three years, and $R_o^i$ is the number of infections generated from the $i$th infectious person, assuming that the population is fully susceptible. Because the calculation of $R_o$requires the assumption of fully susceptible population, any dual infection was counted towards $R_o^i$, as a new infection generated by an infectious host. The number of simulated malaria cases originated from the $i$th infectious person, thus, differs from $R_o^i$. Note that $N_{inf}$ increases with time and that $R_o^i$ is dictated by the time-varying vector population and environmental conditions. $\widehat{R_o}$ can also be defined as the average of $R_o^i$ values.

(Estimation of $R_o$ over the Ethiopian Highlands) We used HYDREMATS to estimate $R_o$ over the Ethiopian Highlands, assuming the same climatological and environmental conditions as in Ejersa, except for spatial variation of temperature from one location to another. In order to produce *annual temperature—*$R_o$ *relationships* for a range of temperature patterns over the Ethiopian Highlands, HYDREMATS was applied to 13 major cities in Ethiopia and Ejersa (supplementary figure 6), where the seasonality of temperature was represented through three-hourly data sets from MRCM and the mean annual temperature was prescribed. The curves were created both for *P.f.* and *P.v.* malaria and were presented as a function of annual temperature (figure 2(a), supplementary figure 7). When the $R_o$ curves are read in terms of rainy season temperature in Ejersa, which approximates to the main malaria transmission season, the curves compare well with the '*transmission season temperature*'— $R_o$ *curve* presented by Mordecai *et al* [27] (supplementary figure 7).

The values of $R_o$ under current and future climate at any location *i* over the Ethiopian Highlands were estimated by (1) choosing the *annual temperature—*$R_o$ *curve* that best represents the seasonality of temperature at location *i*, and (2) applying current and future annual temperatures to the curve. The curve of best fit (corresponding to location *j*, $j \in [1, 14]$) was determined such that removed-mean monthly squared difference is the smallest:

$$\min_{j\in[1,14]} S_j = \sum_{m=1}^{12} ((T_{i,m} - \mu_i) - (T_{j,m} - \mu_j))^2,$$

where $T_{i,m}$ and $T_{j,m}$ are the mean temperature of month *m* for location *i* and *j*, respectively, and $\mu_i$ and $\mu_j$ are the annual mean temperature for location *i* and *j*, respectively. Removed-mean monthly temperatures for the 14 sites (*j* locations) are shown in supplementary figure 6(a), and the best-fitting *j* locations for any given site over the Ethiopian Highlands (*i* locations) are illustrated in supplementary figure 6(b).

(Moderate-resolution Imaging Spectrometer (MODIS) Estimation of Current Temperature Distribution) For the estimation of malaria transmission intensity over the Ethiopian Highlands, the village-scale mechanistic model of malaria transmission, HYDREMATS, was combined with satellite observations of temperature (figure 1(a)). The moderate-resolution imaging spectrometer (MODIS) Acua product, MYD11C3, was used to obtain distribution of temperature in current climate [20] (supplementary figure 8(a)). This data set provides monthly land surface temperature for daytime and nighttime with a high resolution of 0.05°, which is ideal to resolve the sharp gradient of temperature over the highlands due to diverse topography. However, because MODIS daytime and nighttime land surface temperature are known to give biased estimates of maximum and minimum temperature in this region [21], an empirical equation by Zhang *et al* [22] was employed in this study to estimate current distribution of mean air temperature at high resolution from MODIS surface temperature data.

(Dynamic Downscaling of Future Climate Projections from CMIP5 GCMs using MRCM) Our approach integrates dynamically-downscaled projections of future climate for estimating malaria transmission. Future (2070–2100) temperature over the Ethiopian Highlands was projected using a regional climate model, MRCM [23, 24], through regional dynamical downscaling over East Africa and rigorous selection of GCMs (figure 1(a), supplementary figure 8). At topographically diverse regions, such as the Ethiopian Highlands, climate prediction benefits significantly from dynamic downscaling. For more details see supplementary Methods.

## Results

Assuming that changes in temperature exclusively determine the future of malaria in the Highlands, figure 3(a) delineates the low-risk (blue), high-risk (red), and endemic areas (green) for *P.f.* malaria. Population and area in each category are summarized in table 1. Population estimates for year 2010 and 2100 were obtained for the Shared Socioeconomic Pathway (SSP) 5, which is the most likely scenario in Africa under RCP 8.5 [29]. Under the high-emissions-no-mitigation baseline scenario of future GHG emissions, we project that approximately 14% of the country's land area will be at high-risk for *P.f.* malaria by the year 2100, hosting about a third of the national population (27 million and 33 million people based on the population estimate for year 2010 and 2100 [29], respectively). The high-risk area is mostly located at elevations between 1500 and 2200 m (figure 3(b)). The low-risk areas for *P.f.* malaria will host about 42% of the population in 2100, yet this area will be limited to merely 11% of the national land, which includes Addis Ababa. A large fraction of the low-risk areas are located at elevations above 2200 m (figure 3(b)). Inhabitants already living in the endemic areas, including Ejersa, are likely to suffer from increased morbidity of malaria with global warming, but their acquired immunity would restrict a significant rise of mortality. Those represent about 21% of Ethiopian population; inhabitants living in the non-populous area may also be classified under this category. Our results show that the fraction of population living in malaria endemic areas would triple in the future. The high-risk population in Ethiopia is likely to be much larger than today due to its large population growth rate (2%–3% increase annually). Our results suggest that a significant proportion of the Ethiopian Highlands will be most severely threatened by malaria outbreaks due to

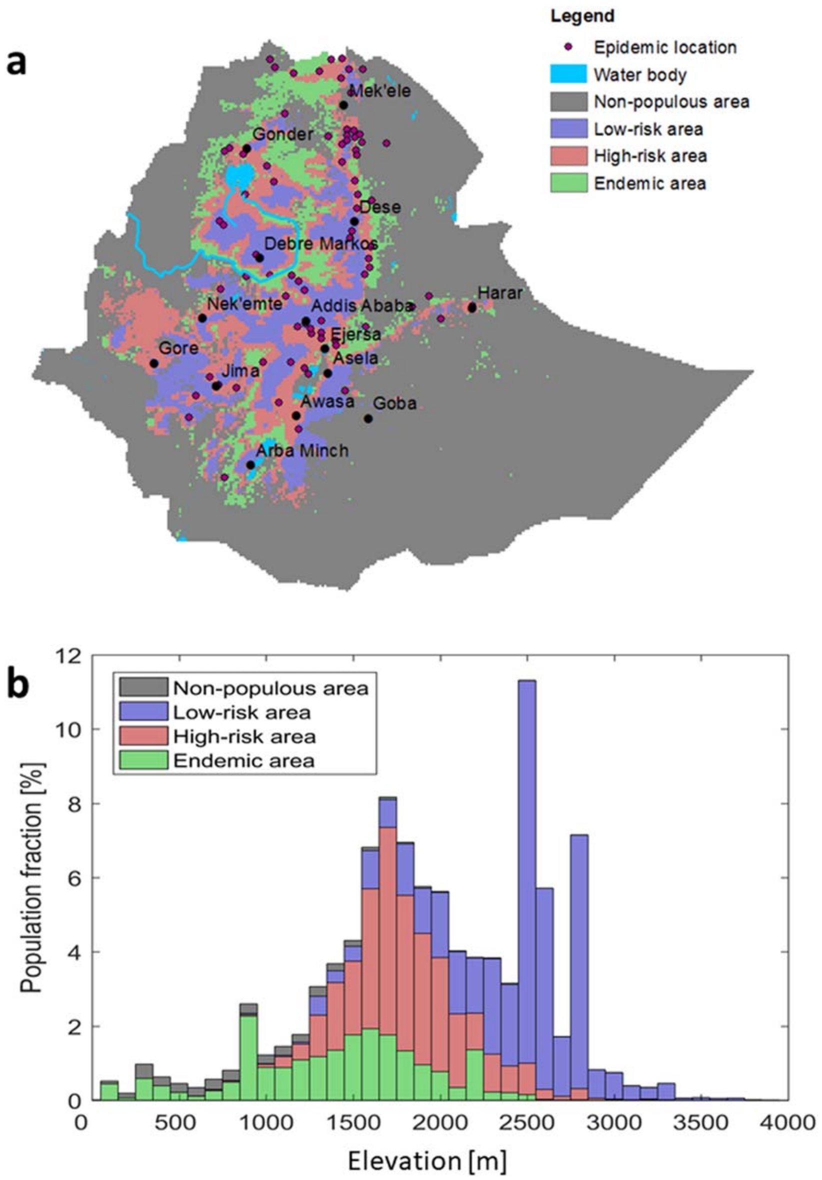

**Figure 3.** Risk map for *P.f.* malaria over the Ethiopian Highlands and affected population. The regions (a) and the affected fraction of population (b) in low-risk, high-risk, and endemic areas are shown in blue, red, and green, respectively. The non-populous areas (population density $<50/\text{km}^2$) and the population there are shown in gray. Historical epidemic locations [28] are also overlaid in red circles. The analysis was conducted for future (2070–2100) climate under the RCP8.5 and SSP5 scenarios.

**Table 1.** Population and area in each category of the risk map for *P.f.* malaria. The absolute and relative distributions of the risk areas within the national total are shown. The estimates outside the brackets are based on annual temperature increase. The estimates inside the brackets are made with the minimum and maximum monthly temperature increases, respectively (minimum- and maximum -risk scenario). Population estimates for year 2010 and 2100 were obtained for the RCP8.5 and SSP5 scenarios [29]. Detail may not sum up to totals because of rounding.

| | | Population, 2010 | | Population, 2100 | | Area | |
|---|---|---|---|---|---|---|---|
| *P.f.* | | Million | % | Million | % | 1000 km$^2$ | % |
| Populous highland area | Low-risk area | 27 [32;24] | 33 [39; 31] | 43 [47; 40] | 42. [47; 40] | 125 [149; 109] | 11 [13; 10] |
| | High-risk area | 27 [23; 31] | 34 [28; 37] | 33 [28; 35] | 32 [28; 35] | 151 [127; 168] | 14 [12; 15] |
| | Endemic area | 17 [17;17] | 21 [21; 21] | 21 [21; 21] | 21 [21; 21] | 114 [114; 114] | 10 [10; 10] |
| Non-populous lowland area | | 10 | 12 | 4 | 4 | 714 | 65 |
| Total | | 82 | 100 | 101 | 100 | 1104 | 100 |

global warming, including some populous cities. Although the results presented in this study indicate areas where people are expected to live under high-risk of malaria transmission towards the end of the 21st century, it is recommended that more resources are allocated as soon as possible to those areas, as warming is happening gradually, and because those areas may be susceptible to epidemic of malaria associated with abnormal heat conditions.

## Discussion

History also testifies that most epidemics occurred [28] primarily at the high-risk areas (figure 3(a)). These epidemics have occurred due to climate variability [28, 30], most likely due to unusually high temperature. In the same way as the malaria epidemics occurred through the combination of low immunity and high temperature in the past, we expect to experience malaria endemicity in the future in the same high-risk areas, under global warming.

The assumptions used in this analysis lead to several uncertainties, the most important of which are assumptions regarding temperature. For example, by using projections of annual temperature change, we assumed temperature increases uniformly over the course of the year. However, the magnitude of the projected temperature rise varies from month to month (supplementary figures 9 and 10). Temperature in some months is more important than others for malaria transmission dynamics. The uncertainties derived from intra-annual variability of temperature were evaluated by repeating the analysis using the projected minimum and maximum monthly temperature increases as the uniform annual temperature increase (minimum- and maximum-risk scenario, respectively). For example, under the minimum- and maximum risk scenarios, the high-risk area for *P.f.* malaria by the year 2100 are projected to be 12% and 15% of the country's land area, covering 28 million and 35 million people, respectively, in 2100 (table 1). The corresponding results are shown for *P.f.* malaria in supplementary figures 11(a), (b) and are summarized in table 1 (for *P.v.* malaria, see supplementary figures 11(c), (d), and supplementary table 1).

Uncertainty also stems from ignoring differences in local environments, such as rainfall, topography, and density of dwellings. Aside from temperature, we assumed environmental conditions are the same as those in Ejersa over all the Ethiopian Highlands. The impact of spatial and temporal variability in rainfall on malaria transmission is assumed to be small over the Ethiopian Highlands because most of the Ethiopian Highlands receive adequate amount of rainfall ($>800$ mm yr$^{-1}$). Historical epidemics in the Ethiopian Highlands are shown to have no association with increase in rainfall [17], while other research [10–12] reports that variability in rainfall is associated with observed increase in malaria transmission. Population density also affects malaria transmission potential. Higher population density may make malaria transmission more likely [6], but the associated economic development may also suppress malaria transmission [31, 32]. The change in land-use associated with population growth was also neglected in this analysis. Although our assumption is reasonable given that malaria is largely limited by temperature over the Highlands [4–6, 9, 30] and that the predicted $R_o$ reasonably reproduced the map of the Malaria Atlas Project (MAP) [16] estimates of parasite rate (figures 2(c), (d), main text), inclusion of other environmental variables based on future field studies may identify malaria risk areas more accurately.

Unlike West Africa, where climate change is unlikely to increase malaria burden [33], malaria in the East African Highlands, and more specifically, the Ethiopian Highlands, will most certainly be exacerbated [34, 35]. For example at the fringe of Sahel in West Africa (N10°–N20°, W18°–E16°), studied by Yamana and Eltahir [33], temperatures during rainy seasons are around 30 °C, closer to the warm side of the curves in figure 2(a) (figure 2(b)). Beyond that temperature, warming adversely affects mosquitoes' malaria transmission capacity. On the other hand, warming at a colder locations in the East African Highlands, closer to the cold side of the curves in figure 2(a), increases the transmission potential [35] (figures 2(a), (b)). Lack of immunity in those colder areas makes inhabitants even more vulnerable to malaria transmission. In adaptation to climate change, the distribution of malaria intervention resources over Africa needs to be guided by clear understanding of at least the direction of the impact of warming on malaria transmission, which varies significantly across the continent.

## Conclusions

This study shows that a large fraction (around 33%) of Ethiopia's population—currently about 27 million people and 33 million by 2010—would live at high risk of malaria under the high-emissions-no-mitigation baseline scenario of future climate change. The high-risk areas are, however, concentrated in relatively a small fraction (14%) of the land area, which are mainly located at the fringes of the Ethiopian Highlands. Our analysis is based on the worst-case scenario for warming. The projections regarding the size of the population living in areas with potentially high risk of endemic malaria should inform climate change adaptation efforts that aim at preventing this potential problem. The map of the high-risk areas identified in this study should help guide implementation of efficient measures to prevent malaria endemicity in this region.

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## Author contributions

NE conducted the analysis. NE lead field campaigns in Ethiopia and updated the malaria model based on field observation data. EABE conceived the study, and supervised the design and implementation of the research plan. All authors participated in writing and approved the final version of the manuscript.

## Competing financial interests

The authors declare no competing financial interests.

## Data availability statement

The data that support the findings of this study are available upon request from the authors.

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