Spatial targeting of interventions against malaria

Richard Carter,[1] Kamini N. Mendis,[2] & Donald Roberts[3]

Malaria transmission is strongly associated with location. This association has two main features. First, the disease is focused around specific mosquito breeding sites and can normally be transmitted only within certain distances from them: in Africa these are typically between a few hundred metres and a kilometre and rarely exceed 2–3 kilometres. Second, there is a marked clustering of persons with malaria parasites and clinical symptoms at particular sites, usually households. In localities of low endemicity the level of malaria risk or case incidence may vary widely between households because the specific characteristics of houses and their locations affect contact between humans and vectors. Where endemicity is high, differences in human/vector contact rates between different households may have less effect on malaria case incidences. This is because superinfection and exposure-acquired immunity blur the proportional relationship between inoculation rates and case incidences. Accurate information on the distribution of malaria on the ground permits interventions to be targeted towards the foci of transmission and the locations and households of high malaria risk within them. Such targeting greatly increases the effectiveness of control measures. On the other hand, the inadvertent exclusion of these locations causes potentially effective control measures to fail. The computerized mapping and management of location data in geographical information systems should greatly assist the targeting of interventions against malaria at the focal and household levels, leading to improved effectiveness and cost-effectiveness of control.

Keywords: malaria, prevention and control; malaria, transmission; Anopheles, breeding; geography; risk factors; space clustering.

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Introduction

The spatial aspect of malaria risk, i.e. the location of human habitations in relation to specific types of environment, and its relevance to protection against malaria, has long been recognized (*1*). For example, many years before the role of mosquitoes in the transmission of malaria was understood, Italy's anti-malaria regulations of 1809 required irrigated land to be at least 500 m from general housing and at least 8 km from the capital of a kingdom (*2*). When, at the end of the 19th century the transmission of malaria by mosquitoes was proven (*3, 4*), effective malaria control became largely an exercise in the identification and elimination of the sources of *Anopheles* mosquitoes from around human habitations. Protection of the inhabitants at malaria risk from contact with the mosquitoes was also practised in some situations, most notably in the form of house screening. Success depended on gathering information about the types of anopheline mosquitoes, their behaviour, and their interactions with human populations. Some were significant vectors of human malaria but many were not. Thus, malaria control was heavily evidence based. Accurate geographical and spatial data on vector breeding sites and human habitations were central to the way in which malariologists thought about and approached their problem.

A major advance in malaria control came in the late 1940s with the introduction of mass spraying of houses with the residual insecticide DDT (*5*). However, because it could be adopted widely, effectively and relatively inexpensively this approach partly undermined interest, previously so strongly maintained, in the collection and analysis of detailed information on factors underlying malaria transmission. Today, malaria control again faces many of its traditional challenges. In attempting effective and cost-effective interventions, we can no longer afford to disregard questions of location, environment and the biology and behaviour of vector and host.

Definitions and terms of reference

We discuss below the relevance of spatial or geographical data concerning malaria transmission and risk, and their collection and management for the purposes of control.

The matters under consideration are most evident where there is a low-to-moderate intensity of

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[1] Professorial Fellow, University of Edinburgh, Division of Biological Sciences, ICAPB, Ashworth Laboratories, West Mains Road, Edinburgh EH9 3JT, Scotland (email r.carter@ed.ac.uk). Correspondence should be addressed to this author.

[2] Senior Adviser, Roll Back Malaria Project, World Health Organization, Geneva, Switzerland.

[3] Professor, Division of Tropical Public Health, Department of Preventive Medicine, Uniformed Services University of the Health Sciences, Bethesda, MD, USA.

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transmission, and it should be taken that we are referring to such situations unless otherwise stated. The relevance of our analysis to situations of high transmission intensity is discussed towards the end of the article.

Malaria transmission refers to anopheline mosquitoes actively transmitting malarial infections in human populations at particular locations. The intensity of transmission is related to the frequency with which a person at a given location may be exposed to the bite of an anopheline mosquito infected with malaria sporozoites, and thus to the possibility of becoming infected with malaria parasites. The intensity of malaria transmission is commonly discussed in terms of the malaria sporozoite inoculation rate, often referred to as the entomological inoculation rate (EIR).

Malaria risk refers to the probability of an episode of clinically active malaria being experienced by an individual in a particular location and situation. In principle, malaria risk can be quantified by recording the number of malarial episodes experienced over time among all individuals in a given situation and location. It thus equals the malaria case or malarial disease incidence among individuals in the situation. At low malaria transmission intensities, under which most sporozoite inoculations give rise to a clinical episode of malaria, malaria risk is numerically equivalent to, and roughly interchangeable with, the malaria case incidence or the malaria sporozoite inoculation rate. At higher transmission intensities, malaria risk still equals the malaria case incidence but is not directly equivalent to the malaria inoculation rate. This arises because the effects of both superinfection and exposure-acquired protective immunity reduce the risk of a clinical episode to a small fraction of the prevailing malaria inoculation rate, especially as the individual grows older.

Spatial characteristics of malaria transmission and malaria risk

Malaria is non-randomly distributed across a landscape in patches of higher or lower transmission intensity and malaria risk which are separated by greater or lesser distances from each other. Two distinct levels of such spatial aggregation can be identified. One is the focal unit of malaria transmission, the area over which human malaria is actively transmitted by *Anopheles* mosquitoes originating from a specific aqueous breeding site. The other is the household or other reasonably identified point of contact between a small group of humans and mosquito vectors, which generally has some particular and characteristic level of malaria risk (*6*).

The focal unit of malaria transmission. The association of malaria transmission with specific locations is attributable to the presence of breeding sites of the anopheline vectors. Each breeding site can be the centre of a focus of malaria transmission. The habitats that support breeding by the vectors of human malaria are extremely diverse and in general are highly species specific (*7*). Almost their only feature in common is the presence of fresh water, or sometimes brackish water. Recorded sources of malaria vectors include marshlands and other areas of poor drainage (*8–10*), silted rivers, civil engineering sites, surface water retained by dams and other means (*8*, *11*), rice cultivation in some environments (*12*), shaded ponds (*13*), unshaded ponds (*14*), pools in drying rivers (*11*, *14*), fast-flowing hillside streams (*15*, *16*) and water that has accumulated in bromeliad plants (*17*). Each type of habitat in each region is associated with particular species of anopheline vectors. The *Anopheles gambiae* complex of sub-Saharan Africa, for example, characteristically breeds in small, often temporary, collections of water close to human habitations such as those formed by wheel tracks, domestic containers and cattle wallows. Such breeding habitats tend to give rise to foci of transmission closely associated with particular locations, e.g. a single village or part of a village (*18*). However, more extensive water surfaces such as rice fields, river margins and seepage plains are also highly suitable habitats for *A. gambiae* and can create much larger and more diffuse foci of malaria transmission (*10*, *12*, *19*).

The dimensions of and dispersal from a focus of malaria transmission depend on a number of factors. These include the productivity of the breeding site and the effective dispersal range of the vector mosquitoes emanating from it. Although the *Anopheles* vectors of human malaria in South America can disperse for 5 km or more (e.g. *20*), the range of dispersal, especially in African settings, is generally less than 1 km (*21–24*). The sources from which malaria vectors disperse may change during and between years as breeding sites dry out or are created (*22*, *25*, *26*). Wind speed and direction influence the contours of foci (*27*), as do specific features of the surroundings, including the ground surface, the vegetation and the fauna.

Especially for anthropophilic mosquitoes, such as members of the *A. gambiae* complex, the area of a single focus of malaria transmission is crucially dependent on the distribution and behaviour of the human population. Thus the range of mosquito dispersal is generally short in high human population densities, whereas at low population densities the female mosquitoes disperse to the limits of their capacity in search of a blood meal. Studies carried out in urban and periurban locations in Africa (Fig. 1) showed that malaria cases generated from known mosquito breeding sites usually declined to very low levels at distances of much less than 1 km from the sites (*9*, *22*, *28–30*). Data from some rural settings suggest that malaria cases can occur several kilometres from known breeding sites (Fig. 2) (*31*, *32*), although other data indicate very short dispersal distances (*18*).

The reasons for these differences are largely spatial in nature, since dispersal from a focus of malaria transmission is strongly influenced by the patterns of distribution of vector breeding sites and human habitations on the ground. Where these are effectively superimposed in a compact village generating its own local breeding sites, the dimensions of the foci are generally contained within about 100 metres of the edge of the village (*18*, *28*). This kind of situation is characteristic of much of sub-Saharan Africa and lends itself strongly to malaria control targeted on small areas, in accordance with the principles described here. Where, on the other hand, both human habitations and vector breeding sites are widely dispersed and separate from each other, the dimensions of the foci of transmission become stretched and generally intermingled so that malaria control measures have to be extended over a correspondingly larger continuous area in order to be effective. A focus reaches its greatest extent when the nearest vulnerable human population of any size or density is located at the very limit, with respect to malaria transmission, of the effective dispersal range of the vectors from their breeding site. This maximum range appears to be approximately 2–3 km in Africa, but may be as much as about 5 km in some settings elsewhere, e.g. in the Americas.

Longer gradients of decline in malaria incidence have been recorded, extending over 10 km or more (*8*, *33*). These, however, relate to changes in the density and productivity of the foci of transmission. This can occur as the physical environment changes from being suitable for mosquito breeding to being unsuitable, e.g. from marshy ground or areas of stagnant water to well-drained land (Fig. 3). Gradients of malaria transmission and malaria risk that are determined by environmental factors can also be extremely sharp, declining to levels of zero over less than 1 km, as for example in an upland region where the fall in ambient temperature over several tens of metres of altitude is the critical factor (*28*, *31*).

An active focus of malaria transmission, as described above, clearly contains human habitations within its boundaries. However, there are inactive foci where all the conditions for malaria transmission occur except for the permanent presence of humans. These foci produce dangerous isolated areas where malarial infections are sporadically transmitted from and picked up by travellers and where severe epidemics may arise among pioneers.

A malarious region thus comprises fairly numerous foci of malaria transmission, each being a mosquito breeding site in a particular location, environment and human setting. The enormous diversity of malaria transmission intensities generated in different locations over large and small distances has been documented in a recent summary of recorded malaria entomological inoculation rates across Africa (*34*) (Fig. 4 and Fig. 5) and in an account of malaria in Bengal in the early 20th century (*8*) (Fig. 6).

Fig. 1. **Relationship of malaria incidence and *Anopheles* mosquito numbers to distance from breeding sites of the *Anopheles* malaria vectors in urban or periurban locations in Africa and the Indian Ocean.** The data are re-expressed from published studies as indicated. The malaria index is the value of the parameter used to measure malaria incidence (e.g. spleen rate (*28*)) malaria seropositivity rate (*22*), parasite rate (*9*) expressed as a fraction of its maximum in relation to distance from a vector breeding site. The *Anopheles* index is the recorded density of *Anopheles* expressed as a fraction of the maximum densities recorded in relation to distance from the breeding site. *Anopheles* densities were measured by means of indoor insecticide spray collections from houses (*22*).

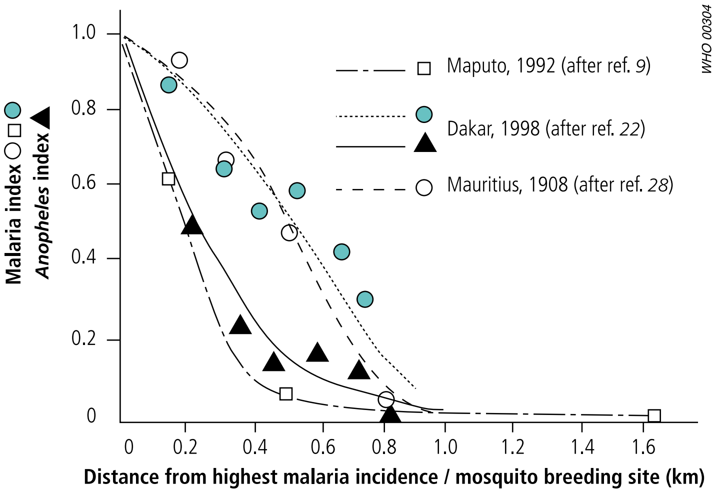
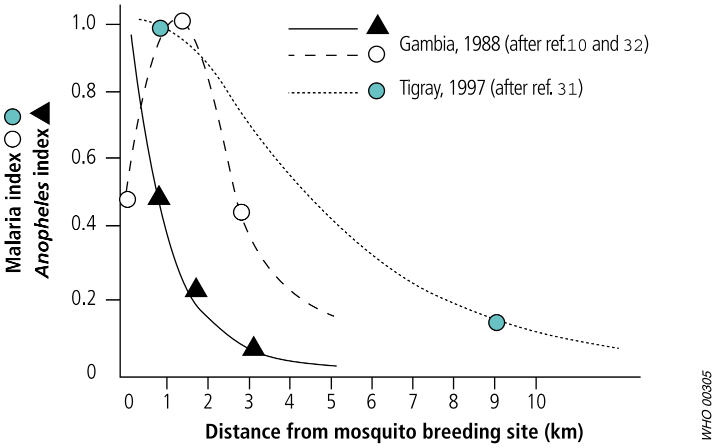


Fig. 2. **Relationship of malaria incidence and *Anopheles* mosquito numbers to distance from identified *Anopheles* breeding sites in two rural locations in Africa.** The data are re-expressed from published studies following the same principles as in Fig. 1. Malaria incidence was measured by clinical attack rate and malaria entomological inoculation rate (*32*) and by clinical attack rate (*31*). *Anopheles* densities were measured by human biting catches, and knockdown and light trap collections from houses, and are expressed in relation to the distance from the locations of peak density (*10, 32*). In one study (*32*), case incidence peaked at 2–3 km beyond the peak of transmission intensity (as determined on entomological parameters). This almost certainly reflects another level of complexity in the distribution in space of malaria case incidence, attributable to the more rapid attainment of protective immunity under the high transmission rates as found at the heart of the focus. This effect would, in areas where foci generate very high transmission rates, lead to lower malaria case incidences at the centre of such a focus than at some distance, in this case 2–3 km, from its centre. At distances beyond this maximum of disease incidence the malaria cases declined over a gradient that probably covered several more km.



Clustering of malaria cases in household units. An active focus of malaria transmission normally equates to a neighbourhood or locality and is generally populated with multiple households or dwelling units, e.g. free-standing houses, compounds or similar arrangements. Among such a collection of dwellings the distribution of malaria risk

Fig. 3. **Changing incidence of malaria across a landscape: examples from the Indian subcontinent and England.** The data are re-expressed from published studies using the same principles as in Fig. 1 and Fig. 2. Malaria incidence in the original reports was represented by spleen rates (*8*) and by differential mortality rates (*33*).

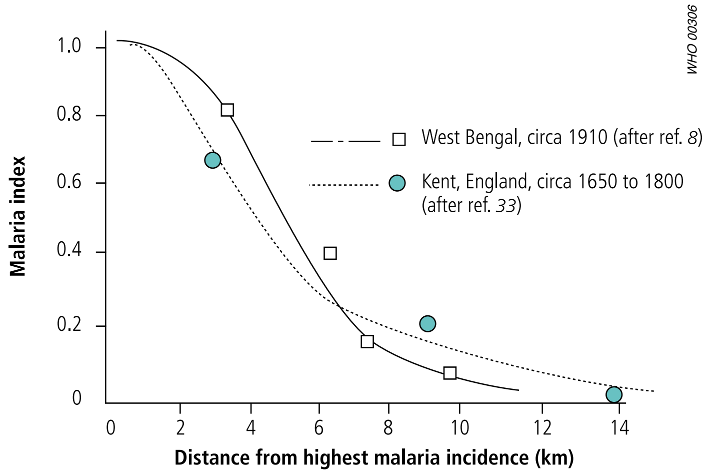
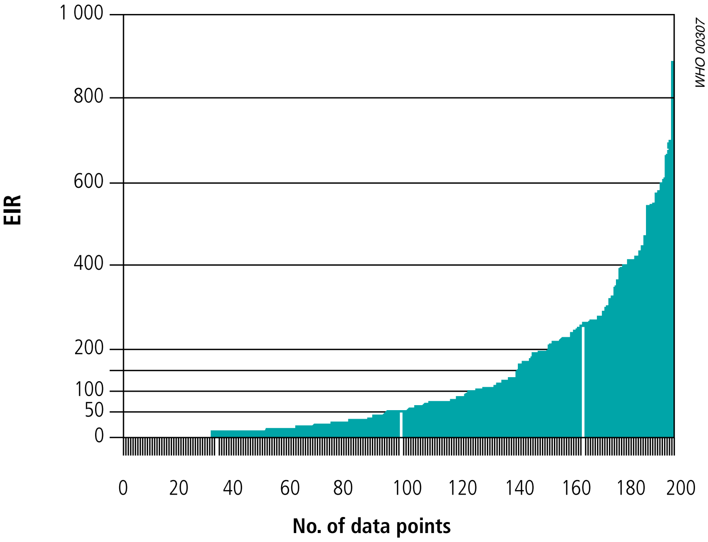


Fig. 4. **Spread of recorded values of annual malaria entomological inoculation rates (EIRs) across tropical Africa** (after ref. *34*)



is invariably uneven, i.e. the incidences of malaria cases are clustered in some households much more than in others (*6*, *29*, *35*). Risk factors include location, e.g. increased numbers of cases occur in houses near larval habitats, as well as other attributes of houses or living units, among them the structural features (*29*, *30*, *35*, *36*) and the economic, cultural, experiential and genetic characteristics of the occupants (*37*).

Wherever appropriate records have been kept, the clustering of malarial infection in different households in malarious localities has been readily demonstrable (*27*, *29*, *30*, *35*) (Table 1, Fig. 7). In each instance a small proportion of households carried most of the malaria case burden. For example, in Belize (Fig. 7), 50% of malaria cases occurred in only 8% of households, while in Tigray, Ethiopia, 18% of households experienced 50% of the cases and 95% of the cases occurred in 75% of the houses (*35*). Such data reveal, moreover, that the relative malaria risk of the most vulnerable households in a small locality can be multiples of ten higher than that associated with the least vulnerable (Table 1).

The non-random distribution of malaria case incidences in the different households recorded in the studies quoted here appear to conform fairly closely to the "20/80 rule" (*38*), whereby approximately 20% of a host population contributes 80% of the cases of an infectious organism.

Spatial targeting of control

The uneven distribution, or clustering, of malaria risk in certain individuals and households has been recognized as a potent factor underlying the robustness of malaria transmission (*39*). In other words, the clustering of malaria risk makes untargeted interventions highly inefficient, i.e. ones that fail to cover many of the high-risk individuals and households. However, clustering can also be turned to considerable advantage. Thus, knowledge of the location of individuals and households at high risk allows malaria control measures to be targeted for maximum effect. The relative impacts of targeted control and random control are seen clearly in Fig. 8 (*35*).

Similarly, a correct understanding of the location, extent and distribution of the foci of malaria transmission in relation to human habitations enables malaria control to be practised efficiently over an entire area. The successful interruption of malaria transmission requires complete units of transmission to be eliminated, each of which may cover an area of a radius < 1 km or, rarely, > 2–3 km, from a vector breeding site. For the same reasons, human habitations can be made completely or almost completely malaria-free by locating them at an appropriate distance from the centre of the nearest focus of transmission.

In the light of the general facts concerning the spatial distribution of malaria, the following questions arise in relation to the practical control of the disease.

- Is it operationally possible to reliably distinguish households, or other spatial clusters, with markedly different malaria case incidences and to determine the locations and extents of all the foci of malaria transmission in a district or locality?
- If this can be achieved, can the information be exploited in order to conduct highly effective malaria control by the accurate targeting of an intervention?
- What tools for malaria control can be used more effectively and cost-effectively in any given situation by applying such spatial information?
- In which situations of endemic malaria is spatial targeting of interventions against malaria practical and effective, and in which, if any, is it not?

Collection and management of data for the geographical location of foci of malaria transmission and clusters of high malaria risk. Two general types of data can be collected for the identification of foci of malaria transmission and the location of clusters of malaria risk in human habitations. The first type requires the traditional methods of locating vector breeding sites, recording mosquito densities, rates of infection with sporozoites or oocysts, and human malaria case incidence rates, and locating and characterizing houses and the domestic environment. For these purposes the accurate location of sites on the ground is now greatly assisted by the use of hand-held, satellite-dependent global positioning systems (GPS). The second type of data is obtained by remote sensing (RS) from space. This provides high-resolution images that reveal patterns of vegetation and other environmental features and conditions on the ground.

All forms of geographical data can be assembled using computer-assisted management of spatial information in what are known as geographical information systems (GISs). These can easily be applied in support of national malaria control programmes. Once developed, GISs or GIS analyses and other outputs, can be exported to the regional or local levels in order to target and manage more precisely the limited resources for sustainable malaria control. The major objectives in the application of GISs to malaria control are the characterization and mapping of the distribution of sources of malaria transmission and malaria risk, where possible down to the household level.

GISs can also be used to generate predictive models of malaria risk and transmission in specific situations and locations. For example, in studies in Belize and Mexico, satellite data on vegetation and other ground features, obtained by RS and entered into a GIS, were used to develop predictive models for the presence and abundance of malaria vectors in rural villages and houses (*13*, *40–42*). The distance between villages and mosquito larval habitats was an important parameter in the predictive models (*41*). The satellite data were used to locate specific types of vector breeding sites. The GIS was then used to examine the relationships between breeding sites and distances to human habitations. Predictive models for two of the three vectors in Belize have proved particularly accurate (*12*, *41*).

Properly used, GPS, RS and GISs should therefore allow the location and quantification of malaria risk to be determined in a much more time-effective and cost-effective way, and probably more accurately in many situations, than was previously possible. Affordable hardware and software for using GISs and RS are now available. These systems are valuable tools allowing information on malaria transmission and malaria risk to be processed and used to guide the management of malaria control campaigns.

Fig. 5. **Distribution of annual malaria entomological inoculation rates (EIRs) recorded for a region of tropical Africa (in Sierra Leone, *= town of Bo):** 1+ = EIR 1–10; 2+ = EIR 10–30; 3+ = EIR 30–100; 4+ = EIR 100–300; 5+ = EIR >300.

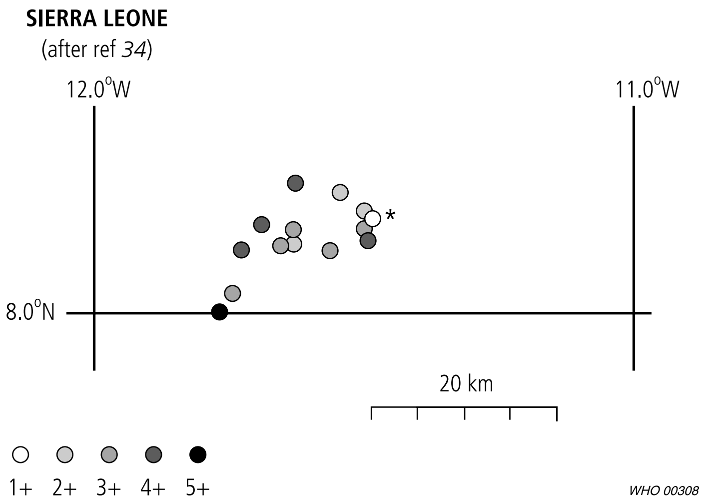


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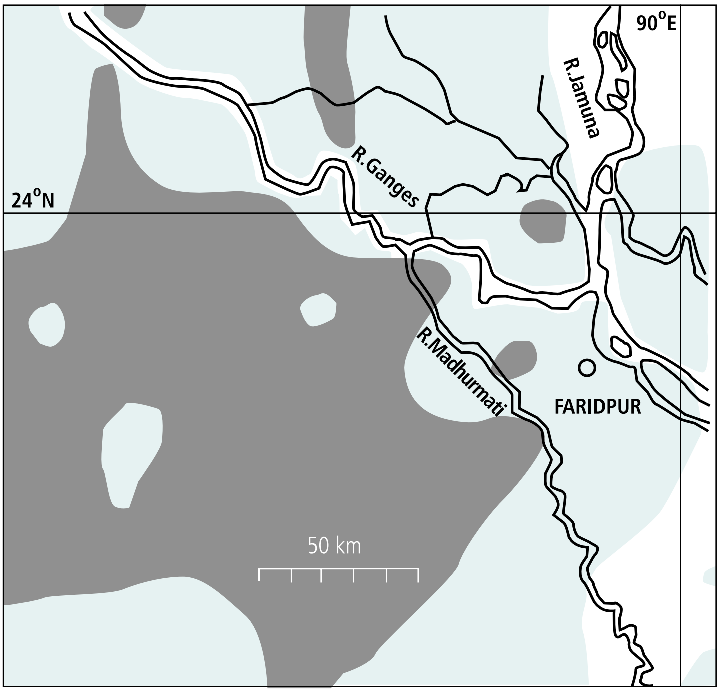
Fig. 6. **Distribution of malaria in central West Bengal at the beginning of the 20th century** (after ref. *8*). Intensely malarious (dark shading), moderately to slightly malarious (light shading), very little or no malaria (unshaded). Note the small areas (as little as 10 km in diameter) of relatively low malaria intensity within a large area of intense malaria. Conversely, there are areas of similar size of high or intense malaria within regions of otherwise lower, or no, malaria. Note, in particular, the effect of the River Ganges in carving a malaria-free corridor, perhaps 5–10-km wide, through a region of high, and in parts intense, malaria. The River Madhurmati appears to have had no similar effect on malaria intensity in the regions through which it flowed.



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Tools for malaria control by spatial targeting. Which methods of control can benefit most from the application of information on the distribution of malaria transmission foci and malaria risk? Clearly, every method of control loses effect if misdirected. Nevertheless, it is worth reviewing the different specific options for malaria control in relation to spatial targeting.

Table 1. **Domestic risk factors for malaria in Tigray, Ethiopia (*35*)**

Risk factor	Relative risk	95% confidence interval	*P*-value
Type of roof			
Thatch	1	–	–
Earth	2.15	1.31–3.52	< 0.05
Type of eaves			
Closed	1	–	–
Open	1.85	1.19–2.88	< 0.05
Windows			
No	1	–	–
Yes	1.47	1.30–2.63	< 0.05
No. of people sleeping in room			
>1	1	–	–
1 only	1.52	1.05–2.20	< 0.05
Separate kitchen			
Yes	1	–	–
No	1.57	1.10–2.23	< 0.05
Animals sleeping in house			
No	1	–	–
Yes	1.92	1.29–2.85	< 0.05
Use of irrigated land			
No	1	–	–
Yes	2.68	1.64–4.38	< 0.05
Combinations of above risk factors			
0 or 1	*1*[a] (1)[b]	—	—
Any 2	*2.52* (3.76)	—	—
Any 3	*3.05* (7.07)	—	—
Any 4	*8.38* (13.30)	—	—
Any 5	NA[c] (25.00)	—	—
Any 6	NA (47.01)	—	—
All 7	NA (88.39)	—	—
Any 5 or more	*14.00*[a] (>25.00)	—	—

[a] Figures in italics are the recorded relative risk.

[b] Figures in parentheses are the mean predicted relative risk.

[c] NA = not available.

Location of human habitation

In order to prevent malaria risk within a community completely, or almost completely, all human habitation is placed at an appropriate distance from the nearest malaria vector breeding site: this may be up to 5 km in some circumstances but can be effective at 1 km or even less.

Reducing vector densities

If it is not practicable to locate human habitation beyond the range of vector breeding sites, the productivity of these sites can be reduced, e.g. by drainage, larvicidal treatment and, perhaps above all, by modifying the human activities which produce them and so avoiding rutted roads, borrow pits, cattle wallows, uncovered water containers, open sewers close to human habitations, and so on. Accurate knowledge and identification of the different types of vector breeding sites is the key to all these approaches to control.

Reducing contact between humans and blood-feeding female *Anopheles* vectors

If it is not possible to site human habitations outside the range of foci of malaria transmission, a powerful approach to reducing transmission involves minimizing contact between humans and blood-feeding female mosquitoes. For example, domestic animals can be brought close to human habitations so that the mosquitoes feed more often on animals and less often on people; however, this is just as likely to attract much greater numbers of mosquitoes towards human habitations (*35*). Probably of more general effect is direct protection of humans from contact with mosquitoes, e.g. by means of mosquito repellents, whether applied to the body or to furnishings such as bednets and curtains, and by physical screening with bednets and the incorporation of mosquito proofing into the design of dwellings. Historically, house screening was probably one of the most efficient measures for reducing malaria transmission rates and malaria risk (*2*, *43*, *44*). Clearly, information on the location of households at highest malaria risk is crucial to the targeting of these measures and to their effectiveness and cost-effectiveness.

The effectiveness of residual insecticides in malaria control has traditionally been explained in terms of the reduced life expectancy of blood-fed female mosquitoes after they alight on surfaces that have been sprayed (*45*). However, there is now evidence that large reductions in contacts between humans and mosquitoes may also occur because the insecticides also have a repellent effect (*46*). Whatever mechanisms are in play, there is no doubt that house spraying with residual insecticides is a very powerful method of reducing malaria transmission rates. It is clearly crucial that this intervention should be targeted at those houses with the highest malaria case incidence.

Health services and reduction of parasite load in the human population

Good access to health services for effective malaria treatment has a major effect on the amount of morbidity and mortality caused by the disease. For example, because of the generally good access to free and effective health services in Sri Lanka, the malaria inoculation rates (ca. one per annum) result in point prevalences for malaria of much less than 1%, whereas similar inoculation rates in Africa, where such services are generally neither free nor widely available, are associated with point prevalences of malaria of around 40% (*47*). Likewise, case fatality rates attributable to *Plasmodium falciparum* malaria in Sri Lanka are about 1 per 10 000, whereas in Africa they are believed to be around 1 per 100 (*48*).

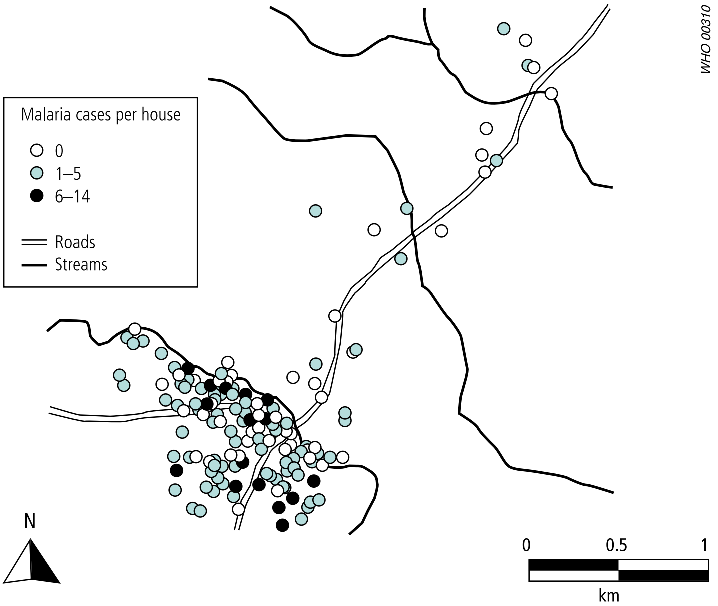
The role that health services can play, not only in the immediate treatment of cases but also in diminishing case incidences by reducing transmission, should be considered. The timely provision of effective drug treatment of malaria cases is actually a self-targeting intervention. This is because, where good health services are available to a community, people who are at most frequent risk of malarial infection seek and receive the most frequent treatment. Subject to the qualifications discussed below, these people are the most likely to be, or to become, infectious to mosquitoes, and consequently their effective treatment reduces the reservoir of infection in the community. In Sri Lanka, for example, large reductions in case incidences have followed the introduction of accessible and effective treatment centres in areas that were previously less well served (K.N.Mendis, unpublished observations, 1996–97).

There are, however, circumstances in which even very good health services may be relatively ineffective in reducing transmission rates. This is true where asymptomatic carriers of infectious gametocytes constitute a significant reservoir of infection for the vectors, as occurs if intense transmission leads to early immunity to disease but does not eliminate the parasites. Because asymptomatic carriers do not seek or receive drug treatment, they remain a source of infection. Similarly, because *Plasmodium vivax* is most infectious to mosquitoes at the earliest stages of an infection, i.e. usually before a patient has presented for treatment, even rapid treatment of cases of *P. vivax* malaria may have only a limited effect on transmission.

On the other hand, under conditions of relatively low transmission, *P. falciparum* should be particularly vulnerable to rapid and effective drug treatment as a means of reducing transmission. This is because *P. falciparum* gametocytes do not circulate in infectious form until many days after the symptoms first appear. Early and effective case treatment that kills the parasites before there has been a significant production of gametocytes should greatly reduce the infectivity of *P. falciparum* infections to mosquitoes. Malaria case incidences were dramatically reduced in Viet Nam during the early 1990s when artemisinin antimalarials replaced chloroquine, to which *P. falciparum* had become almost totally resistant (*49*).

Because they can reduce the burden of current malarial disease, good health services are a critical public health requirement in any malaria control programme. They also provide an effective and accurately targeted intervention for reducing *P. falciparum* case incidence and, therefore, death rates, especially where transmission is low and in the absence of significant resistance to the first-line antimalarial drug (*49*, *50*). Of course, health services that are inadequate, particularly those that are inaccessible to the people most in need, cannot have much effect on transmission and case incidences. It is therefore vital to ensure that health services reach these people. The mapping of malaria risk across areas on the larger scale, i.e. tens of kilometres, is essential for decision-making on the location and deployment of these services.

Fig. 7. **Clustering of malaria cases in 198 houses in the village of San Pedro, southern Belize.** From 1989 to 1996, 50% of malaria cases occurred in only 16,i.e. 8%, of houses (shown in black) (cf. Table 1, Fig. 8). Landsat data (not shown) on ground features of this area are also available (from *D.R.* on request) assisting the location of potential mosquito breeding sites. The map illustrates the potential for combining malaria, census and satellite data within a GIS profile of malaria risk at the neighbourhood down to the household level.

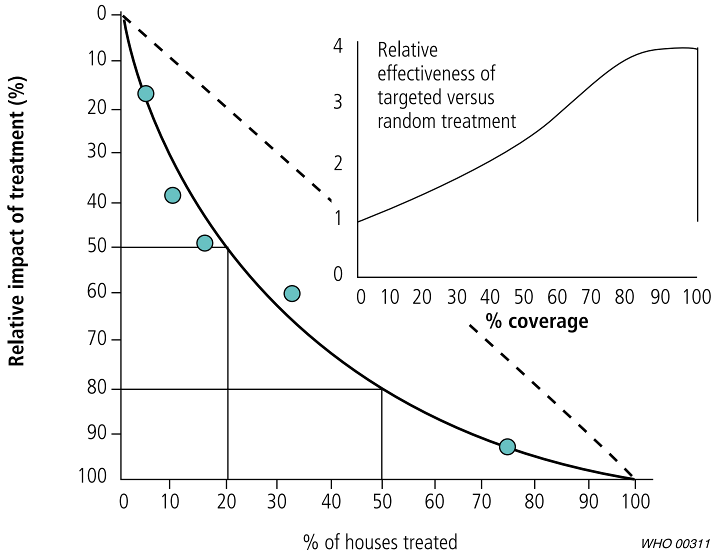


Targeted interventions for malaria control in various environments and at various levels of endemicity. It has been suggested that the reduction of malaria inoculation rates in areas where transmission is intense, notably in tropical Africa, is neither desirable, because of the early acquisition of protective immunity, nor achievable, because of overwhelming vectorial capacities (*48*). Moreover, under these conditions, since individuals are overwhelmingly superinfected with malaria regardless of the location and other environmental factors, little difference is to be expected in case incidences between locations or households. Both of these considerations might suggest that the fine mapping of malaria risk under conditions of intense transmission would have little relevance to practical control. Below, we examine the issue of targeted malaria interventions under different malaria transmission intensities.

Under low-to-moderate transmission represented by annual malaria EIRs of around 10 or less, the distribution of malaria risk is usually very uneven (*27–30*, *35*) (Fig. 7). Under these conditions, accurately targeted interventions to reduce transmission rates can be expected to give greatly improved control (Fig. 8).

The situation under intense malaria transmission, notably in sub-Saharan Africa, presents a more complicated control problem; it is also an uneven one

Fig. 8. **Relative impact on malaria of targeted versus untargeted treatment of houses** (data after ref. *35*; see Table 1). The impact of treating houses starting first with those with the highest case incidence and proceeding to those with successively lower incidences (targeted treatment —●—) is compared with treating increasing proportions of houses on a random basis (untargeted treatment – – –).



as transmission intensity across Africa is itself very uneven. This unevenness is indicated in the compilation of recorded EIRs from Africa by Hay et al. (*35*) (Fig. 4 and Fig. 5), although, being the available reports of field investigations, it is difficult to know if they are truly representative or contain a bias towards the upper or lower range of EIRs. Nevertheless, about one third of records were of EIRs of less than 10, representing the moderate to low range of transmission intensities, and one third had EIRs of 100 or above, which may be taken as the start of range of extremely intense malaria transmission.

A very considerable proportion of the locations where malaria is endemic in Africa thus seems to have transmission intensities represented by EIRs <10. In principle, malaria is controllable in these locations by means of conventional approaches; the interruption of transmission would certainly be achievable and the benefits of spatial targeting of interventions would be obtainable. Furthermore, the majority of locations in Africa where the disease is endemic fall within an EIR range 30–50, in which the spatial heterogeneity of malaria risk and transmission intensity in small areas and neighbourhoods would probably still be evident. Well-managed campaigns with appropriate tools, which should certainly include effective health services, could use targeting to achieve significant reductions of case incidences in these locations.

Under extreme transmission intensities, i.e. EIR >100, the small-scale clustered distribution of malaria risk may become relatively obscured. However, even under these conditions, spatial variation in malaria transmission intensity, and probably also in malaria risk in the very young, still occurs. Large differences in transmission intensity can occur over distances of a few kilometres within areas of generally high transmission intensity (Fig. 5). In such circumstances it is clearly of value to be able to define the contours of transmission intensity so that appropriate decisions can be made on the management of malaria in different locations.

Conclusions

The intensity of malaria transmission and the degree of malaria risk are distributed in a highly uneven way across any malarious landscape. This is true for every degree of resolution from the district or region down to the household and the individual person. In almost any malaria situation, therefore, there are pockets of exceptionally high transmission intensity and/or malaria risk relative to the mean for the location, district or region. For an intervention to be fully or, in many situations, even moderately successful, it is necessary to identify and treat all pockets and individuals of high malaria risk and high transmission intensity. The difficulty of accurately targeting these pockets and individuals has probably had much to do with the persisting transmission that occurs in many regions of endemicity where antimalaria campaigns have been conducted for decades. However, the elimination of malaria from areas of low-to-moderate endemicity may be quite feasible with the tools now available, provided that they are accurately targeted in relation to the clustering of malarial infections.

Affordable technical capability is now available in the form of computerized GISs and satellite-dependent GPS and RS, which, when combined with traditional forms of collection of malariological data, can map malaria transmission and malaria risk at any degree of resolution down to that of the household. These systems are beginning to be incorporated into national control programmes, in line with the renewed emphasis on evidence-based approaches to malaria control. They should allow more accurate targeting of interventions to where they are most needed, leading to more effective control and reduced burdens of malarial disease.

Risk factors for malaria are almost always concentrated in the lowest social and economic categories of societies. In a malaria endemic region the poor cannot afford to live in areas where the malaria risk is low because the land prices are correspondingly high. Consequently poor people tend to inhabit the areas of highest malaria risk. Moreover, their houses are usually of inferior construction and this makes poor people even more vulnerable to malaria. The health needs of the poorest in society are usually also the least addressed by health systems. Health care centres tend to be located at considerable distances from high-risk areas, and the cost of purchasing antimalarial drugs and other interventions precludes the poorest people from using them. In regions where malaria is endemic, therefore, the economic status of individuals, households and neighbourhoods provides an important guide to the areas on which interventions for malaria control should be targeted.

Evidence-based targeting of interventions for malaria control on high-risk individuals and locations can be expected to bring many economic benefits for the countries concerned. Among these are the increased cost-effectiveness of interventions and the consequent reductions in the huge burdens that malaria control imposes on health budgets. In some countries these cost reductions could help to bring effective malaria control within reach for the first time; however, it has to be borne in mind that malaria control should continue for as long as the problem lasts, which may mean indefinitely, if necessary. Any approach that does not allow for this carries many dangers. ■

Résumé

Ciblage spatial des interventions de lutte antipaludique

La transmission du paludisme est fortement localisée, avec deux caractéristiques spatiales principales.

En premier lieu, la maladie est focalisée autour des étendues d'eau qui fournissent des gîtes larvaires aux anophèles vecteurs. La densité et d'autres caractéristiques de la population humaine en rapport avec les foyers de transmission sont également d'importants déterminants du risque de paludisme et de l'étendue de sa distribution autour des gîtes larvaires des moustiques. La transmission n'est sensible que dans un rayon limité autour des gîtes larvaires, qui dépend de la taille de la population d'anophèles, de celle de la population humaine et de facteurs qui influent sur les interactions entre ces deux populations. Dans la plupart des cas, la transmission a lieu dans un rayon d'environ un kilomètre, ou même moins, mais elle peut parfois s'étendre sur une distance de plusieurs kilomètres.

La deuxième caractéristique est le regroupement marqué de l'incidence ou du risque de cas parmi les occupants de certains ménages. Cet aspect est particulièrement net lorsque l'intensité de la transmission est faible à modérée. Le degré de risque peut présenter des différences considérables d'un ménage à l'autre du fait des associations possibles entre les facteurs propres à l'habitation et son emplacement à l'intérieur du foyer de transmission. Des informations exactes sur les emplacements et sur la distribution du risque de paludisme et des sources humaines de transmission permettraient de cibler les interventions sur les emplacements à haut risque et même sur certains ménages. En procédant ainsi, on augmenterait considérablement l'efficacité et la rentabilité des programmes de lutte. Lorsque la transmission est intense, le regroupement des cas cliniques de paludisme peut être masqué par les surinfections et par l'immunité acquise par les personnes les plus âgées du fait de l'exposition. Cependant, même dans ces conditions il est probable que le risque de paludisme clinique sera regroupé parmi les membres les plus jeunes de la population en présence de facteurs analogues à ceux qui influent sur le regroupement du risque dans les conditions de transmission peu intense.

Le développement de technologies satellitaires financièrement accessibles pour la localisation géographique exacte des emplacements et la cartographie des éléments du sol, associé à la transmission électronique et à la gestion informatisée des données cartographiques, a largement amélioré les possibilités pratiques de rassemblement, d'analyse et de diffusion d'informations spatiales utiles sur la transmission du paludisme et le risque qui en découle. Les systèmes d'information géographique permettent d'associer des informations classiques sur les gîtes larvaires des vecteurs et sur l'incidence des cas au niveau des ménages avec les données satellitaires pour construire des modèles prévisionnels du risque de paludisme dans l'espace et dans le temps pour des zones et emplacements particuliers. Grâce à ces prévisions, les campagnes de lutte antipaludique peuvent axer les interventions sur les emplacements et les moments où le risque de paludisme est maximal ou qui correspondent aux principaux points de départ de la transmission. La plupart des régions où le paludisme est endémique, dont une grande partie de l'Afrique subsaharienne, pourraient tirer parti de l'efficacité et de la rentabilité accrues des interventions de lutte antipaludique reposant sur cette approche.

Resumen

Despliegue espacial selectivo de las intervenciones contra el paludismo

La transmisión del paludismo se concentra especialmente en determinados lugares. Cabe destacar dos aspectos de esa distribución espacial.

En primer lugar, la enfermedad se centra alrededor de masas de agua que se convierten en criaderos de los *anofeles* que usa como vectores. La densidad de la población humana y otras características de la población relacionadas con los focos de transmisión del paludismo son determinantes igualmente importantes del riesgo de paludismo, así como del alcance de su distribución alrededor de los criaderos de mosquitos. La transmisión sólo es importante dentro de un radio de acción limitado en torno a los criaderos. Esa distancia depende de las dimensiones de las poblaciones anofelina y humana, así como de factores que afectan a la interacción entre ellas. En la mayoría de los casos, el radio de acción parece ser de un kilómetro o menos, pero en algunas ocasiones puede alcanzar varios kilómetros.

En segundo lugar, cabe destacar el marcado agrupamiento de la incidencia de casos o del riesgo entre los integrantes de ciertos hogares. Esto resulta evidente cuando la intensidad de la transmisión es baja o

moderada. Puede haber diferencias muy grandes entre los niveles de riesgo de los diferentes hogares, debido a una combinación de características específicas de la vivienda o de su situación dentro de un foco. El hecho de tener acceso a información precisa acerca de la situación y la distribución exactas del riesgo de paludismo y de las fuentes de transmisión humanas permitiría focalizar las intervenciones en los lugares de alto riesgo, e incluso en hogares específicos. De este modo, aumentaría enormemente la efectividad y la eficacia en relación con el costo de los programas de control. En los casos de alta intensidad de transmisión, el agrupamiento de los casos clínicos de paludismo puede verse difuminado por los casos de sobreinfección y de inmunidad postexposición en los grupos de edad avanzada. Sin embargo, incluso en esas condiciones, el agrupamiento del riesgo de paludismo clínico tiende a darse entre miembros de los grupos de edad más jóvenes sujetos a influencias parecidas a las que afectan al agrupamiento en las intensidades de transmisión más bajas.

El desarrollo de tecnologías asequibles por satélite para calcular con exactitud las coordenadas del terreno y representar sus características, unido a las comunicaciones electrónicas, la cartografía computadorizada y la gestión de los datos posicionales, ha aumentado enormemente las posibilidades prácticas de reunir, analizar y divulgar información espacial de utilidad sobre el riesgo de paludismo y sobre su transmisión. La información tradicional respecto a los criaderos de los vectores y la incidencia de casos en los hogares se puede combinar con los datos de satélite de sistemas de información geográfica para establecer modelos predictivos del riesgo de transmisión del paludismo en el espacio y en el tiempo, adaptables a zonas y poblaciones específicas. Gracias a esas predicciones, las campañas de control del paludismo pueden centrar las intervenciones en los lugares y el momento precisos de máximo riesgo de la enfermedad, o allí donde surjan las principales fuentes de transmisión del paludismo. La mayoría de las regiones donde el paludismo es endémico, incluida gran parte del África subsahariana, podría beneficiarse de la mucho mayor efectividad y eficiencia de las intervenciones de lucha antipalúdica que permite este modelo.

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