

EDITORIAL

ENHANCEMENT AND SUPPRESSION OF MALARIA IN THE AMAZON

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Malaria in the Amazon over the past 100+ years has been driven by ecosystem transformations consequential to human migration and the opening of frontier lands for agricultural settlement, cattle ranching, and natural resource extraction. Deforestation, and even some limited reforestation, has been an omnipresent part of this process. However, the linkage between deforestation, as such, and malaria transmission is a subtle process requiring analysis at several temporal and spatial scales. Ultimately, the critical explanatory step requires a delineation of how transformation of local ecosystems relates to the promotion or suppression of *Anopheles darlingi*—the primary malaria vector in the Amazon—larval habitats and compatibility, or the lack thereof, of human behavior with *A. darlingi* biting patterns.

A substantial literature^{1–3} supports the general characterization of *A. darlingi* larval habitats as zones of partial shade, proximal to a forest fringe or river edge, in relatively deep and clear water of high pH (relative to the more acidic Amazon streams), and with temperature greater than 25°C. Taking this characterization as a starting point, it is useful to relate it to past and contemporary openings of new areas for settlement and/or resource extraction. A fundamental point is that whenever dense forest is rapidly cut and cleared, leaving large open areas that could be immediately occupied by persons engaged in mineral extraction or cattle ranching, the result has been minimal malaria transmission. This is a consequence of the creation of land cover inhospitable to *A. darlingi* larvae. Indeed, this rapid clear-cutting land clearance process has been the norm for the corporate sector in Brazil.⁴ It has served to protect workers from malaria while, at the same time, creating serious tension with the international biodiversity lobby. There is a disturbing trade-off: what is most malaria protective for workers at Amazon sites is most destructive in terms of preservation of biodiversity, exemplified by the removal of vast stands of primary forest.

In stark contrast to corporate-sector expansion in the Amazon, government-sponsored colonization projects and substantial informal migration, all accompanied by deforestation, have resulted in considerable malaria outbreaks.^{5–7} The interesting analysis of one such setting in the Peruvian Amazon presented in this issue⁸ exemplifies the malaria situation in the early phase of human incursion and deforestation. More generally, the work of Vittor and others⁸ represents one piece of the broader phenomenon of *frontier malaria*, formulated by Sawyer⁹ in the context of the Brazilian Amazon, but applicable more generally. *Frontier malaria* is defined as a phenomenon operating at three spatial scales and with a distinctive time path. First, at a micro/individual level, vector densities are high (as a consequence of ecosystem transformations that promote *A. darlingi* larval habitats), human exposure is intense (reflecting limited knowledge of transmission among settlers, and the bimodal biting pattern of *A. darlingi*¹⁰—at dawn and dusk—just when settlers are going

to and returning from their fields). The apparent unimodal—middle of the night—biting pattern demonstrated in the Peruvian Amazon⁸ could be indicative of just the early phase of the deforestation/human incursion process, but this is a point that needs further investigation. Continuing at the micro/individual level, *Plasmodium falciparum* is the primary parasite augmented by limited abundance of *Plasmodium vivax*. Morbidity is high and mortality is low (reflecting an unusual evolution of virulence of *P. falciparum* in the Amazon), and immunity is low among new settlers (they mostly come from malaria-free areas). Housing quality is poor, thereby rendering indoor residual spraying ineffective. Curative health services are sparsely available, thereby limiting antimalarial drug distribution.

Second, at a community level, *frontier malaria* is characterized by weak institutions, minimal community cohesion, political marginality of settlers, and high rates of both in- and out-migration. This combination of conditions severely limits organized attempts at ecosystem management to minimize malaria risk and development of health clinics. The human mobility ensures proliferation of parasites. Third, at a state and national level, *frontier malaria* is characterized by unplanned development of new settlement areas, stimulated by agricultural failures at previous settlement localities and by a desire of people to avoid further malaria episodes. This process, however, only serves to promote further transmission.

Frontier malaria tends to follow a distinctive time path.¹¹ At the opening of a settlement area, malaria rates rise rapidly, and the first two levels of the above spatial characterization are fully operative. After 6–8 years, the unstable human migration (both in and out) and the highly variable ecological transformations (driven by variation in land clearance practices and local ecology) is replaced by a more organized process of urbanization and development of community cohesion. *Frontier malaria* is gradually replaced by more stable low levels of transmission and lower malaria rates. The process of urbanization itself (especially the introduction of impervious surfaces and drains) is an important intervention, as it creates environments that are inhospitable to *A. darlingi* larvae and that are increasingly remote from forest fringes and river edges, thereby substantially reducing human exposure.

The contemporary Peruvian and Brazilian Amazon situations of frontier expansion, heavy deforestation, and accompanying outbreaks of malaria transmission would seem to make a strong case for sharply curtailing this process and, simultaneously, preserving an invaluable ecosystem. However, as clearly indicated by current frontier expansion in the Brazilian state of Amazonas, the practical issue regarding malaria is one of providing effective mitigation strategies, linked to broad-gauged monitoring and surveillance. Here, fine-grained entomological and community assessments, such as described in Vittor and others,⁸ can provide ground-truth for

risk assessment using satellite imagery that captures the ongoing transformation of forest fringe, partial shade areas, and sites of standing water. Although a full discussion of malaria mitigation on the Amazon frontier lies beyond the scope of this commentary, we feel that this is where the future emphasis needs to be placed.

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