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Mapping the global extent of malaria in 2005

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Abstract

Guidelines for travellers on malaria chemoprophylaxis, the altitude limits of dominant vector species, climate suitability for malaria transmission and human population density thresholds have been used to map the crude spatial limits of *Plasmodium falciparum* and *Plasmodium vivax* transmission on a global scale. These maps suggest that 2.510 and 2.596 billion people were at possible risk of transmission of *P. falciparum* and *P. vivax*, respectively, in 2005. Globally, 75 per cent of humans who are exposed to *P. falciparum* risk live in only ten countries.

The spatial limits of malaria

During the halcyon days of global malaria eradication, mapping the precise spatial extents of malaria transmission was central to the control efforts of the World Health Organization (WHO). Between the 1940s and 1970s, a huge investment was made to synthesize the available information on the distribution of malaria risk. Since the 1970s, the public health focus has shifted away from malaria eradication, and the interest in mapping global malaria risk has therefore waned [1,2]. After a renewed commitment to financing comprehensive malaria control on a global scale, the significance of defining the disease burden attributable to malaria has re-emerged as a priority [1], not least to articulate better the specific regional and national requirements for drugs, insecticides, nets and other commodities needed to ‘roll back’ the disease [2,3].

Despite an obvious need to map risk, until recently there remained no comprehensive definition of the spatial limits of malaria. Previously, information provided by the WHO on the extent of risks due to *P. falciparum* and *P. vivax* for the year 2002 (hereafter referred to as the ‘WHO-2002 map’) was used to define limits [2], and this information was based largely on advice to travellers [4–6]. The precise details of how the WHO constructed these limits are difficult to obtain, however, and several other public-domain sources of travel advice are available [7–10] to complement the WHO sources [6].

Here we review a recent exercise that has used geographic information systems to collate international travel health guideline (ITHG) information with more refined country-specific altitudinal exclusions based on the tolerances of dominant *Anopheles* vectors, climate suitability for malaria transmission criteria, and human population densities in order to

construct an evidenced-based spatial description of the global distribution of *P. falciparum* and *P. vivax* risk in 2005 [11].

Step-by-step guide to creating the global limits of malaria risk in 2005

In this section, we provide a detailed overview of the methods implemented and sources used to define the global spatial limits of malaria transmission in 2005 [11]. The relevant URLs can be found in Table 1.

(i) ITHGs

International travel health guidelines have been developed to advise travellers on appropriate malaria chemoprophylaxis on their journeys. Three primary sources are available in the public domain: the International Travel and Health guidelines of the WHO [5,6], the World Malaria Risk Chart of the International Association for Medical Assistance to Travellers [9,10], and the Health Information for International Travel ('Yellow Book') of the Centres for Disease Control and Prevention [7,8] (Table 1). To map these data, the three main criteria outlined in the ITHGs were considered: administrative boundaries, altitudinal limits and urban centres.

(ii) ITHG administrative boundaries

To define crude spatial limits, subnational descriptions of malaria distribution were combined with databases of administrative areas within countries. First- and occasionally second-level subnational administrative boundaries for all malaria-endemic countries were obtained from the Food and Agriculture Organization's GeoNetwork portal, the International Centre for Tropical Agriculture, and the Environmental Systems Research Institute (Table 1). All classifications of malaria risk in the ITHG entries were defined as presence of malaria, except those of 'no risk', 'negligible risk' and 'sporadic cases', which were classified as absence of malaria. Descriptions of subnational malaria risk that were not geographically specific were ignored. An exception was made if malaria risk was described as present in 50% or more of the administrative area, whereupon transmission was considered possible throughout. Where data were available from more than one source, the finest spatial resolution and most comprehensive information were maintained.

(iii) ITHG altitude mask

A digital elevation model with a spatial resolution of 1×1km [12] (Table 1) was used to implement national altitudinal transmission limits reported in the ITHGs. Nonspecific 'highland' or 'lowland' descriptions could not be mapped. If the ITHG sources provided conflicting limits, then the higher altitude threshold was maintained. Altitudinal limits for malaria transmission were available for 42 countries included in the ITHGs. Most of the nations for which there was no information were in Africa (44 out of 62), so no altitude thresholds could be applied. For the 18 remaining non-African malaria-endemic countries, limits were defined by using those of neighbouring countries with similar dominant vector species [13].

(iv) ITHG urbanization mask

In the ITHGs, 70 cities were reported as malaria free. These cities were geo-referenced by the Encarta Premium Suite 2005 Atlas (Microsoft Corporation) and online gazetteers (Table 1), co-located to their urban extents as defined by the Global Rural-Urban Mapping Project (GRUMP) [14], and then excluded.

(v) Africa climate suitability mask

The Mapping Malaria Risk in Africa (MARA) project (Table 1) fuzzy climate suitability (FCS) model [15,16] was used to constrain further the malaria transmission limits in Africa, because altitudinal information for this continent was scarce in the ITHGs. The MARA model includes climatology-derived temperature limits, so it can be also considered as a surrogate altitudinal mask. FCS values of zero were assumed to be incompatible with malaria risk, an assumption supported by analysis of parasite prevalence and FCS values in East Africa [17]. The spatial resolution of the MARA model was too coarse to apply exclusions to some island territories.

(vi) Global population density mask – high

There are areas where the population density is so high that conditions become unsuitable for transmission through the process of urbanization [18]. Cities with populations of 1 million or more people [19] in malaria-endemic countries ($n = 204$) were geo-referenced and co-located to the urban extents of GRUMP [14]. In addition, projected population counts for the years 2000–2005 were generated by applying national, medium-variant, intercensal growth rates (using the 2004 Revision Population Database; Table 1) to the GRUMP extent by country, before deriving contemporary population densities. Intensely urban areas were then masked as ‘no malaria risk’, using the median of the distribution of mean population density associated with these urban extents by region.

(vii) Global population density mask – low

Those areas where environmental conditions might support malaria, but where there are no people to sustain transmission (population density < 1 person per km^2) were identified and excluded by using the projected (see Step vi) GRUMP population surface [14].

(viii) Distinguishing *P. falciparum* and *P. vivax* risk

Global information on the distribution of *P. falciparum* and *P. vivax* is not comprehensively detailed in the ITHGs. Subnational statistics are available from other sources, however [11]. In countries where no subnational data were available, national average data were used [20,21]. Areas reporting 95% or more *P. falciparum* cases of malaria were defined as predominantly *P. falciparum* endemic and those reporting 5% or less *P. falciparum* cases were defined as predominantly *P. vivax* endemic. The remainder of the distribution was defined as mixed (*P. falciparum* and *P. vivax*) endemicity. *Plasmodium ovale* and *Plasmodium malariae* were not considered because these human parasites are relatively rare and infrequently reported in national statistics.

(ix) Estimation of population at risk

The GRUMP population counts grid [14] was first projected to 2005 (see Step vi), before overlaying it on the final map. Estimates of the population at risk (PAR) were then derived with the programme ArcView 3.2 (Environmental Systems Research Institute).

Global population at malaria risk

The resulting global maps of *P. falciparum* and *P. vivax* malaria risk are shown in Figure 1. Combining these maps with those of human population distribution [14] enabled estimates of the PAR of *P. falciparum* and *P. vivax* malaria to be generated for 2005 [11]. Merging the three ITHG sources generates limits that suggest that 3.616 billion people might be at risk of *P. falciparum* and/or *P. vivax* infection in 2005. In comparison, the estimate using only the WHO-2002 boundaries suggests that 3.133 billion persons might be at risk.

The altitude mask and climate mask marginally reduce the combined *P. falciparum* or *P. vivax* risk to 3.596 billion persons, and implementing the population mask further reduces the estimate to 3.126 billion. The regional distribution of the PAR is provided in Table 2. These regional differences are emphasized at the country level in the continuous area cartograms [2] (Figure 2). These maps show that there is a substantial PAR for both *P. falciparum* and *P. vivax* in the South East Asian Region and that the PAR in Africa and resulting malaria epidemiology is predominantly, but not exclusively, determined by *P. falciparum*.

The WHO-2002 map

The most widely cited map of the current global malaria distribution was produced by the WHO in 2002 [4]. There are important discrepancies between this map, which was described as being for “illustrative purposes only” [4], and the information source cited [5]. These geographical inconsistencies and the lack of detailed information on their genesis make them of unknown fidelity for mapping malaria risk [22-25].

By contrast, the method reviewed here has taken a new approach that is transparent and easily reproducible because it uses public-domain data (see the step-by-step guide above) that had not been reconciled. In addition, separate maps of parasite species distributions have been defined globally for the first time. These maps are suggested to be more comprehensive surfaces against which to assess the PAR of malaria in 2005. Capturing the spatial extent of the often neglected *P. vivax* risk [26] is an important advance, providing the first opportunity for more accurate mapping of *P. vivax* burden.

Future improvements

These maps come with obvious caveats because they have been implemented with crude rules on a global scale. Noticeable anomalies (e.g. Argentina, Egypt, Morocco, North Korea, Paraguay and possibly China) are highlighted [11], and it is clear that, at a subnational level, discrepancies will be found because risk is not a static phenomenon and global information is incomplete. These maps should therefore be considered as a working template for future refinement.

Reconnaissance of global malaria data is required to refine distributions at the margins, and can be done only with higher spatial resolution data on malaria risk. These data probably exist at the country level and need to be collated on a global scale within a geographic information system framework. Globally, the top ten malaria-endemic countries, by PAR, are India, China, Indonesia, Bangladesh, Pakistan, Nigeria, Vietnam, Thailand, Democratic Republic of the Congo and the Philippines [11]. Error in global PAR estimates would be reduced most substantially by focusing on improving the distribution limits and information on the *P. falciparum* to *P. vivax* ratios for these territories. Ultimately, all regions will need to be investigated.

During this process the main areas for refinement will be (i) keeping track of modifications in future iterations of the ITHGs and incorporating information from a wider range of sources [27]; (ii) improving the spatial fidelity of the administrative area data used (the increasingly comprehensive and well-documented Second Administrative Level Boundaries project (Table 1) is likely to become a future standard); (iii) augmenting our knowledge base on the global spatial distribution of dominant *Anopheles* vectors and thus altitude limits for transmission; and (iv) making use of improved human population maps as more recent and higher spatial resolution census data become available [28], which will facilitate the application of more accurate high and low population density masks.

The Malaria Atlas Project

An extensive exercise is underway to assemble a global database of the prevalence of malaria parasites under the auspices of the Malaria Atlas Project (Table 1). This database will be used to test independently the fidelity of the spatial limits defined and the assumptions made in many of the decision rules applied in generating the maps. In addition, modelling malaria endemicity within the spatial limits defined is also a primary objective. Local endemicity within these transmission limits will be substantially mediated by the influences of land-use change (e.g. deforestation [29] and urbanization [18]), prevalence of other conditions such as HIV/AIDS [30], tuberculosis, helminths and malnutrition, and local control and intervention efforts. The immediate goal is to generate plausible scenarios for some of these confounding influences of risks so that historical malaria endemicity maps [31] can be corrected to reflect contemporary risk more reliably. The longer-term goal is to construct an independent global map of modern-day malaria risk within the boundaries that have been defined and will continue to be refined.

Concluding remarks

Although uncertainties remain about the precise global extent of malaria, they have been reduced as far as is possible without systematic country surveys, by using transparent methods and public-domain information sources. Urgent attention is required to reduce the uncertainty surrounding factors that affect the spatial extent of malaria on a global scale. This will allow the international community to define better the needs for therapeutic and disease prevention commodities, before well-intentioned governments and United Nations agencies make requests for insufficient financial resources to address the public health need of the ~3 billion people at risk of malaria.

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Figure 1. Global distribution of *P. falciparum* and *P. vivax* in 2005. **(a)** Distribution of *P. falciparum*. **(b)** Distribution of *P. vivax*. Several sources of information on malaria risk (notably ITHGs on malaria chemoprophylaxis, altitude limits for dominant vectors, climate limits for malaria transmission and human population density thresholds) have been combined in a geographic information system to generate these maps. See the step-by-step guide in the main text for a full description of the methods used to derive these limits.

Figure 2.

Cartograms of the PAR of malaria from *P. falciparum* and *P. vivax* in 2005. **(a)** *P. falciparum* risk. **(b)** *P. vivax* risk. In these cartograms, the area is distorted in proportion to the national PAR of malaria [2]. These maps are useful global indicators and represent broad spatial patterns, but it should be remembered that the risk of developing disease, disability or death from malaria infection is specific to parasite and region [3], and the exact implications of the regional differences will be examined in more detail in future work.

Table 1

URLs for the data and software used in mapping the global spatial limits of malaria

Website	URL
Environmental Systems Research Institute, data and maps	http://www.esri.com/data/
FAO GeoNetwork	http://www.fao.org/geonetwork/
Global Rural-Urban Mapping Project (GRUMP)	http://sedac.ciesin.columbia.edu/gpw/
CDC Traveller's Health Yellow Book	http://www.cdc.gov/travel/yb/
International Association for Medical Assistance to Travellers (IAMAT)	http://www.iamat.org
International Center for Tropical Agriculture	http://www.ciat.cgiar.org/
Malaria Atlas Project	http://www.map.ox.ac.uk
Mapping Malaria Risk in Africa (MARA) project	http://www.mara.org.za
MAPresso	http://www.mapresso.com
Microsoft Encarta	http://www.encarta.msn.com
National Geophysical Data Center: the Global Land One-km Base Elevation project (GLOBE)	http://www.ngdc.noaa.gov/mgg/topo/globe.html
<i>Online gazetteers:</i>	
The Getty	http://www.getty.edu/research/
Alexander Digital Library	http://webclient.alexandria.ucsb.edu/mw/index.jsp
GEOnet-Names Server	http://earth-info.nga.mil/gns/html/cntry_files.html
Second Administrative Level Boundaries	http://www3.who.int/whosis/gis/salb/salb_home.htm
WHO International Travel and Health guidelines	http://www.who.int/ith/
World Population Prospects: the 2004 Revision Population Database	http://esa.un.org/unpp/

Table 2

PAR of malaria derived from extractions using the global spatial limits for *P. falciparum* and *P. vivax* in 2005

WHO region	<i>P. falciparum</i> risk ^a	<i>P. vivax</i> risk ^a
SEARO	1.252	1.347
AFRO	0.525	0.050
WPRO	0.438	0.890
EMRO	0.245	0.211
AMRO	0.050	0.078
EURO	0.000	0.020
Total	2.510	2.596

^aThe risk is given in billion (1,000,000,000) persons. Abbreviations: WHO, World Health Organization; SEARO, South East Asian Regional Office; AFRO, African Regional Office; WPRO, Western Pacific Regional Office; EMRO, Eastern Mediterranean Regional Office; AMRO, American Regional Office; EURO, European Regional Office.