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CENTENNIAL REVIEW

A global assessment of closed forests, deforestation and malaria risk

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Global environmental change is expected to affect profoundly the transmission of the parasites that cause human malaria. Amongst the anthropogenic drivers of change, deforestation is arguably the most conspicuous, and its rate is projected to increase in the coming decades. The canonical epidemiological understanding is that deforestation increases malaria risk in Africa and the Americas and diminishes it in South–east Asia. Partial support for this position is provided here, through a systematic review of the published literature on deforestation, malaria and the relevant vector bionomics. By using recently updated boundaries for the spatial limits of malaria and remotely-sensed estimates of tree cover, it has been possible to determine the population at risk of malaria in closed forest, at least for those malaria-endemic countries that lie within the main blocks of tropical forest. Closed forests within areas of malaria risk cover approximately 1.5 million km^2 in the Amazon region, 1.4 million km^2 in Central Africa, 1.2 million km^2 in the Western Pacific, and 0.7 million km^2 in South–east Asia. The corresponding human populations at risk of malaria within these forests total 11.7 million, 18.7 million, 35.1 million and 70.1 million, respectively. By coupling these numbers with the country-specific rates of deforestation, it has been possible to rank malaria-endemic countries according to their potential for change in the population at risk of malaria, as the result of deforestation. The on-going research aimed at evaluating these relationships more quantitatively, through the Malaria Atlas Project (MAP), is highlighted.

Human malaria is a disease of global extent that has been eradicated from most temperate areas relatively recently and is now predominantly restricted to tropical zones (Hay *et al.*, 2004). This substantial geographical reduction has not been followed by a similar decrease in the population at risk of malaria (PARM). The PARM has, in fact, increased exponentially because of population growth and a failure to control the disease within its restricted range (Hay *et al.*, 2004). It has been estimated that the PARM currently exceeds 3000 million people (Guerra *et al.*, 2006) and that, each year, there are >500 million cases of *Plasmodium falciparum* malaria globally (Snow *et al.*, 2005) and 1 million malaria-attributable deaths in Africa (Snow *et al.*, 2003; Hay *et al.*, 2005). Several environmental factors are known to affect the transmission of the parasites that cause human malaria (Walsh *et al.*, 1993; Robert *et al.*, 2003; Hay *et al.*, 2005, 2006*a*; Keiser *et al.*, 2005*a*; Snow *et al.*, 2006). One such factor, deforestation, is of particular concern because of its scale and ubiquity in tropical areas. The size of

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the PARM in forested areas is not known with precision (Keiser *et al.*, 2005*b*), however, and this hampers reliable quantification of the effects of deforestation on the burden of malaria.

Although estimates of the global extent of humid tropical forest vary greatly, from 11.16 million to 15.71 million km^2, the largest surviving areas of such forest are to be found in Latin America (6.53 million–7.80 million km^2), chiefly in the Amazon region, followed by Africa (1.93 million–5.19 million km^2) and South–east Asia (2.70 million–2.72 million km^2) (Anon., 2001*b*; Achard *et al.*, 2002; Mayaux *et al.*, 2005). Deforestation in these areas is extensive, with global estimates of its rate ranging from 36,000–69,000 km^2/year. The mean annual rate of deforestation in South–east Asia (0.71%–0.79%) is higher than that in Latin America (0.33%–0.51%) or Africa (0.34%–0.36%) (Anon., 2001*b*; Achard *et al.*, 2002; Mayaux *et al.*, 2005). Tropical deforestation not only has obvious environmental and socio–economic impacts, including loss of biodiversity, loss of agricultural productivity, and alteration of the carbon and water cycles (Fearnside, 2005), but also detrimental effects on vector-borne diseases (Walsh *et al.*, 1993).

In this article, the relevant literature relating to deforestation and human malaria is systematically reviewed, to elucidate the relationships between the disease and forest cover and any regional variation in these links. Articles dealing directly with these issues and those on the bionomics of relevant vectors were made the focus of the literature review. Geographical information systems (GIS) were used, with maps of forest cover and the distribution of human populations, to determine the areas of forest cover within the spatial limits of malaria transmission, and then to derive estimates of the PARM in these areas. These values were then combined with country-specific estimates of deforestation rates, to identify those countries in which the epidemiological impact of deforestation on malaria is likely to be of most concern. Finally, the results of the literature review and data analysis were used to fuel a discussion of the probable implications of deforestation on the future risks of malaria transmission across the world.

DEFINING FOREST EXTENTS AND REGIONS

In order to quantify the relationship between malaria transmission and forests, ‘forest’ must be defined. In 1973, the United Nations Educational, Scientific and Cultural Organization’s Standing Committee on Classification and Mapping of Vegetation on a World Basis established a vegetation classification (Anon., 1973). Eighteen years later, the forest component of this classification was revised and extended by the Food and Agricultural Organization (FAO). In this revision, forest is defined as ‘land with a tree canopy cover of more than 10% and an area of more than 0.5 ha’, including natural forests and forest plantations but excluding tree stands specifically established for agricultural production (Anon., 2001*b*). Natural forests (i.e. those not planted by humans) are subdivided in the revision, as ‘closed’ (>40% canopy cover) or ‘open’ (>10%–40% canopy cover). In this review, the definition of forests has been limited to the closed (or ‘deep’) types, since these represent a biological barrier for the development of many vectors of the parasites that cause human malaria, and the discussion is restricted to the remaining tracts of tropical forest in the world (i.e. those in Amazonia, Central Africa and Asia). Asia is split, according to malaria epidemiological zones (Macdonald, 1957) and vector distribution (Service, 1993), into South–east Asia [corresponding to the eastern half of the Indo–Iranian epidemiological zone and the whole Indo–Chinese epidemiological zone (Macdonald, 1957)] and the Western Pacific [corresponding to tropical forests in the

Malaysian and Australasian epidemiological zones (Macdonald, 1957)]. The present analyses are therefore focused on the 30 malaria-endemic countries encompassed by these regions. Thailand, Myanmar and Cambodia fall mostly, but not exclusively, in South–east Asia, and Vietnam mostly in the Western Pacific (Macdonald, 1957), and are allocated accordingly (Fig. 1).

THE LINKS BETWEEN MALARIA TRANSMISSION, FOREST COVER AND DEFORESTATION

The relationship between malaria transmission, forest cover and deforestation is complex. Aspects related to microclimate and/or the chemical composition of soils can be important (Smith, 1981). Ecological factors can regulate the species composition of the mosquito populations, and thus the numbers and types of malaria vector, by, for example, changes in host-preference and predation patterns (Deane, 1986). Human population migrations to and from forests (usually driven by economic and social pressures) and the associated changes in land cover are often critical (Walsh *et al.*, 1993). Such migrations often bring human populations closer to the forest. The direction of land-use that follows forest clearing — usually towards grasslands or crops — is also important but its influence will be mediated by the local ecology and vectors (Kondrashin *et al.*, 1991). The replacement of forest with rice cultivation, for example, may provide more favourable conditions for *Anopheles gambiae* s.s. or *An. albitarsis* s.s. (Forattini *et al.*, 1993*a*, *b*; Briet *et al.*, 2003) but can reduce transmission in areas where *An. dirus* is the main vector (Kondrashin *et al.*, 1991). In contrast, *An. dirus* can find tree-crop plantations suitable for breeding since such plantations provide conditions that are similar to this vector's natural habitat (Kondrashin *et al.*, 1991). As the result of such links, the effects of deforestation on malaria transmission are spatially variable and largely dependent on vector distribution, since the vector species have adapted to different types of land cover, including forests and near-forest habitats. This makes the effects of deforestation on malaria transmission regionally distinctive and even locally specific. A basic knowledge of vector bionomics leads to the generally accepted (though largely qualitative) opinion that deforestation increases the risk of malaria transmission in Africa and tropical America but decreases it in Asia (Mouchet and Brengues, 1990; Walsh *et al.*, 1993; Anon., 2005).

In the following sections, an overview of the relationships between deforestation and malaria is presented, and the epidemiologically important issues are highlighted by region. The vectors that are most important when studying malaria transmission and forest cover are listed in Table 1. Table 2 provides a comprehensive listing of studies that have, directly or indirectly, investigated the relationship between forest cover and malaria risk, grouped into the dominant themes.

Malaria and Forests in the Amazon Region

Amazonia holds the highest risk of malaria transmission in the Americas, with 80% of all cases reported in 2002 coming from the nine countries that share the Amazon basin (PAHO, 2003). Despite its large area, the Amazon region has a relative low diversity of competent malaria vectors (Rubio-Palis and Zimmerman, 1997; Tadei and Dutary Thatcher, 2000). Of the 54 *Anopheles* species described in Brazil, for example, only 10 have been reported to be naturally infected with parasites that cause human malaria (Rosa-Freitas *et al.*, 1998; Tadei *et al.*, 1998). Nine of these 10 species (i.e. all except *An. darlingi*) are zoophilic and/or exophilic and therefore possibly of limited epidemiological significance (Deane, 1986).

There are no known closed-canopy vectors in Amazonia (Table 1) and forests

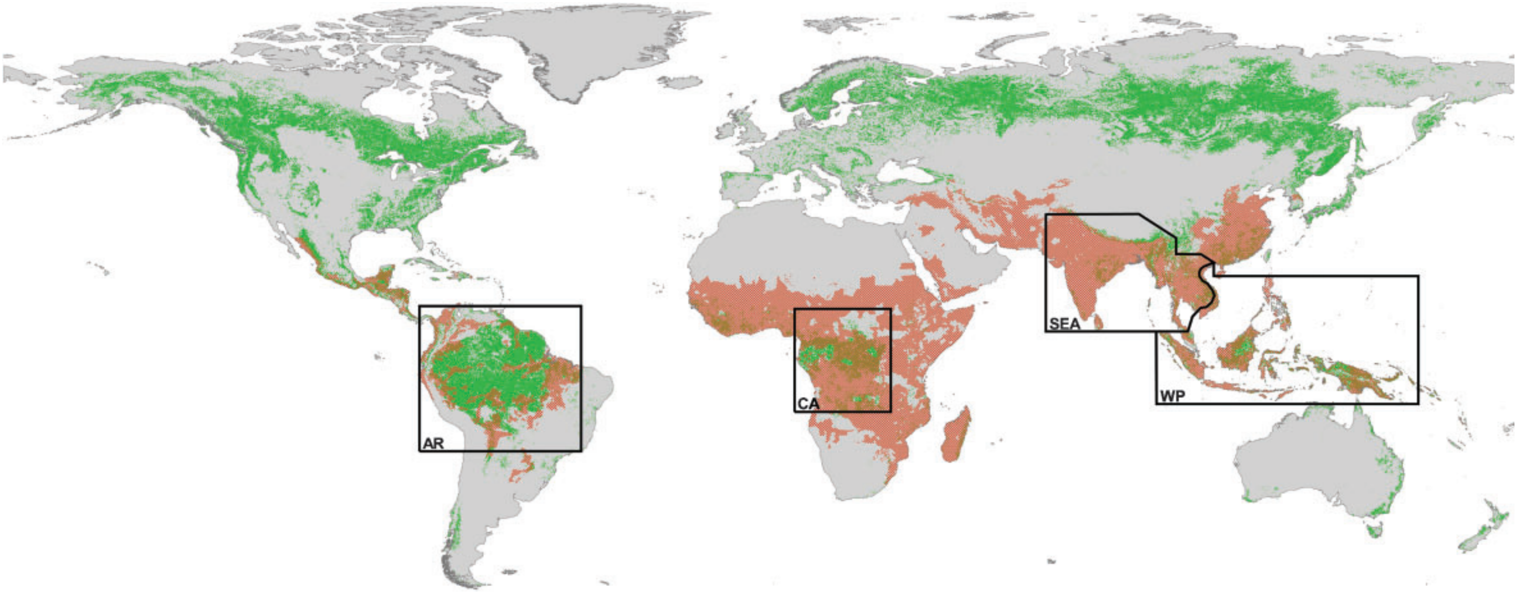

FIG. 1. The global spatial limits of malaria in 2005 (🟥) overlaid on the areas of closed forests [🟩; as indicated on the Global Forest Cover map (Anon., 2001*a*)]. The Amazon region (AR), Central Africa (CA), South–east Asia (SEA) and the Western Pacific (WP) are roughly indicated; the sinuous limit between SEA and WP is based on the map of malaria zones developed by Macdonald (1957).

support a lower density and diversity of potential vectors than deforested areas (Tadei and Dutary Thatcher, 2000). Given its anthropophilia, endophagy and common endophilia, *An. darlingi* is by far the most important malaria vector in the region (Forattini, 1962; Deane, 1986). It breeds in partly shaded pools found in flooded areas of forests and in forest creeks, river edges and pools left after river-level recession during the dry season (Forattini, 1962; Rozendaal, 1990). The human colonization of forest or near-forest areas in the Amazon typically promote the establishment and expansion of *An. darlingi* populations, by increasing human exposure to this species' natural breeding habitats and by the generation of new breeding habitats on the forest fringes. By eliminating deep shade and changing the acidity and chemical composition of the soil, slash-and-burn techniques often create favourable conditions for the breeding of *An. darlingi* and so increase the local risk of human malaria (Singer and Caldas de Castro, 2001). This phenomenon has led to the expression 'frontier malaria' (Sawyer, 1993; Singer and Caldas de Castro, 2001). In the longer-term, however, the establishment of agriculture and urbanization after forest clearance eventually tend to decrease malaria transmission, through classic mechanisms (Hay *et al.*, 2005), and render it largely dependent upon human behaviour (Caldas de Castro *et al.*, 2006; Table 2).

Malaria and Forests in Central Africa

The most competent malaria vectors in Africa are *An. gambiae* s.s., *An. funestus*, *An. moucheti* and *An. nili* (Mouchet *et al.*, 2004). Importantly, the geographical range of all of these species encompasses the Central African forest block (Rogers *et al.*, 2002; Mouchet *et al.*, 2004). *Anopheles gambiae* s.s. and *An. funestus* are considered 'main' vectors (being both dominant and wide-spread) throughout their ranges (Service, 1993). *Anopheles nili* and *An. moucheti*, which are more incidental or localized in their distribution, are usually considered to be 'subsidiary' vectors but can be locally important. Three of these Central African vectors are mainly non-forest

TABLE 1. *The most relevant regional vectors that merit consideration when studying the links between malaria transmission and forests*

	Region			
Vector type	Amazonia	Central Africa	South–east Asia	Western Pacific
Deep or closed forest*		*Anopheles nili*	*An. dirus*†	*An. balabacensis*† *An. dirus*† *An. donaldi*† *An. flavirostris*† *An. leucosphyrus*†
Near- or non-forest‡	*An. albitarsis*† *An. darlingi*† *An. marajoara* *An. nuneztovari* *An. pseudopunctipennis*†	*An. funestus*† *An. gambiae* s.s.† *An. moucheti*	*An. culicifacies*† *An. fluviatilis*† *An. minimus*†	*An. farauti*† *An. koliensis*† *An. letifer*† *An. maculatus*† *An. minimus*† *An. punctulatus*†

*Deep-forest vectors are considered as those for which deep shade is a requisite for breeding. This categorization is not absolute and vectors considered as deep-forest species are sometimes responsible for malaria transmission on forest fringes or in anthropic environments.

†Considered a main vector (dominant and wide-spread) throughout its range (Service, 1993).

‡Vectors considered non-forest or forest-fringe species are seldom, if ever, implicated in deep-forest transmission.

TABLE 2. *Compendium of published studies (excluding review articles) related to malaria transmission and forests*

	Region			
Research focus	Amazonia	Central Africa⋆	South–east Asia	Western Pacific
Human movement to/from forest, its impacts, and phenomena such as ‘frontier malaria’	McGreevy *et al.* (1989), Sawyer (1993), Singer and Caldas de Castro (2001), Caldas de Castro *et al.* (2006)		Butraporn *et al.* (1986, 1995), Singhanetra Renard (1986, 1993), Somboon *et al.* (1998), Pichainarong and Chaveepojnkamjorn (2004)	Lansang *et al.* (1997), Erhart *et al.* (2004, 2005)
Studies specifically dealing with the impacts of deforestation on malaria transmission[†]	Vittor *et al.* (2006)	Manga *et al.* (1995)		Chang *et al.* (1997)
Vector displacement as the result of land-use change	Conn *et al.* (2002)			
Evaluation of the transmission of malaria in or near forested areas		Coz *et al.* (1966), Carnevale *et al.* (1992), Coene (1993), Bockarie *et al.* (1995), Manga *et al.* (1997*a*, *b*), Meunier *et al.* (1999), Nzeyimana *et al.* (2002), Cohuet *et al.* (2004)	Banerjee *et al.* (1991), Lwin and Htut (1991), shrestha *et al.* (1991), Kobayashi *et al.* (1997, 1998), Prakash *et al.* (1997), Singh *et al.* (1999, 2003), Shukla *et al.* (2001), Oo *et al.* (2003), Sharma *et al.* (2004)	Harbach *et al.* (1987), Seng *et al.* (1999)

⋆Three examples from West Africa (Coz *et al.*, 1966; Bockarie *et al.*, 1955; Nzeyimana *et al.*, 2002) are included because the vector ecology described is similar to that in Central Africa.

[†] There is a striking lack of primary research directly measuring the impact of deforestation on malaria.

species (Table 1). *Anopheles nili* is the exception because it can breed in shaded streams (Gillies and de Meillon, 1968) but its role in transmission is generally restricted to localised forested areas (Carnevale *et al.*, 1992). The wide-spread, main vectors, *An. gambiae* s.s. and *An. funestus*, are generally absent from deep forests since their larvae require sunlit pools (Gillies and de Meillon, 1968). They can, however, play an important role in transmission after deforestation or forest degradation. Although *An. moucheti* has a more localised range than *An. gambiae* s.s. and *An. funestus*, its sporozoite 'rates' are high enough for it to be considered a main vector in specific areas (Mouchet *et al.*, 2004). It is confined to Central Africa and is described as a forest species (Gillies and De Meillon, 1968). The penetration of sunlight into its breeding sites is an obligate requirement, however, so canopy discontinuities, such as those made by rivers or human intervention, are essential.

In summary, deforestation in Africa tends to increase malaria transmission by creating habitats that are suitable for the breeding of the very efficient, non-forest vectors, although a modest reduction in transmission might be expected following deforestation in the localised settings where *An. nili* is the main vector (Table 2).

Malaria and Forests in South–east Asia and the Western Pacific

The transmission of malaria in forests is particularly prominent in South–east Asia and the Western Pacific. Clusters of malaria cases in the Mekong region, for example, are closely associated with dense forest cover, with cultivated areas supporting relatively low levels of transmission (Singhasivanon, 1999). In 1990, when forest covered only 20% of the land area of the malarious countries in the World Health Organization's South–east Asian region, 40% of all the malaria cases in the region and 60% of the cases of *P. falciparum* malaria were reported from forest areas (Kondrashin, 1992). In 1989, 87% of the malaria cases and almost all (99%) of the *P. falciparum* cases recorded in Bangladesh occurred in forests (Sharma *et al.*, 1991). In India in 1987, tribal communities living in forested areas represented only 7% of the country's population but contributed 30% of the country's malaria cases, 60% of the *P. falciparum* cases, and 60% of the malaria-attributable deaths (Narasimham, 1991). One of the main risk factors for malaria in these areas is the movement of humans to and from the forest (Kondrashin, 1992), which not only exposes immunologically naïve individuals to high levels of transmission (Rosenberg and Maheswary, 1982) but also provides a constant flow of malarial parasites from the forest to rural communities (Verdrager, 1995).

A crucial reason for the high levels of malaria transmission seen in and near many forested areas of South–east Asia and the Western Pacific is the existence of many species of highly efficient vectors that have adapted to forest habitats (Table 1). For some of these species, closed forests provide favourable ecological conditions that result in long adult-mosquito life-spans and an abundance of breeding sites. Moreover, most of these species, including *An. dirus*, *An. balabacensis*, *An. donaldi*, *An. flavirostris* and *An. leucosphyrus*, are considered main vectors throughout their ranges (Service, 1993). *Anopheles dirus* is probably the most important because of its wide geographical range and its efficiency and ecological plasticity as a vector. In addition, forest-fringe and deforested areas create adequate breeding habitats for several main vectors, including *An. minimus*, *An. maculatus*, *An. culicifacies*, *An. fluviatilis*, *An. farauti*, *An. koliensis*, *An. letifer* and *An. punctulatus*. The wide diversity of both the deep-forest and near-forest main vectors, as well as their great potential to adapt to habitat changes, mean that the consequences of deforestation on malaria transmission in South–east Asia and the Western Pacific are difficult to predict and unlikely to be unidirectional. Although deforestation may deplete the populations of deep-forest vectors and so initially reduce malaria transmission, in some localities this depletion may be followed by the invasion of the deforested areas by other efficient vectors and an increase in transmission. The position is therefore more complex than generally considered (Table 2).

CONVERGENCE OF POPULATIONS AT RISK OF MALARIA AND CLOSED FORESTS

GIS platforms allow the study and quantification of the spatial associations between forest cover, malaria and patterns of human settlement. For the present investigation, the spatial limits of malaria were defined using a contemporary map of the disease, which has already been described in detail (Guerra *et al.*, 2006; Fig. 1). Briefly, this map was generated using existing information, retrieved from international travel and health guidelines, to identify areas at risk of malaria transmission at sub-national level. The administrative areas of malaria-endemic countries that were categorized as ‘no risk’ in these guidelines were excluded first. The maximum altitudinal limits of recorded malaria were then used to generate an altitudinal mask that excluded highland areas. A population-density mask, derived from a contemporary global population grid (Balk *et al.*, 2006), was used to exclude areas with human population densities that were considered too low or too high for malaria transmission. Areas with less than one person/km^2 were deemed free of malaria risk, because human–vector contact in such areas would be sufficiently low to interrupt transmission. Population-density thresholds were then defined, by region, as a proxy of urban agglomerations, to allow for the effect of urbanization on malaria transmission (Hay *et al.*, 2005).

A land-cover map developed by the FAO as part of the Forest Resources Assessment (FRA) for the year 2000 (Anon., 2001*a*) was used to identify areas of closed forest. This map classifies land cover into ‘closed forests’, ‘open forests’, ‘other wooded land’, ‘other land cover’, and ‘water’. The first two classes were derived by applying a mixture-analysis model to normalised-difference-vegetation-index (NDVI) imagery derived from the Advanced Very High Resolution Radiometer for the year 1995; the use of this imagery in epidemiology has been reviewed by Hay *et al.* (1996, 2006*b*) and Hay (2000). The other three classes were adapted from an existing land-cover classification developed by the United States Geological Survey (Loveland *et al.*, 1999). The rationale of using the FRA 2000 map is its explicit differentiation between closed and open forests, in accordance with the standards set by the FAO (Anon., 2001*b*) and the definitions adopted here.

Values for the PARM were derived from the human-population map created by the Global Rural–Urban Mapping Project for the year 2000 (Balk *et al.*, 2006). This surface was developed, on a 30-arc-second grid, from the areal weighting of census data and the re-allocation of population according to urban-area proxy data. Since this data-set was generated for the year 2000, country-specific medium-variant rates of intercensal population growth (http://esa.un.org/unpp) were used to project the population totals to 2005, for consistency with the map of the spatial limits of malaria that was used (Hay *et al.*, 2005).

By overlaying the malaria-distribution map on the FAO’s delimitations of ‘closed forest’, it was possible to identify areas of closed forest that are malarious (Fig. 1). An equal-area projection and GIS software (ArcView 3.2; ESRI, Redlands, CA) were then used to evaluate the areas (in km^2) of the malarious closed forests and the numbers of individuals (i.e. the PARM) living in such forests. The largest extent of closed tropical forests is that of the Amazon region, which, according to the FAO map (Anon., 2001*a*), covers >6 million km^2 and

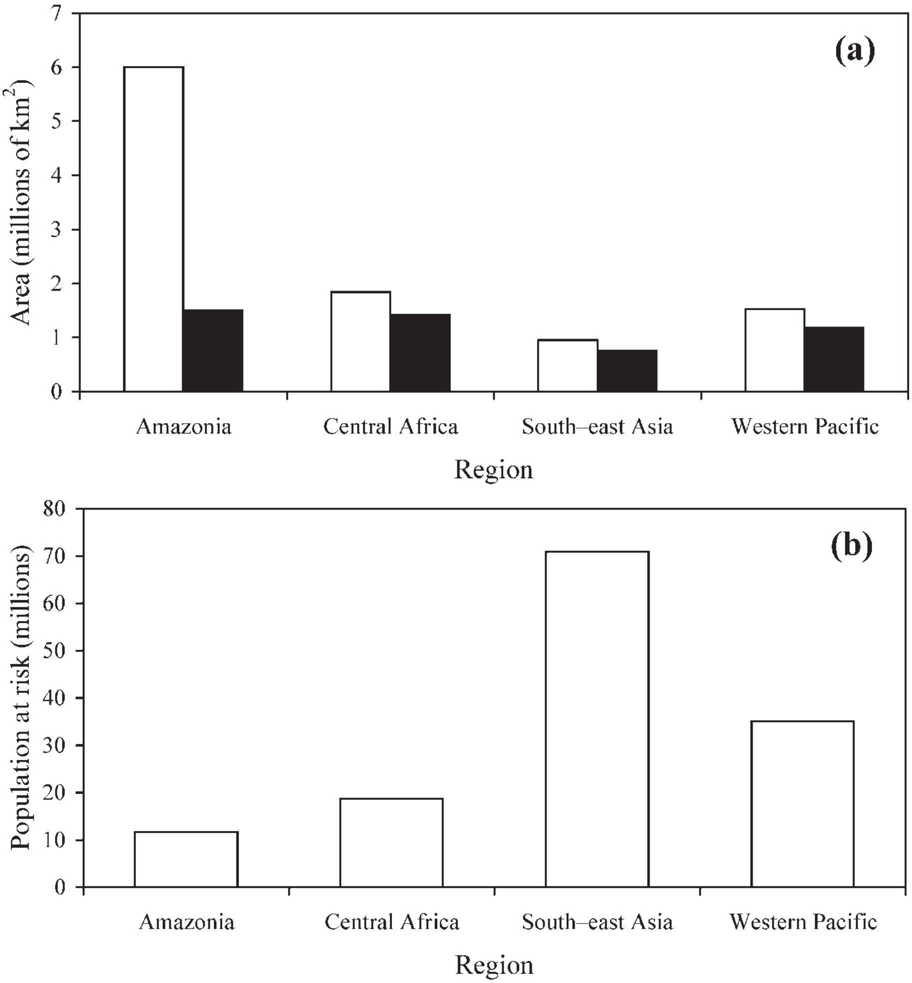

FIG. 2. Regional comparisons of (a) the areas of closed forest (□) and malarious closed forest (■), and (b) the populations at risk of malaria within areas of closed forest.

accounts for about 60% of the estimated global area of closed humid forests. [Table 3 and Figure 2(a)]. Only 25.1% of the area covered by closed Amazonian forest is deemed malarious, however, mainly because of extremely low human-population

TABLE 3. *Regional estimates of the total areas of closed forest and malarious closed forest and of the populations at risk of malaria (PARM) living in closed forests*

	Area of closed forest (km^2)		% of area of closed forest	
Region	Total	Within malaria limits	that is malarious	PARM in 2005
Amazonia	6,004,864	1,507,395	25.1	11,654,151
Central Africa	1,838,338	1,417,118	77.1	18,713,936
South–east Asia	951,356	760,352	79.9	70,879,923
Western Pacific	1,528,344	1,188,253	77.8	35,093,490
All four	10,322,902	4,873,118	47.2	136,341,500

densities (Guerra *et al.*, 2006). In contrast, the total areas covered by closed forest in Central Africa, South–east Asia and the Western Pacific are much smaller (1.83 million, 0.95 million, and 1.53 million km^2, respectively) but mostly malarious (77.1%, 79.9% and 77.8%, respectively). The regional differences in the estimated sizes of the PARM living in areas of closed forest are even more striking [Table 3 and Figure 2(b)]. Although about 71 million and 35 million people are estimated to be at risk of malaria in areas of closed forest within South–east Asia and the Western Pacific, respectively, the corresponding numbers for the Amazon region and Central Africa are markedly lower (11.65 million and 18.71 million, respectively). The differences are largely attributable to regional variation in human population densities, which are, in general, substantially higher in the forested areas of Asia than in the corresponding areas of Amazonia and Central Africa. In addition, South–east Asia, the Western Pacific and Central Africa have higher rates of forest degradation than Amazonia (Achard *et al.*, 2002). In Amazonia, therefore, the level of forest fragmentation is probably relatively low, and so relatively few people are driven close to the deep forests.

Country Estimates and Ranking

Table 4 shows the estimated area of closed forest and the estimated PARM for each country of interest. In order to identify those countries where the problem of deforestation might have the greater impact on the epidemiology of malaria, the countries investigated were ranked in terms of three variables: the total areas of malarious closed forest; the PARM living in these areas; and the annual rates of deforestation between 1990 and 2000. [The latter were derived by the FAO as part of FRA 2000 (Anon., 2001*b*) and, although based on all-forest surveys of national inventories and mapping reports, were assumed to be applicable to the 'closed forest' class.] Ranking scores were assigned for each of these variables and then totalled to yield a final country score. Countries that rank high in the list, such as Indonesia and Myanmar, are therefore those with a combination of relatively large extents of closed forest in malarious areas, high numbers of people living in these areas, and high rates of deforestation.

Seven of the 10 highest scoring countries are in South–east Asia (three) or the Western Pacific (four). These seven rank highly because of their high deforestation rates and the large numbers of people at risk of malaria in their closed forests. Brazil is ranked fourth on the list, largely because it has a very large area of malarious closed forest. The Democratic Republic of the Congo (DRC) and Cameroon are the only African countries ranked in the top 10. The DRC has a greater area of malarious closed forest than any other country, whereas Cameroon has higher rates of deforestation and larger extents of malarious closed forests than Congo, the Central African Republic or Equatorial Guinea. Unfortunately, Bhutan, French Guiana, Gabon and Suriname could not be ranked because there have been no estimates of the deforestation rates in these countries.

An important consideration when ranking countries in this way is that of vector competence. In the present study, the lack of a consistent classification of vector competence hindered its inclusion as a ranking criterion. To compensate, Table 4 includes an indication of the countries in which there is at least one, main, deep-forest vector. The transmission of malaria in the forests of such countries, which are all in South–east Asia or the Western Pacific (Table 1), is more severe than that in the other countries considered.

DISCUSSION

By using the best knowledge available on the distribution of malaria, closed forests and human populations, it has been possible to identify regional differences in the sizes of the human populations and areas at risk of malaria within closed forests (Fig. 2). The results indicate that, in South–east Asia and the Western Pacific, high population densities in or near areas of malarious closed forest expose large numbers of people to malarial parasites transmitted by highly efficient forest vectors. The prevalence of such vectors has historically represented a challenge for malaria control and stimulated environmental-management approaches such as vegetation clearing — including deforestation (Mouchet and Brengues, 1990; Arbani, 1992). Because of the complexity of interactions that may involve populations of closed-forest, near-forest and/or non-forest vectors, it is not easy to predict the impact of deforestation on

TABLE 4. *The country-specific data, showing the areas of closed forest and malarious closed forest, the populations at risk of malaria (PARM) living in closed forests, deforestation rates, and ranking according to the size of the malaria problem that deforestation is likely to pose*

		Area of closed forest (km^2)					
Region*	Country	Total	Within malaria limits	PARM in 2005	Deforestation rate[†] (%)	Rank[‡]	Deep-forest vectors?
WP	Indonesia	917,003	629,179	19,035,489	−1.2	1	Present
SEA	Myanmar	267,609	175,667	5,387,273	−1.4	2	Present
CA	Democratic Republic of the Congo	1,161,386	1,018,804	15,113,330	−0.4	3	
AR	Brazil	3,613,076	783,221	5,448,638	−0.4	4	
SEA	India	330,681	302,441	46,756,606	+0.1	6	Present
SEA	Nepal	52,233	26,075	5,938,885	−1.8	6	
WP	Malaysia	160,405	144,192	2,089,900	−1.2	7	Present
CA	Cameroon	161,570	160,739	1,802,808	−0.9	9	
WP	Papua New Guinea	319,490	300,115	2,745,244	−0.4	9	
WP	Philippines	42,607	28,209	3,574,096	−1.4	10	Present
SEA	Thailand	61,989	56,128	3,446,919	−0.7	11	Present
AR	Colombia	494,133	164,125	1,558,926	−0.4	13	
SEA	Laos	118,906	115,931	2,372,844	−0.4	13	Present
AR	Peru	593,014	223,020	1,262,409	−0.4	13	
AR	Ecuador	127,174	51,618	1,352,002	−1.2	16	
SEA	Sri Lanka	13,817	12,213	1,653,265	−1.6	16	
WP	Viet Nam	87,151	84,941	7,563,063	+0.5	16	Present
SEA	Cambodia	66,959	55,570	1,304,546	−0.6	18	Present
AR	Bolivia	419,198	172,149	721,302	−0.3	19	
AR	Venezuela	371,158	36,408	964,271	−0.4	20	
CA	Congo	203,479	124,141	524,650	−0.1	21	
SEA	Bangladesh	10,913	10,224	3,243,854	+1.3	22	Present
AR	Guyana	173,933	66,238	304,571	−0.3	23	
CA	Equatorial Guinea	17,920	12,582	260,588	−0.6	24	
CA	Central African Republic	97,951	59,967	488,335	−0.1	25	
WP	Timor-Leste	1687	1618	85,698	−0.6	26	
SEA	Bhutan	28,248	6103	775,732			
AR	French Guiana	80,977	124	21,960			
CA	Gabon	196,031	40,886	524,225			
AR	Suriname	132,200	10,491	20,070			

*AR, Amazonian region; CA, Central Africa; SEA, South–east Asia; WP, Western Pacific.

[†] The mean percentage change in forest cover/year, between 1990 and 2000 (Anon., 2001*b*).

[‡] Countries with the same relative ranking score are ordered alphabetically. Bhutan, French Guiana, Gabon and Suriname could not be ranked because deforestation rates for these countries were not available.

malaria transmission in South–east Asia and the Western Pacific. A different set of circumstances shape the relationships between forests and human malaria in Amazonia and Central Africa. The PARM living in closed forests in these regions are much smaller (almost an order of magnitude lower) than those in South–east Asia and the Western Pacific combined. It is the vast area of the closed forests in Amazonia that is the most important contributor to the estimates of the PARM in the region [Fig. 2(a)]. Most of the Amazonian rainforests harbour such low numbers of humans that there is no or only a negligible risk of human malaria (Fig. 2). These rainforests are being felled and degraded at an increasing rate (Fearnside, 2005), however, and, in the current absence of a deep-forest vector, malaria is more likely to get worse than to get better after deforestation, with the generation of new habitats for heliophilic vectors such as *An. darlingi*. As Central Africa resembles the Amazon region, in terms of vector ecology within its closed forest, deforestation will probably have similar malaria-related outcomes in the two regions. In Central Africa, however, a much larger proportion of the area covered by closed forest is categorized as malarious (77.1% *v.* 25.1% in Amazonia) and the PARM is about 50% greater. The presence of extremely efficient vectors such as *An. gambiae* s.s. and *An. funestus*, which both generally benefit by the clearing of forests, means that deforestation in Central Africa may dramatically increase the incidence of human malaria in the region.

A country-level analysis has allowed those territories where the problem of deforestation is highest and its impact on malaria transmission would be most significant to be identified (Table 4). The ranking of countries supports the results of the regional comparisons, with Asian countries generally ranking higher on the list than African or South American ones. If predictions of the effects of future deforestation on human malaria are to be made more accurate, the precise distributions of the vector mosquitoes, with respect to the deforestation, need to be mapped. Unfortunately, there are currently few, if any, relevant and reliable maps of vector distribution and deforestation. A better knowledge of the relative competence of each *Anopheles* species as a vector of the parasites causing human malaria is also needed, to allow more accurate predictability and comparability between countries. In those countries that have deep-forest and near-forest *Anopheles* species as main vectors (i.e. most South–east Asian and Western Pacific countries; Table 4) there is a particular uncertainty about the consequences of deforestation on malaria transmission.

CONCLUSIONS

An understanding of the relationships between forests and malaria transmission is important to guide strategies designed to reduce malaria burden in endemic forested areas. This review article provides a global overview of these relationships, highlighting the regional differences, and assessing the extent to which qualitative assertions about malaria and deforestation are supported by hard data. The numbers of people at risk of malaria within closed forests are estimated here, for the first time. South–east Asia and the Western Pacific have the highest PARM in forests but assessing future trends within these areas is particularly problematic because of the complex interaction of influences on the forest and non-forest vectors. It is more straightforward to predict the impacts of deforestation in Central Africa and Amazonia. Deforestation in Central Africa is of more concern globally, because of the efficacy of the non-forest vectors and the high densities of the human populations in this region's forests. 'Frontier' malaria remains the greatest concern for malaria epidemiology in South America, because of the significance of malaria transmission in Amazonia.

This review forms part of the Malaria Atlas Project (www.map.ox.ac.uk), which aims to build up a comprehensive, global, spatial and epidemiological framework for mapping malaria. The core of this project is the development of a map of malaria endemicity based on a global database of malaria prevalence. In conjunction with current land-cover data-sets, this database will eventually allow a more detailed examination of the links between malaria and deforestation, and contribute to improving our knowledge in this neglected area.

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