REVIEW

Malaria-associated rubber plantations in Thailand

Adisak Bhumiratana a,*, Prapa Sorosjinda-Nunthawarasilp b, Wuthichai Kaewwaen c, Pannamas Maneekan d, Suntorn Pimnon a

a Department of Parasitology and Entomology, Faculty of Public Health, Mahidol University, 420/1 Rajvithi Road, Rajthewee, Bangkok 10400, Thailand
b Department of Fundamentals of Public Health, Faculty of Public Health, Burapha University, Chonburi 20131, Thailand
c Department of Geoinformatics, Faculty of Geoinformatics, Burapha University, Chonburi 20131, Thailand
d Department of Tropical Hygiene, Faculty of Tropical Medicine, Mahidol University, Bangkok 10400, Thailand

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Summary Rubber forestry is intentionally used as a land management strategy. The propagation of rubber plantations in tropic and subtropic regions appears to influence the economical, sociological and ecological aspects of sustainable development as well as human well-being and health. Thailand and other Southeast Asian countries are the world’s largest producers of natural rubber products; interestingly, agricultural workers on rubber plantations are at risk for malaria and other vector-borne diseases. The idea of malaria-associated rubber plantations (MRPs) encompasses the complex epidemiological settings that result from interactions among human movements and activities, land cover/land use changes, agri-environmental and climatic conditions and vector population dynamics. This paper discusses apparent issues pertaining to the connections between rubber plantations and the populations at high risk for malaria. The following questions are addressed: (i) What are the current and future consequences of rubber plantations in Thailand and Southeast Asia relative to malaria epidemics or outbreaks of other vector-borne diseases? (ii) To what extent is malaria transmission in Thailand related to the forest versus rubber plantations? and (iii) What are the vulnerabilities of rubber agricultural workers to malaria, and how contagious is malaria in these areas?

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* Corresponding author. Tel.: +66 02354 8543 9x1202; fax: +66 02644 5130.
E-mail address: adisak.bhu@mahidol.ac.th (A. Bhumiratana).

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Growing rubber plantations and mimicking forest

The *Hevea brasiliensis* (Mull.), or the rubber tree, is a main source of natural rubber, which is manufactured from the tree’s milky sap. This tree is the most economically important member of the genus *Hevea* that can grow normally on plantations in the tropics and subtropics and extensively in the Southeast Asia, South Asia, South China and West Africa. Due to the world market’s demand for rubber commodities, rubber prices have continuously increased along with the growth of the world economy. Thus, the growing natural rubber industry in most producing and exporting countries has supported the establishment of rubber plantations (Fig. 1).¹⁻⁴ Those governments that rely on rubber exports in Southeast Asia allocate monetary resources to promote the intensification of rubber cultivation, i.e., the expansion and exploitation of rubber plantations by local rubber farmers, to create an ample supply of natural rubber products.¹⁻³,⁵ This phenomenon promotes increased development of rubber-planted areas by both estates and smallholdings. The pros and cons of exploiting this monoculture plantation have been reflected in changes in provisional policy, state economy, demography (settlement and migration patterns), irrigation and agricultural practices, agro-ecosystem biodiversity, agri-environmental and climatic conditions, landscape ecology (land use and land cover patterns), and disease regulation (increases in vectors and diseases).¹⁻¹⁰

Of note, Thailand and Indonesia, the world’s largest producers of natural rubber, have demonstrated a steadily increasing number of rubber plantations from 2003 to 2010.³,⁴ Interestingly, Indonesia has projected improvement in their productivity of rubber agroforestry. Because Thailand is located at a latitude of 13° 45’N and a longitude of 100° 31’E and Indonesia is located at 6° 10’S and 106° 49’E, the geographic coordinates of these two countries are ideal for the agri-environmental and climatic conditions suitable for rubber tree forestry. Thailand had been subject to controversy regarding rubber, as both rubber plantations by the estates and private-owned smallholdings were associated with negative social and environmental repercussions. However, the collective management solutions seem to be acceptable and applicable to many newly planted areas of non-traditional rubber cultivation. By 2010, 64 of 77 provinces were used as planting (2,702,349.76 ha) or tapping (1,883,690.24 ha) areas. Most traditional rubber plantation areas are in the South, covering 1,814,345.28 ha, whereas many non-traditional rubber plantations have expanded to the Northeast (455,286.72 ha), Central and East (336,625.28 ha) and Northern regions (96,092.48 ha).³ Moreover, the rubber and oil palm that are the most economical monoculture crop species are grown in the Southern region, resulting in agricultural intensifications that mediate the conversion (i.e., changes of forestland) rather than the modification (i.e., the maintenance of the forest while significantly changing its structure or function) of land cover.

The natural forest and rubber forests are similar land use types from which humans benefit from intentional utilizations and management strategies. Distinctly cultivated from other forested plantations, such as oil palm and eucalyptus, rubber plantations are harvested by local rubber farmers and workers who usually harvest the products by rubber tapping, rubber sheet processing and logging.

**Figure 1** World natural rubber production and plantation increments. (A) Growing trend in world natural rubber production by three major producing and exporting countries, 1988–2011. Data modified from the Rubber Research Institute of Thailand (RRIT), Ministry of Agriculture and Cooperatives.³ (B) Growing trend in rubber plantation area (both total planting and tapping areas) by country, 2003–2010. Data modified from the Association of Natural Rubber Producing Countries.⁴
of rubber wood. Presently, both Thailand and Indonesia, the world’s leading rubber wood exporters, rely on rubber forestry for industrial purposes. Economically, increasing the world market demand for natural rubber and wood products has become a driving force for Southeast Asian rubber productions by both the estates and smallholdings. However, socio-ecologically, it is a major challenge to policy makers, planners and scientists to gather the needed data, monitor the magnitude and better understand the connections between rubber forestry, human movements and activities (e.g., revisiting rubber plantations, rubber tapping and rubber sheet processing) and other major human causes of land use and land cover changes that might affect changes in global climate and emerging vector-borne diseases.

Rubber forestry and malaria epidemiology

In the context of public health, all stakeholders should understand how substantially the interrelations of ecological, sociological and economical aspects of sustainable development can determine a provision of broadly defined health care services and disease management put in place for the local agricultural workers, especially within the rubber forestry sector. It is essential to explore the connection between rubber plantation intensification and increased malaria and the risk of other vector-borne diseases among the vulnerable populations because these life-threatening diseases continue to be epidemic. Some evidence supports the fact that, as a result of land cover/land use changes, more rubber plantations have created dynamic situations of emergence and re-emergence of malaria in Southeast Asia and regions of South and West Africa. In this regard, the local vulnerable population, including rubber farmers and workers themselves, are integral components of ecosystems that can shape malaria transmission dynamics in areas surrounding rubber plantations. To determine the association between malaria risk and rubber plantations, we reviewed past and current records of malaria transmission in Thailand as a case study of which the national malaria control program (NMCP) has given particular attention to forests and associated malaria.

Thus far, it has been well established that malaria transmission in Thailand is caused by two main parasites, *Plasmodium falciparum* and *Plasmodium vivax*, and to a very lesser extent by *Plasmodium malariae* and *Plasmodium ovale*. The disease is closely forest-related along international borders, especially on the Thai-Myanmar border. The principle vectors, *Anopheles dirus*, *Anopheles minimus* and *Anopheles maculatus*, are sessile to the forest and forest fringe. Only the *An. minimus* is predominantly found in forest fringe areas across the country. Due to its geographically wide distribution, this latter species is important for epidemiology and vector control. Malaria affects all age groups but appears to be gender-specific: male patients are twofold more prevalent than female patients. Due to their occupational risk, farmers or adults that are engaged in agricultural work are at the greatest risk for malaria infection and normally account for 30–40% of cases. Alternatively, 20–25% of general workers or agricultural workers contract the disease.

With these epidemiologic figures, the NMCP initially implemented a vertically specialized program after 1951 that emphasized reduction of malaria morbidity and mortality rates by primarily making use of microscopically diagnosed case detection, treatment with antimalarial drugs and vector control with insecticides. These malaria control measures are specifically applied to or appropriately used in stratified control areas, i.e., in endemic areas where seasonal malaria transmission occurs regularly and in high risk areas where introduced transmission of malaria possibly occurs. Having had revised the policy and strategy after 1995 in accordance with the guidelines of the Global Fund to Fight AIDS, Tuberculosis and Malaria (GFATM), the NMCP has adopted global malaria strategies to be implemented in all malaria control areas. The new malaria control strategies include rapid diagnosis and prompt treatment by the use of rapid diagnostic tests and artesunate combination therapy (ACT), indoor residual spraying (IRS) in combination with insecticide-treated nets (ITNs) or long-lasting insecticidal nets (LLINs) for vector control. As a result of the implementation of these malaria control strategies, the NMCP has achieved the goal of malaria control by dramatically reducing overall malaria morbidity rates (MMRs), as shown in Fig. 2. However, the burden remains in malaria-endemic provinces along the border areas. The MMRs for the ten-top malaria-endemic provinces are closely associated with the annual parasite incidences (APIs), suggesting that, at the provincial level, there must be fluctuating numbers of local people affected with, or at risk of, malaria infections. The API is more appropriately used as the outcome indicator to determine whether the forest and forest fringe are related to this metric (Fig. 3). Fig. 3A shows categorical maps that use a mosaic pattern to illustrate the number of landscape classes in each of malaria-endemic provinces. These mosaic pattern classifications can be adjusted to reflect the vegetation index, which is often done for mixed forests such as those in Thailand. The landscape classes include forestland, evergreen forest (e.g., hilly, perennial, moist, dry or mixed), mixed deciduous forest, dry dipterocarp forest, tropical pine forest, bamboo forest, mangrove forest, swamp forest, beach forest, secondary or disturbed forest, forested plantations (e.g., rubber, oil palm, teak and eucalyptus), highland agriculture, field crops (e.g., pineapple and corn), orchards and mixed orchards, paddy field, shrimp farm, shellfish farm, urban and built-up land, water bodies and all other uses. Therefore, only the total areas (km²) of forest patches and forest fringes containing rubber trees, oil palms, orchards and other forest plantations, which appear as shaded areas, are considered endemic with the *Anopheles* vector, and these areas are used in the calculation of the forest-fringe index (FFI). Fig. 3B illustrates that the calculated values of the FFI are significantly and linearly related to the API. Interestingly, two endemic provinces, including Tak and Mae Hong Son, cover large areas of the forests (Fig. 3A) but have relatively lower FFI values than other endemic provinces (Fig. 3B). Before the remodel of association between the two metrics, we considered that these provinces are known for cross-border migration of highly mobile people and other human movements, such as revisiting the forests for other purposes. After minimizing these effects,
the fitted curve estimation model shown in Fig. 3B seems to more effectively predict a direct relationship between the two metrics. It may be the case that if there are more suitable methods used in the collection of needed data and the analysis of land cover/land use changes, the application of the FFI metric is the best option to measure the spatial-temporal distribution of malaria cases in endemic provinces. Regarded as the second leading cause of vector-borne
Figure 3 (continued)
disease morbidity, malaria remains an important public health problem in Thailand. As discussed earlier, the continuing malaria burden in the ten-top malaria-endemic provinces leads us to ask why the local people remain susceptible to malaria in spite of the fact that the NMCP has implemented extensive services and malaria control strategies.

Understanding the vulnerability to malaria in relation to rubber plantations is a topic of interest. Rubber trees normally have 19- to 22-year life spans. Their normal growth requires heavy rain and humidity. Rubber forestry, in essence, creates a micro-climatic environment rather than a macro-climatic environment. The micro-climatic environment is attributed to agroforestry-ecosystem biodiversity as a result of the biological, physiological, and chemical pathways and processes that potentiate growth and diversification, as measured by richness of species, populations and genetic diversity in communities and ecosystems. However, such rubber forestry has negative effects from human activities because deforestation and intensification of rubber plantations can disturb the natural habitats of An. dirus, which is autochthonous to the evergreen forest but intolerant to the forest fringe areas.19,26 This species can disappear permanently or appear intermittently on rubber plantations. Meanwhile, the positive influences of rubber plantations can create breeding sites for a multitude of Anopheles populations, including some potent malaria vectors such as An. minimus and An. maculatus, especially if irrigation and agricultural practices are also available. Therefore, rubber forestry seems to have the potential to radically increase the Anopheles population. Some rubber plantation areas of the Prachuap Khiri Khan Province show strong evidence that malaria-associated rubber plantations (MRPs) do indeed exist [Fig. 4]. Sattivipawee et al.7 analyzed the health-related behaviors of malaria-affected villagers in a transmission-prone rubber plantation area in relation to the performance of the Global Fund-supported malaria program. Findings revealed that the predictors for MRPs included occupation (daily worker), misconceptions of malaria (mosquito and prevention) and misuse of mosquito-nets. The use of mosquito-nets is debated in relation to the occupational risks to better understand the spatial and temporal patterns of malaria risk.

Due to human movements and outdoor activities, such as revisiting rubber plantations, rubber tapping and rubber sheet processing at the smallholding(s), the vulnerable persons such as rubber farmers and workers who tap the rubber trees may be exposed to multiple bites at multiple locations. It is likely that frequent human-vector contact in and around rubber plantations increase malaria risk because the blood-feeding Anopheles vectors, including An. minimus, An. maculatus and An. dirus, are more exophagous (feeding outdoors) than endophagous (feeding indoors).19,21–25 These malaria vectors are also anthropophagous feeders that can bite vulnerable persons during routine rubber plantation practices. This may be a reason why rubber forestry is such a complex epidemiological setting in which at-risk households, including rubber farmers, workers and schoolchildren who accompany their parents, are chronically affected with malaria. More fluctuating numbers of malaria-infected people involved in rubber plantations may reflect the effectiveness of the implementation of malaria control because the vector control operation in areas of rubber plantations is less effective against outdoor-feeding Anopheles. The public health challenge of malaria prevention and risk reduction in these vulnerable populations is complex. Indeed, this challenge does not reflect the effectiveness of NMCP implementation. However, the NMCP has attempted to cope with the following malaria risk situations: (i) migration of cross-border people and foreign migrant workers along the international borders, (ii) emergence of epidemics in relation to internal migration of either non-immune workers into endemic or high-risk areas implementing the development projects or non-immune agricultural workers, including foreign migrant workers, that travel into endemic or high transmission risk areas, (iii) spread of drug resistance along the Thai–Cambodia and Thai–Myanmar borders, (iv) low household levels of acceptance and willingness to use IRS and ITNs/LLINs, (v) poor education of at-risk populations about high-risk behaviors and (vi) high case-fatality rates among non-immune groups, such as migrants, ecotourists and trekkers.

**Human–vector interactions: spatial and temporal patterns of malaria risk**

Rubber plantations create suitable micro-climatic conditions for potent Anopheles vectors by promoting the survival, growth and reproduction of these vectors during the rainy season. Moreover, the shaded environment of rubber plantations can facilitate feeding and breeding of Anopheles mosquitoes even in the dry season. The abundance and distribution of these mosquitoes are basically dependent on both seasonal variation, such as increasing rainfall with increasing density of Anopheles, and geospatial variation.16,18,21–24,26–31 It is essential to understand the population biology of the Anopheles vectors that

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**Figure 3** Landscape ecology and forest-related malaria. (A) Land use and land cover patterns of forests, forest plantations and crop plantations are used to analyze malaria risk in association with forest and forest fringe by calculating the forest-fringe index (FFI) for each of the top ten malaria-endemic provinces with respects to the geographical regions of Thailand: A1 – North; A2 – Central; A3 – East; and A4 – South. The FFI is mathematically expressed as the sum of geospatially populated Anopheles areas (forest patches and forest fringes of rubber plantations and other related patches) divided by the sum of geospatially populated Anopheles areas and agriculture areas. (B) Left panel, a fitted curve estimation shows a poor prediction of a linear relationship between the observed values of the FFI and API (adjusted $R^2 = 0.034, P = 0.284$). It is likely that high API values are not directly influenced by FFI values, which are responsible for infection rates in Tak and Mae Hong Son provinces (arrows). Right panel: When excluding these observations, there is a statistically significant linear relationship between the two metrics (adjusted $R^2 = 0.503, P = 0.049$).
○ Malaria households in which any member was diagnosed with malaria from 2007-2010
○ Malaria households located close to known *An. minimus* breeding sites
○ Rubber plantations with mixed irrigation and agricultural practices, but with no known breeding sites

○,○ Malaria-affected household that has a small farm located within a transmission focus of *An. minimus* with at least 2 members diagnosed from April to June 2010
○ This malaria-affected household located in the community that practices irrigation agricultural activities that have no known breeding site
are endogenous to rubber plantations and how they interact with each other and the environment. As mentioned earlier, many *Anopheles* vectors, including *An. dirus*, *An. minimus* and *An. maculatus*, behave anthropophagically rather than zoophagically and are night biters with photophobic behaviors. Among these, *An. maculatus* is more likely to be zoophagous. They are all careful feeders that strike when the victim is stationary. Most studies of malaria epidemiology in many endemic settings are based on the assumption that patients are infected through *Anopheles* bites indoors. Nonetheless, there is evidence that many patients who work outdoors in high-risk areas, especially in forests or rubber plantations at night, are more likely to be exposed to malaria through *Anopheles* bites outdoors. Generally speaking, the exophagic *Anopheles* vectors have greater potential for transmission of malaria sporozoites than do their endophagic counterparts due to their proportionately larger number of bites and species. Therefore, *An. minimus* is more likely to forage for human blood meals than other species in the rubber plantation ecosystem. Like other endemic settings, the foci investigation in MRPs is based on relating epidemiologic malaria infections to the time and location at which the exposed patient came into close contact with an infective *Anopheles* mosquito. However, the investigation needs to analyze rubber plantation practices in addition to observed occupational exposures to bites of *Anopheles* vectors.

**Figure 4** Malaria-associated rubber plantations (MRPs). (A) All malaria households located in the transmission risk area. (B) A malaria household has a farm located in a transmission focus and a home in a non-transmission focus. The data were obtained from household surveys in 2010 in Chaiyarat Sub-district, Bang Saphan Noi District, Prachuap Khiri Khan, one of top ten malaria-endemic provinces of Thailand.

**Figure 5** Human movements and revisiting of polygonal rubber plantations. (A) Effect of revisiting rubber plantations on initial time of exposure for rubber tappers (living in malaria-free low-lying households) that routinely practice rubber tapping and/or rubber sheet processing at smallholdings confined to malaria transmission foci. Continuations of these practices (red) at small farms are considered rubber tapping-associated exposures. These people are susceptible to multiple bites from *Anopheles* at multiple locations over a longer exposure time. (B) Returning from rubber plantations with or without being exposed to multiple *Anopheles* bites. If clinical malaria or prodromal infections are absent, this is considered a no risk (green) for malaria zone; usually, rubber tappers revisit rubber plantations on subsequent days. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Rubber tapping and malaria exposure

Human movements into polygonal rubber plantations
There are two possible factors that render rubber farmers and workers susceptible to frequent Anopheles vector exposure in rubber plantation areas (Fig. 4). First, the rubber farmers who own the smallholding(s) at which the workers have productive activities may have different household settings that vary from simple wooden houses with basic amenities to cement houses with high-end amenities. These homes are mostly located at the fringe of hilly rubber smallholdings and are more likely to be within malaria transmission foci than homes located in populated low-lying areas (Fig. 4B). Second, during a period of rubber tapping that normally starts in the rainy season and extends into the winter season, rubber tappers (both farmers and plantation workers) do not always sleep under nets during the nighttime because they leave a house for harvesting the rubber for several work hours before returning to sleep.

Due to their movements and outdoor activities, rubber tappers have occupational exposures to malaria vectors in MRPs due to rubber tapping patterns. In fact, rubber plantations are normally polygonal rather than rectangular and, topologically, the hilly rubber plantations are on slopes of varying angles of inclination and altitudes (Fig. 4). Therefore, in uphill areas of rubber plantations, rubber tappers can be more frequently exposed to multiple bites on multiple locations if they revisit more rubber plantations and perform more night-time rubber tapping (Fig. 5). Interestingly, rubber tappers’ exposure to malaria is largely dependent on human movements into polygonal rubber plantations, and factors such as the geospatial and agri-environmental and climatic conditions are known to contribute to the risk of infection because a dynamic abundance and distribution of the Anopheles populations indigenous to polygonal rubber plantations depend upon species—species interactions, predator—prey interactions and aggregating-segregating forages. The bionomics of potent Anopheles vectors will enlighten our understanding of the connection between vector ecology and human movements into polygonal rubber plantations where occupational exposures to malaria vectors occur at different locations and times. Rubber plantation practices during the night are related to malaria risks in MRPs that are likely due to occupational risk alone. For example, the rubber tappers reduce their night-time sleeping hours and are housed in low-lying homes that do not increase risk of infection; however, they usually practice rubber tapping and rubber sheet processing during the night at smallholdings in malaria transmission foci. It is possible that most rubber tappers and accompanying persons or schoolchildren who work at night in smaller polygonal rubber plantations may have a lower chance of malaria vector exposure. It is unlikely that these susceptible persons who have more work hours at night in the polygonal rubber plantations have increased malaria risks as a result of anything other than work exposures.

Person-time sleeping hours
Generally, the tapping area is relative to the size of the planting area (Figs. 1B and 4). Most rubber tappers work from 09:00 p.m. to 5:00 a.m. or from 1:00 to 5:00 a.m. to obtain a maximal yield. This work schedule is economically driven and can result in a 4–5% increase in natural rubber production as compared to optimal tapping from

Figure 6  Person-time sleeping hours of rubber tappers. Measurement of person-time sleeping hours of rubber tappers (n = 30) that sleep under mosquito-nets during seasonal rubber tapping is based on the frequency of individual sleeping hours (06:00 p.m.—06:00 a.m.) at different times divided by the total persons sleeping under mosquito-nets multiplied by 100. The person-time sleeping hours are adjusted accurately to reflect the practices of the rubber tappers during a course of rubber tapping days, regardless of the types of mosquito-nets and epidemiologically distinct settings, including low-lying malaria-free households versus hilly households on small farms within known transmission foci. Data were obtained from the Chaiyarat Sub-district, Prachuap khiri Khan.
6:00–8:00 a.m. in the morning. This method is practiced in malaria-endemic provinces of South Thailand, including Ranong, Chumphon and Phang-nga (Fig. 3-A4). Most rubber tappers who are foreign migrant workers are more likely to practice rubber tapping that starts before midnight, whereas the local Thai rubber farmers normally start work at approximately 3:00 a.m.; however, these schedules differ between farms.

Additionally, rubber tappers in the MRPs attribute sleeping-under-net (SUN) behaviors of occupational exposures to malaria risks. SUN behaviors are the desired actions displayed by a person or any household member that sleeps...
under a mosquito net in the desired manner. This practice can reduce mosquito-human contact by avoiding or protecting the person from endophagic of malaria-infected Anopheles mosquitoes at night. SUN behaviors also result from increasing knowledge, attitude, awareness, belief and perception surrounding malaria infection. Not all of the rubber tappers have the same sleeping hours or use mosquito nets at night during seasonal rubber tapping. Regardless of the ownership and intra-household allocation of mosquito nets, including ITNs/LLINs, two common SUN-related factors, which include night-time sleeping hours and use of mosquito nets, can be measured as person-time sleeping hours between 6:00 p.m. and 6:00 a.m. With this measure, SUN behaviors can fall into three categories: no exposure, semi-exposure or positive exposure to malaria-carrying Anopheles vectors (Fig. 6A).

Similar to other portions of the population that have no occupational risks, rubber tappers that have no-exposure to malaria have long sleeping hours generally from sunset to early morning. There are two common reasons for rubber tappers to sleep in this pattern: (i) a dry season during which the rubber trees have no or little sap; (ii) a heavy rain during which rubber tapping is delayed until the morning. Then, the rubber tappers have no or little contact with malaria-carrying Anopheles vectors. Those who practice rubber tapping either in the early night to obtain coagulated rubber or in the early morning to harvest fresh rubber will have a semi-exposure or probable contact with malaria-carrying Anopheles vectors. Regarding exposure to malaria, those who normally practice rubber tapping during the night, both before and after midnight, will have a high probability of contact with malaria-carrying Anopheles vectors. Moreover, based on the 13- to 16-year yield expectancy of rubber trees, the different maximal yields of rubber are also due to differences in optimal rubber tapping patterns, i.e., daily, every 2–3 days or 2–3 consecutive days after a day of recovery. These varying rubber-tapping exposures will lead to the exacerbation of malaria transmission unless rubber tappers perform protective behaviors.

MRPs in South Thailand and other regions

In many rubber plantations in South Thailand, rubber tappers practice more frequent nighttime rubber tapping during harvest season when there are increased numbers and densities of An. minimus and An. maculatus. Klungwang et al demonstrated that in malaria-endemic areas of rubber plantations in the Trang province of South Thailand, the seasons regulate species diversification and produce an abundance of Anopheles mosquito larvae and adults. Both larvae and adult populations of An. minimus and An. maculatus are predominantly found in rubber plantations at shaded breeding sites as well as in nearby households between the dry and wet seasons. Additionally, the secondary vectors, such as Anopheles aconitus and Anopheles barbirostris, can breed their progeny in malaria-endemic areas of the rubber plantations in the dry season. For the potential transmission of malaria in the MRPs, the anthropophagous An. minimus and An. maculatus vectors seem to forage aggregately with host-seeking exophagy and endophagy after sunset (06:00 p.m.) and until early morning (05:00 a.m.) regardless of the seasonal variation. Their blood-feeding time is 08:00–11:00 p.m., with a maximal peak at approximately 09:00 p.m. However, there exist differences in abundance and dispersion. An. minimus has higher numbers and average man-biting rates, which is defined as bites per person per night (1.6 for dry season and 10.5 for wet season), compared to An. maculatus (0.4 for dry season and 2.9 for wet season).

Sorosjinda-Nunthawarasil et al also demonstrated that in malaria-endemic areas of rubber plantations in Kanchanaburi (Fig. 7A), both the primary vectors (An. dirus, An. minimus and An. maculatus) and secondary An. aconitus vector engage in aggregating forages of human blood meals. The man-biting rate is 6.2 regardless of the Anopheles species. Of note, An. minimus and An. dirus have the propensity for exophagy with a maximal peak approximately 09:00 p.m. Similar observations in the Trat province (Fig. 3A3 and Fig. 7B), for both anthropophilic An. minimus and An. dirus, which are both endogenous to rubber plantations, show that more exophagous than endophagous feeding occurs after sunset until midnight. The man-biting rate is 8.8 regardless of the Anopheles species. Taken together, the potential transmission of malaria on rubber plantations does not seem to be dependent on the abundance of Anopheles vectors but rather is significantly related to the infection and infectivity. However, the dry season has a relatively low number of anthropophagous Anopheles vectors but they can still potentially transmit malaria through their infective bites.

Future perspectives

In many endemic countries implementing global malaria control strategies, most investigations have established the coverage and determinants of the use of ITNs/LLINs in at-risk populations, particularly addressing knowledge of the disease as well as attitudes and practices, awareness, perception, ownership, and intra-household allocation of devices. Obviously, the use of ITNs/LLINs often applies to any family member who owns or shares ITNs/LLINs and assumes that all household members sleep under nets during the night because most people living in malaria-endemic settings are at risk due to night-time mosquito bites inside the home. In contrast, the household-level implementation of the ITNs/LLINs, even in combination with IRS, might not be effective against malaria in MRPs due to either human movements on rubber farms or at-risk persons revisiting rubber plantations during or after work hours. These occupational exposures result in an increased malaria risk. In spite of the fact that the household settings in MRPs have full access to the IRS and ITNs/LLINs, the vulnerable groups do not always practice protective actions against either endophagous or exophagous Anopheles vectors. In summary, rubber tappers have relatively short person-time sleeping hours during the night but have long work hours with increased exposures to malaria. If a rubber plantation is considered a long-lasting agricultural practice in the producing countries, we should better understand how rubber forestry is associated with malaria. We will also need to explore how land cover/land use changes relating
to rubber plantations and other forested plantations and human outdoor activities can shape malaria transmission dynamics.

Conflict of interest

None declared.

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