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PEER REVIEWED ARTICLE

Felling trees, furthering malaria: links between deforestation and disease in developing nations

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Abstract

Malaria represents a leading illness and cause of death throughout areas of the Global South. Since malaria is transmitted through the bite of the Anopheles mosquito, environmental conditions are paramount in understanding malaria vulnerabilities. A burgeoning area of research connects anthropogenic deforestation and subsequent land-use changes to the expansion of mosquito habitats and malaria outbreaks. This paper explores those literatures, and also examines the drivers of deforestation in the Global South to demonstrate how population pressures, agricultural production, and rural migration patterns underlie motivations for deforestation and land transformation in poorer countries.

Keywords: Malaria; deforestation; land-use change; rural migration; population growth

Introduction

Malaria is a parasitic disease that has plagued human societies throughout history, and continues to represent a major threat to health and well-being today. In 2017, there were over 219 million cases of malaria, including nearly 500,000 deaths (WHO, 2019). The majority of deaths from malaria are among infants, children, and pregnant women. In fact, malaria claims the life of a child under the age of 5 years every two minutes (WHO, 2019). The continued impact of malaria is somewhat of a conundrum, as malaria represents a preventable and curable infection. However, new trends in antibiotic resistance may threaten this claim. As the female *Anopheles* mosquito transmits malaria to humans, changes to the environment are also paramount in facilitating new and continued vulnerabilities (e.g. Yasuoka and Levins, 2007).

Nearly half of the world's population is at risk of malaria (WHO, 2019). Most malaria cases and deaths occur in Sub-Saharan Africa, but regions of Latin America, South-East Asia, the Eastern Mediterranean, and the Western Pacific also represent malaria hotspots. Ninety countries currently have ongoing malaria transmission (WHO, 2019). Although recent decades have wrought significant gains in controlling malaria and preventing deaths, there are clear signs that these trends are reversing. While malaria rates declined from 2000 to 2015, in the most recent years, rates of incidence have increased. According to the latest World Malaria Report, released in November 2018, there were 219 million cases of malaria in 2017, up from 217 million cases in 2016 (WHO, 2019). The re-emergence of malaria is likely tied to many different factors, such as persistent poverty, insecticide resistance, and perhaps, most notably, anthropogenic environmental change (e.g. Pattanayak et al., 2006).

As mosquitoes represent the disease vector for malaria, malaria vulnerabilities are deeply connected to environmental conditions. Even seemingly minor changes to the environment and local ecologies can have profound impacts on mosquito habitats, breeding cycles, biting rates, and other factors that affect malaria transmission. Over the last two decades in particular, a wealth of research from the fields of public health, epidemiology, and entomology have focused on deforestation and land-use change in explaining heightened malaria susceptibilities for rural populations. This article will explore this vein of research highlighting the factors and diverse processes that link forest loss to malaria.

These factors include alterations to landscapes and local ecologies, changes to the availability or composition of water at breeding sites, and influxes of migrant labor. Furthermore, a focus on the causes of deforestation in developing nations illuminates how population pressures and rural migration patterns spur forest loss and heighten vulnerabilities to malaria for marginalized rural populations. Although growing urban populations and export agriculture operations are often implicated as key drivers of forest loss in the Global South, closer examination reveals these as distal causes that shape rural migration to forest frontier zones. The populations most at risk for frontier migration are also among the most vulnerable to malaria due to their poor socio-economic status and lack of access to healthcare.

Malaria: a parasitic and pervasive disease

Malaria is caused by *Plasmodium* parasites. There are five parasite species that cause malaria in humans, with *Plasmodium falciparum* and *Plasmodium vivax* representing the most common parasite strains (WHO, 2019). These species of parasites have distinct regional zones, as *P. falciparum* is responsible for the overwhelming majority of malaria cases in Sub-Saharan Africa and South-East Asia, and *P. vivax* is most common in the Americas (WHO, 2019). *Plasmodium* parasites rely on two hosts throughout their lifecycle: a mosquito and a human (or another mammal) (Mayxay et al., 2004). Only around 30 of the 400 different species of *Anopheles* mosquito can act as vectors for the parasite, and only the bite of a female *Anopheles* mosquito spreads the parasite from one person to another (Mayxay et al., 2004; Neafsey et al., 2015; WHO, 2019). The different types of malaria parasites cause different variations of the disease in humans, with some forms being milder than other strains. Just as the type of parasite species varies by region, different types of *Anopheles* mosquitoes tend to transmit the parasites on different continents. For example, *Anopheles gambiae* is the main vector for malaria in Africa, while *Anopheles darlingi* is the key mosquito associated with malaria transmission in the Americas (WHO, 2019).

The key malaria vector mosquito species tend to be most active between dusk and dawn. *Anopheles* mosquitoes lay their eggs in still or slow-moving water bodies. Eggs become larvae and eventually transform into adult mosquitoes. While male mosquitoes are essentially pollinators that feed solely on plant matter, the female mosquitoes also need blood to nurture and feed their eggs (Mayxay et al., 2004; Neafsey et al., 2015; WHO, 2019). Rainfall patterns, temperature, and humidity also impact the number, survival rates, and breeding activity of mosquitoes (e.g. Norris, 2004); transmission generally accelerates in warm, wet places where the mosquito lifespan is longer.

Human immunity represents another important factor affecting whether or not malaria is acquired, and, if so, the severity of the illness. Individuals that have been exposed to malaria several times throughout their life can acquire partial immunity that reduces the chance of severe disease and death (WHO, 2019). For this reason, most malaria deaths occur in young children and among populations that have not been previously exposed to the disease.

Malaria causes fever and flu-like symptoms, including chills, nausea, vomiting, and aches or joint pains (CDC, 2019; WHO, 2019). Symptoms manifest around one to two weeks after the infected mosquito bite. During this incubation time, an *Anopheles* mosquito can bite an infected human and transmit the parasite to another. Especially among youth and non-immune groups, malaria can quickly lead to death. For example, in infants, some deaths have been recorded just 18 hours after initial symptoms appeared. If untreated, malaria leads to severe anemia, respiratory distress in relation to metabolic acidosis, and cerebral malaria, where there is inadequate blood flow to the brain and other vital organs, leading to permanent disability, even if the malaria is eventually able to be treated effectively (CDC, 2019; WHO, 2019).

Early diagnosis of malaria is essential for management of the disease and prevention of death (CDC, 2019; Stratton et al., 2008; WHO, 2019). Microscopy and rapid diagnostic tests are the most common and effective ways of diagnosing the disease (WHO, 2019). However, these methods may be inadequate, especially in poor areas that often lack sufficient expertise, health personnel, and diagnostic equipment (e.g. Bates et al., 2004). Currently, there are many drugs available to combat the infectious parasite, but reduced effectiveness and antibiotic resistance represent major limitations. The most effective and popular drug consists of artemisinin combination treatments (ACTs) (WHO, 2019). Other drug treatments, including quinine and chloroquine, are now largely ineffective at treating malaria due to the development of resistance. In addition, recent studies document increased tolerance to ACTs in many regions, leading to concerns over the potentials of widespread antibiotic resistance (e.g. Hastings and Ward, 2005; WHO, 2019).

Both the malaria parasites and the *Anopheles* mosquitoes that carry them are highly adaptable and resilient species. Their resilience in part explains why malaria has been a leading cause of death among humans for centuries, if not millennia. In fact, the first evidence of malaria parasites was found in mosquitoes preserved in amber from the Paleogene period approximately 30 million years ago. While malaria is an "old" disease, current transformations to the environment may be producing "new" vulnerabilities, including expanding mosquito habitats, intensifying biting rates, and exposing fresh populations that lack immunity and appropriate access to primary health care.

Links between deforestation and malaria

Human transformations to the environment have become so immense that the current geological age is now denoted the "Anthropocene". Forest loss represents one of the most significant global environmental problems, as new estimates now assert that since humans started cutting down forests, around 50% of all trees have been felled (National Geographic, 2018). Global tree cover loss reached a record 29.7 million hectares (or 73.4 million acres) in 2016. The loss is 51% higher than the previous year, totaling an area about the size of New Zealand (Weisse and Goldman, 2017). Deforestation contributes to other environmental concerns, including global climate change and biodiversity loss. Additionally, the felling of trees impacts human well-being, especially as deforestation is linked to furthering malaria vulnerabilities in a wide range of studies (e.g. Norris, 2004; Lima et al., 2017; Yasuoka and Levins, 2007; Vittor et al., 2006, 2009).

Clearing forests alters local ecosystems in a variety of ways, including changing local temperatures, soil conditions, water resources, and the ecology of flora and fauna. These modifications can have a notable impact on mosquito habitats, lifecycles, and behaviors. Additionally, deforestation predominantly involves the conversion of forest land to agriculture and livestock grazing areas (FAO, 2018), and these activities also influence the mosquito disease vector in a variety of ways. While the number of studies exploring such links have burgeoned over the last few decades, the observed connection between forest loss and mosquitoes was articulated over 50 years ago; Livingstone (1958: 554) comments that "it is only when man cuts down the forest that breeding places for *A[nopheles] gambiae* become almost infinite." Other researchers also illustrate links between land cover change and malaria outbreaks at much earlier points in human history, such as in Ancient Rome (e.g. O'Sullivan et al., 2008).

Current studies examining the links between forest loss and mosquitos generally utilize a mix of satellite or remote sensing data to ascertain forest loss. This typically is combined with entomology data that measure mosquito larvae, the presence of parasites, or biting rates, as well as epidemiological data or secondary data on malaria cases, often gathered from local health centers or through direct malaria microscopy testing. Much of this research is conducted in areas of the Brazilian or Peruvian Amazon (e.g. Barros et al., 2015; Hahn et al., 2014; Vittor et al., 2006, 2009; Yanoviak et al., 2006), as well as other areas in South America, Sub-Saharan Africa, and South East Asia (e.g. Afrane et al., 2008; Basurko et al., 2013; Bonneaud et al., 2008; Himeidan et al., 2012; Kweka et al, 2016; Nath et al., 2012; Saxena et al., 2014; Vanwambeke et al, 2007). While these types of studies are typically concentrated in isolated areas within specific countries or regions, the consistencies of the findings across geographic zones speak to the existence of larger-scale patterns. A few cross-national studies linking deforestation rates to malaria incidence support this claim (e.g. Austin, 2013; Austin et al., 2017); however more cross-regional studies of forest loss and the incidence of mosquitoes or malaria would greatly contribute to the generalizability of these findings.

The processes linking forest loss to malaria vulnerabilities are diverse but, fundamentally, many studies find that there are more malaria parasites or mosquito larvae in deforested areas or areas on the forest fringe (the edge of deforested areas) in comparison to areas of intact forest (e.g. Barros et al., 2015; Bonneaud et al., 2008; Caldas de Castro et al., 2006; Nath et al., 2012; Olson et al., 2010; Saxena et al., 2014; Vanwambeke et al, 2007; Wayant et al., 2010). Deforestation's impact on local temperatures is a subject of detailed examination in current research. As forest cover is lost, temperatures increase, and generally, the incubation period of malaria parasites and the speed of larval development is inversely correlated with temperature (Afrane et al., 2008, 2012; Kweka et al, 2016; Himeidan et al., 2012; Nath et al., 2012; Patz et al, 2006). Amazingly, a mere half-degree centigrade increase in temperature can translate into a 30% to 100% increase in mosquito abundance (Pascaul et al., 2006). For example, Afrane and colleagues (2008) find that the overall parasite infection rate of mosquitoes in deforested sites is greatly increased compared with that in forested sites. Overall, due to changes in temperature and humidity, vectorial capacity in the Kenyan highlands is estimated to be 77.7% higher in the deforested sites than in the forested sites (Afrane et al., 2008).

Other studies have found that indoor temperatures increase in dwellings located in deforested and frontier zones (e.g. Afrane et al., 2012; Himeidan et al., 2012; Kweka et al, 2016). A rise in indoor temperatures attracts more mosquitos into dwellings at night during prime biting hours, and can also increase the biting rates of mosquitoes (Afrane et al., 2012; Kweka et al., 2016). An increase in biting frequency means that mosquitoes feed more frequently on humans and, thereby, enhance rates of malaria transmission, potentially exponentially.

Vittor and colleagues (2006) arrive at a similar conclusion in their research conducted in the Peruvian Amazon. They tested fifty-six sites with varying degrees of deforestation over several weeks and found that *Anopheles darlingi* was captured in the greatest quantities at sites with little remaining forest. Furthermore, deforested sites had biting rates that were more than 278 times greater than in areas that were predominantly forested (Vittor et al., 2006).

In addition to a rise in outdoor and indoor temperatures, researchers highlight other processes connecting deforestation to malaria risk. Many emphasize that water mediates the relationship between deforestation and malaria, and that felling trees greatly impacts aquatic environments that promote mosquito development (e.g. Barros et al., 2015). For example, puddles, ponds, and slow-moving streams that exist under thick forest canopy are too heavily shaded for mosquitos and tend to be highly acidic, as much organic debris, such as falling leaves, lands in such pools. But water pools in deforested areas and frontier zones have greater exposure to sunlight and a lower level of acidity, raising numbers of mosquito eggs and larvae (e.g. Norris, 2004). While completely sun-exposed ponds are generally not preferred by mosquitoes, researchers have found that semi-shaded ponds in frontier zones or on forest fringes have elevated levels of mosquito larvae (e.g. Barros et al., 2015). Micro dams, that slow or stop water flow, are also created when fallen trees obstruct streams and rivers, and represent prime mosquito habitats (e.g. Barros et al., 2015). Thus, felling trees can expose ponds and streams to the correct amount of sunlight and potentially expand mosquito habitats (e.g. Norris, 2004).

It is important to emphasize that deforestation simply represents the first step in a series of land-use changes, and that population growth and expansions in agriculture represent the prime motivation for deforestation in most areas (e.g.

Confalonieri et al., 2014; FAO, 2018; Hahn et al., 2014; Norris, 2004; Pattanayak et al., 2006; Saxena et al., 2014). The secondary growth that is created by crops and plantations often affords mosquitos habitats with the right level of shade and protection, and many studies have found an abundance of mosquito larvae in recently deforested agricultural areas (e.g. Basurko, et al., 2013; Yanoviak 2006; Vittor et al., 2006, 2009). Additionally, agricultural production leads to the creation of dams, irrigation systems, ditches, and roads, all of which greatly expand the availability of standing water, thereby proliferating mosquito breeding sites, with a resultant rise in malaria rates (e.g. Basurko, et al., 2013; Bauch et al., 2015; Confalonieri et al., 2014; Hahn et al., 2014; Silva-Nunesa et la., 2012; Yanoviak et al., 2006). Selective logging also provides the right mix of sun and shade that mosquitoes prefer, leading to significant increases in malaria incidence in nearby populations (e.g. Hahn et al., 2014). Remarkably, mosquito eggs and larvae can develop in just a few millimeters of water, thus fallen plant parts, tree-holes (left-behind rotted out stumps), and even the hoof-prints of cattle can quickly become prime mosquito environments (e.g. Norris, 2004; Yanoviak et al., 2006).

Certainly, the proximity of humans and human residences in relation to mosquito habitats shape malaria vulnerabilities (e.g. Vanwambeke et al, 2007). Malaria epidemics can occur when environmental conditions suddenly favor habitat proliferation and hence transmission (WHO, 2019). They also can occur when people with low immunity move into areas with intense malaria transmission, for instance to work on agricultural plantations or cattle ranches. Many studies illustrate the link between deforestation and malaria incidence as facilitated by the migrant workforce, who often come from other rural areas or urban centers, and thus have limited or no immunity to malaria (e.g. Barbieri et al., 2005; Basurko, et al., 2013; Bauch et al., 2015; Pattanayak et al., 2006). For example, Barbieri and colleagues (2005) find that malaria cases in Brazil are often concentrated among work-age males, defying traditional trends in this disease where infants, children, and pregnant women typically are most vulnerable. Indeed, rates of malaria in the Amazon are often highest among migrant workers, and the high mobility of migrant workers also increases the potential spread of malaria to additional populations. They argue that rural settlement areas are susceptible to the outbreak of malaria in their initial stages due to the intense contact between settlers and mosquitoes, especially during land clearance activities (Barbieri et al., 2005).

Migrant agricultural workers also face other sources of susceptibility. They tend to live in poorly constructed or temporary dwellings that do not provide barriers to mosquitoes at night (Barbieri et al., 2005; Basurko, et al., 2013). They are often without mosquito nets, the main form of malaria prevention during nighttime hours (Basurko, et al., 2013). Similarly, many migrant settlements have outdoor kitchens and living spaces, where workers gather at dusk and after dark when *Anopheles* mosquitoes are most active. Furthermore, non-immune migrant workers typically work in remote areas that lack health centers and basic public health infrastructure. Thus, there can be significant delays between contracting malaria and getting adequate medical intervention, which only increases the possibilities of transmitting the disease to others when mosquitoes bite those with active symptoms (Barbieri et al., 2005; Bauch et al., 2015).

Humans can also affect malaria vulnerabilities in newly established agricultural areas and frontier zones in other ways. For example, many note the importance of fish ponds in facilitating close human-mosquito interactions; studies in areas of the Brazilian Amazon link environmental changes wrought by the emerging local aquaculture industry to increased malaria risk (e.g. Olson et al., 2010; Lima et al., 2017). Farmers and local populations often establish water collection sites and fish ponds in semi-shaded areas very near settlements for convenience, but this creates mosquito breeding sites very close to where humans reside (e.g. Bauch et al., 2015). Indeed, some primary deforestation is done specifically to create areas for fish ponds and wells (e.g. Olson et al., 2010; Lima et al., 2017). Although fish can eat mosquito larvae, these studies clearly document that fish pools tend to have very large populations of larvae, and that the fish are not effective in quelling mosquito populations. For example, Olson and colleagues (2010) find that ponds, wells, and fish farms larger than 50 meters in circumference have a significant abundance of *Anopheles darlingi* larvae. Similarly, Vittor and colleagues (2006) find that large ponds and fish farms surrounded by some secondary vegetation were the most common *A. darlingi* breeding sites, and also that mosquito biting rates are especially high in the deforested zones near established fish ponds.

Some researchers carefully point out that during and in the immediate years after deforestation, mosquito larva numbers, parasite levels, or malaria cases tend to be very high, but can then fall off after a site has been completely cleared for many years (e.g. Barros et al., 2015; Caldas de Castro et al., 2006; Guerra, Snow, and Hay, 2006; Olson et al., 2010). For example, Caldas de Castro and colleagues (2006) argue that rates of malaria begin to decline and remain low about 10 years after complete forest removal. Indeed, the bulk of this research emphasizes that "frontier" zones on the edge of deforested areas or forest "fragments" pose the highest risk (e.g. Lima et al., 2017). As mentioned briefly earlier, this is due to the fact that mosquito larvae do not prefer fully exposed sun-lit areas (e.g. Barros et al., 2015). However, it is important to stress that most areas that are deforested are subsequently used for agriculture and ranching, which do tend to create prime mosquito habitats and introduce non-immune populations. Furthermore, areas that are deforested and left fallow eventually become areas of secondary re-growth, fostering additional mosquito breeding sites, given the shrub and semi-shade conditions that eventually emerge (e.g. Barros et al., 2015; Nath et al., 2012; Vittor et al., 2009).

It should also be acknowledged that not all studies find a link between land cover change and malaria, as some demonstrate no link or point out that deforestation may decrease malaria rates over the long-term, as explained above. Inconsistencies in the literature may be due to differences in research methods, land change definitions, study approach or design, scale, or locational focus (Lima et al., 2017). However, the body of research that asserts clear links between deforestation and malaria is large and growing, and far exceeds the limited number of studies that find no demonstrable link (e.g. Lima et al., 2017).

Trends and causes of deforestation in developing nations

Zones where malaria is endemic are also areas that face some of the highest rates of deforestation, including tropical and sub-tropical regions of Sub-Saharan Africa, Central and South America, and South East Asia (e.g. FAO, 2018). Deforestation is not a natural phenomenon, but rather results predominantly from human activities. The main causes of deforestation in developing nations include expansion in agriculture, fuel wood consumption, livestock ranching, logging, and infrastructure, such as road creation (e.g. FAO, 2018; Population Action International, 2011). It is important to note that these proximate causes tend to vary across regions. For example, logging is very prominent in S.E. Asia, while cattle ranching characterizes many areas of South America, and fuel wood consumption is highest in Sub-Saharan Africa, particularly East Africa (e.g. Carr, Suter and Barbieri, 2005; FAO, 2018; Rudel, 2005). However, agricultural development characterizes each of these areas and is often emphasized as the main driver of forest loss globally (e.g. FAO, 2018; Population Action International, 2011). Certainly, overpopulation and population growth underlie each of these causes. Population pressures on forests in rural areas can manifest in both direct and indirect ways, as will be explained below (e.g. Carr et al., 2005; Rudel, 2005).

The total world population is expected to increase from 7.6 billion to 10 billion by 2050 and global demand for food is also expected to increase by 50% during this period (FAO, 2018). The nations with the highest rates of forest loss tend to have large populations and high population growth rates, such as in Brazil, Indonesia, DR Congo, and Nigeria (FAO, 2018). Fertility rates remain high among many poor nations, especially for rural residents that live on forest frontiers; for example, family sizes in rural areas of the Global South commonly exceed 7 children (Carr et al., 2005; Clark, 2012). Also, many Sub-Saharan African nations in particular have an extreme "youth bulge" where over 50% of the population is under the age of 18. Such demographic patterns will increase the momentum of population pressures on forests.

Small frontier farmers who live on the edges of forested expanses drive the bulk of deforestation in less-developed nations for settlement and food production (Carr et al., 2005; Lopez-Carr and Burgdorfer, 2013). Subsistence farmers have big families, and large household sizes put immediate pressure on forests (Dolisca et al., 2007; Rudel, 2005). Indeed, many researchers point out that despite increases in commercialized agriculture in developing nations, it is small-scale and subsistence farmers that are responsible for the bulk of direct forest felling (Carr, 2009; Lopez-Carr and Burgdorfer, 2013). While rural to urban migration and upwards trends in urbanization are significant, as will be discussed in more detail below, there is a notable and often overlooked level of rural-to-rural migration which puts extreme burdens on forests (e.g. Carr 2009; Rudel, 2005).

Indeed, the highest rates of fertility and household-level population growth will continue to occur among rural people living in or on the edges of forests. Rural or subsistence farmers in less-developed nations are typically poor and rely on cleared land for household food production (e.g. Dolisca et al., 2007; Rudel, 2005). Their agricultural production is expansive rather than intensive, due to a lack of money to afford fertilizers or farm machinery and the ample availability of household labor (Lopez-Carr and Burgdorfer, 2013). As household size continues to increase and soils slowly become depleted over time, these rural families move or expand farm areas, deforesting in order to maintain and expand yields (Clark, 2012; Dolisca et al., 2007; Kong et al., 2019; Lopez-Carr and Burgdorfer, 2013).

These populations are often termed "frontier migrants", and although logging industries or commercial agriculture firms are most often implicated as the main culprits in global forest loss, it is these small-scale farmers that are directly responsible for the highest levels of actual felling, especially in tropical and old-growth forests (e.g. Carr, 2009; Lopez-Carr and Burgdorfer, 2013; Kong et al., 2019). As children mature in frontier households, they follow the examples of their parents and expand to new areas to support their growing families (e.g. Carr et al., 2005). Rural frontier migrants tend to be poor, have low levels of education, and have very limited wage labor prospects, thus they aim to establish new farmlands as a source of household security and resource provision (Carr, 2009; Kong et al., 2019; Rudel, 2005). Indeed, the most pressure is put on forests when rural population growth is high and households are poor (Jha and Bawa, 2005).

Although rural population growth overall has declined over the years, largely due to migration to urban areas within developing nations, deforestation rates have remained steady or even increased in most developing nations. In fact, the World Resources Institute reports that 2017 was the second-worst year on record for tropical forest loss (Weisse and Goldman 2018). These trends suggest that even amid declining rural population levels, the rate of forest-clearing per farmer has increased (Lopez-Carr and Burgdorfer, 2013). This is likely due to increased land fragmentation, land consolidation, and heightened soil depletion, facilitating rural-to-rural migration to new areas by established households or second-generation households (e.g. Carr, 2009; Kong et al., 2019' Lopez-Carr and Burgdorfer, 2013; Rudel, 2005).

Many researchers also note the importance of land tenure insecurity in promoting deforestation among rural farmers (e.g. Dolisca et al., 2007; Lopez-Carr and Burgdorfer, 2013; Rudel, 2005). Frontier migrants moving to new areas deforest in order to make claim to land in regions where there are no formal regulations or land titles, or in areas where land ownership is loosely regulated. Those without land titles are thus pressured to convert forested land to agriculture as fast as possible, leading to rapid felling. Rural people without land titles are more likely to migrate to new areas on the forest frontier in comparison to rural subsistence farmers with land titles (Carr, 2009).

Urbanization and agricultural commercialization or agricultural exports are also recognized as key drivers of deforestation in developing nations, albeit indirectly. Indeed, consumption levels of forest products, such as food and timber, are growing globally, and most of this consumption takes place in urban centers or developed nations far from the sites of forest loss in rural areas of the Global South (e.g. Carr et al., 2005; DeFries et al., 2010). However, this remote demand remains significant. Growing urban populations may be less dependent on solid fuels, but still demand food, and the diets of urban residents are increasingly reliant on meat, which creates elevated forest resource pressures (Carr et al., 2005; DeFries et al., 2010). Researchers emphasize that large-scale cattle ranchers and commercialized agricultural firms may not be responsible for as much primary deforestation as it seems, but rather, are significant in pushing out small-scale rural peasants who have already deforested (e.g. Carr, 2009; Carr et al., 2005; Lopez-Carr and Burgdorfer, 2013). As lands become consolidated and sold off to large-holders, this indirectly motivates deforestation by pushing frontier farmers into new unclaimed areas where they initiate primary forest loss to re-establish production and gain tenure to land (e.g. Carr et al., 2005; Lopez-Carr and Burgdorfer, 2013). In this way, political-economic or core-periphery relationships, related to the acquisition of environmental space in poorer nations to support consumption levels in more affluent areas globally, do play an important role in promoting deforestation in less-developed nations, though this is hard to quantify or measure directly.

Conclusion

The World Health Organization (2016) estimates that nearly a quarter of all deaths worldwide are due to environmental causes. As rates of environmental degradation and transformation continue to grow in scale and scope, this impact is only likely to intensify. Zoonotic diseases, or diseases that affect both humans and insects or other animals, will likely be of growing concern in the coming decades as population growth, increased food consumption levels, and resulting environmental degradation expand human interactions with potential disease pathogens. Malaria, often a disease that is “forgotten” among affluent populations, is experiencing a resurgence, in part due to human impacts on the natural environment that expand potential mosquito habitats and influence biting behaviors.

This paper brings to light a large and growing body of research that links deforestation to malaria epidemics in poor nations. Research has demonstrated that forest loss can lead to heightened malaria vulnerabilities through a number of mechanisms, such as raising indoor and outdoor temperatures, increasing the availability of mosquito breeding sites, and introducing migrant worker populations that lack malaria immunity into endemic regions. Many of these mechanisms necessarily concern establishing water or altering current water sources in ways that proliferate mosquito larvae, such as creating standing water through micro dams, irrigation ditches, road building, crop residues, tree holes, or wells and fish ponds. Overall, this research finds that "frontier zones" located on the edge of deforestation sites, agricultural sites, areas of secondary re-growth, and selective logging in particular offer the right mix of sun, shade, still water sources, and nearby human settlements necessary to increase malaria parasite levels and disease transmission (e.g. Lima et al., 2017).

Deforestation is caused by population pressures by people both near and far from forested areas in malaria-endemic nations (e.g. FAO, 2018). A number of studies emphasize that it is poor, rural frontier migrants that are most directly responsible for felling trees and living on forest fringes (e.g. Carr, 2009; Kong et al., 2019; Lopez-Carr and Burgdorfer, 2013). It should be emphasized that these marginalized populations are among the least educated, have the highest fertility rates, and are likely to have very limited access to basic health resources. Thus, rural people that live nearest to deforestation sites where malaria vulnerabilities are highest due to entomological and ecological factors are also those that face the highest demographic and socio-economic vulnerabilities to the disease. While commercial agricultural producers and ranchers are likely contributing to forest loss indirectly by displacing rural families, these large farms are also often located on forest fringes, can encourage mosquitoes in other ways (e.g. irrigation, road building), and bring in migrant workers who lack immunity to malaria or proper access to healthcare. Thus, it is important to emphasize that patterns in deforestation and land use in developing nations serve to not only further mosquito habitats, but also invite populations who are most at risk of acquiring and succumbing to malaria.

Despite significant improvements in malaria prevention, diagnosis, and treatment over the last several decades, global malaria rates are now rising and this disease remains a leading cause of death in many areas of the Global South (WHO, 2019). In addition to deforestation, many scholars note potential influences of climate change in spreading mosquito habitats (e.g. Pattanayak et al., 2006). Heightened environmental change and population dynamics in rural areas, coupled with increasing insecticide and antibiotic resistance, likely mean that concerns over malaria and other mosquito-borne diseases are only going to magnify in the coming decades. Undoubtedly, understanding and mitigating the underlying anthropogenic causes of malaria transmission deserves vigilant attention.

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