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Deforestation, malaria, and poverty: a call for transdisciplinary research to support the design of cross-sectoral policies

Subhrendu Pattanayak^{1*}, Katherine Dickinson², Catherine Corey³, Brian Murray⁴, Erin Sills⁵, & Randall Kramer²

¹ Public Health and Environment, RTI International, 3040 Cornwallis Road, PO Box 12194, Research Triangle Park, NC 27709 USA (email: subhrendu@rti.org)

² Nicholas School of the Environment and Earth Sciences, Duke University, Box 90328, Durham, NC 27708 USA

³ The Center for Studying Health System Change, 600 Maryland Avenue SW, #550, Washington, DC 20024 USA

⁴ Nicholas Institute for Environmental Policy Solutions, Duke University, Box 90328, Durham, NC 27708 USA

⁵ Department of Forestry and Environmental Resources, North Carolina State University, Box 8008, Raleigh NC 27695 USA

Many of the world's poorest people live in areas with high malaria rates and suffer the associated physical, economic, and social hardships. These same areas are often undergoing extensive forest conversion and degradation. While causality has generally not been established, the scientific literature makes it abundantly clear that the juxtaposition of deprivation, deforestation, and disease is not pure coincidence. We chart a course for using transdisciplinary research to develop more effective policies to control malaria, protect forests, and alleviate poverty. First describing the malaria problem, including its etiologic roots and its social toll, the paper then examines some shortcomings of contemporary societal responses. We discuss why understanding the role of deforestation in linking malaria to poverty is important and present the mixed empirical evidence on the malaria-deforestation-poverty link from macro- and micro-economic studies. The paper concludes with a proposal for strategically linking research and policy at the malaria-deforestation-poverty nexus in a comprehensive decision-analysis framework that channels research to the most pressing policy needs, informs policy with the most conclusive research, and ensures stakeholders are effectively informed about their options.

KEYWORDS: deforestation, malaria, antipoverty programs, economic conditions, health policy, environmental policy, developing countries

Introduction

Many of the world's poorest people live in areas with high malaria rates and suffer the resulting physical, economic, and social hardships (see Figure 1). Many of these same locales are also undergoing rapid and extensive forest conversion and degradation (see Figure 2). Despite the investment of billions of dollars in policies to slow deforestation, eradicate malaria, and foster economic development, about a third of the world's population (2 billion people) live in malaria-infected areas, deforestation continued at the rate of 16 million hectares annually throughout the last decade, and about half the world's population lives on less than US\$2 per day. More people currently die from malaria than was the case forty years ago. The illness is a "reemerging" threat due to its expanded distribution, heightened local incidence, and increased severity, duration, and resistance to treatment (Wilcox & Colwell, 2005; Greenwood et al. 2005). Recognizing that we live in a global society in which ecological, epidemiological, and economic

phenomena truly connect us all, we take seriously the challenge put forward by Guerin et al. (2002) that we "cannot ignore the strategic and moral imperative of alleviating the suffering of a significant number of the world's people."

The design and implementation of policies to combat malaria and to mitigate its consequences require clear understanding of the interrelations between deforestation, poverty, and malaria and the cross-effects (or unintended side effects) of policies targeting each of these three problems. For example, how do deforestation policies affect malaria and poverty? While causality still remains elusive, the scientific literature makes it abundantly clear that the juxtaposition of deprivation, deforestation, and disease cannot be dismissed as pure coincidence. Therefore, more rigorous research and evaluation methods are necessary to better comprehend the complex relationships among these factors and to identify causes and effects that public policy and private action can mitigate. Toward that end, we argue that policy options for malaria control would be enhanced by the appli-

*Corresponding Author

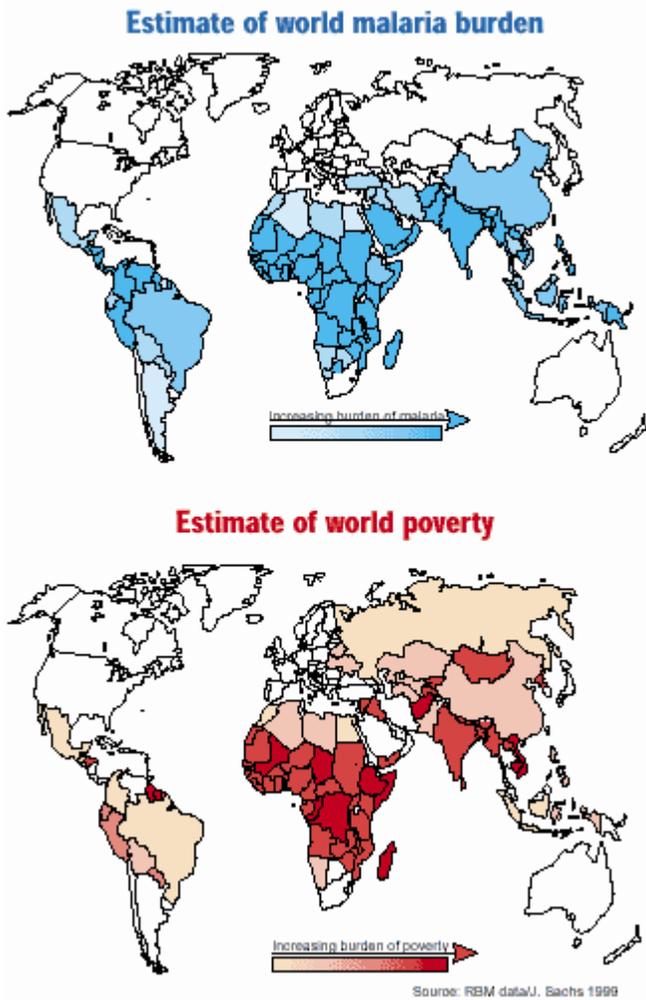


Figure 1 Malaria and poverty in 1995 (WHO, 2001)

cation and dissemination of transdisciplinary research that integrates economics, ecology, and epidemiology to examine the critical nexus of malaria, deforestation, and economic development.

This paper charts a course for using transdisciplinary research to develop more effective policies to control malaria, protect forests, and alleviate poverty. We are not alone in advocating an approach that recognizes the interrelationships among ecology, human behavior, economics, epidemiology, physical processes, and other factors (e.g., Parkes et al. 2003). Kates et al. (2001) call for “sustainability science,” which the authors describe as a new field that “seeks to understand the fundamental character of interactions between nature and society” and involves “problem-driven, interdisciplinary research.” Focusing specifically on emerging and reemerging infectious diseases, Wilcox & Colwell (2005) argue that “a more realistic view [of these] diseases requires a holistic perspective that incorporates social as well as physical, chemical, and biological dimensions of our planet’s systems.” These authors use the term

Estimate of world deforestation

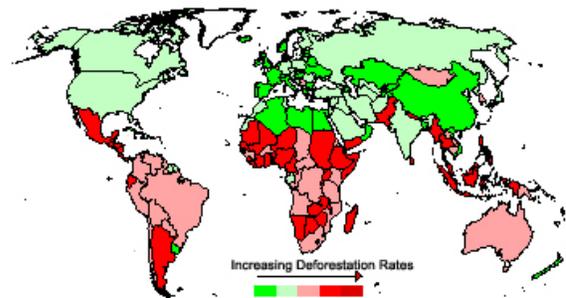


Figure 2 Forest cover change from 1990–2000 (FAO, 2001)

“biocomplexity” to describe this approach, noting that others have used similar arguments to advocate approaches premised on “socioecological systems” (Berkes & Folke, 1998), “human-natural systems” (Gunderson & Holling, 2002), or “eco-epidemiology” (Kaufman & Poole, 2000). We add our voices to this chorus calling for comprehensive frameworks to facilitate better understanding and more effective solutions to complex environmental and social problems such as malaria.

This paper first describes the malaria problem, including its etiologic roots, its health effects, and its economic and social toll on affected populations. We then examine how individuals, households, governments, and the public-health profession have traditionally responded to malaria threats through prevention, control, and treatment measures, and identify some shortcomings of these approaches. This leads us into a discussion of one arguably under-researched area—the ecological link between deforestation, malaria vectors, and disease incidence. Because of the well-documented link between poverty and deforestation, especially in the tropics, we propose and discuss five specific reasons for assessing the role of deforestation in linking malaria to economic development. We present the mixed empirical evidence on the malaria-deforestation-poverty link from macro- and micro-economic studies and conclude that more refined research methods at both scales can help identify these causal connections. Building on knowledge gaps identified in the paper, we conclude with a proposal to strategically link research and policy at the malaria-deforestation-poverty nexus in a comprehensive decision-analysis framework that channels research to the most pressing policy needs, informs policy with the most conclusive findings, and ensures that stakeholders are effectively informed about their options.

The Malaria Burden

Malaria is a vector-borne disease caused by protozoan parasites (e.g., *Plasmodium falciparum*) that complete their complex cycle of development alternating between human hosts and mosquitoes of the genus *Anopheles*. The burden of this disease on human populations in malarial regions is devastating. As Sachs & Malaney (2002) describe:

The numbers are staggering: there are 300 to 500 million cases every year; and between one to three million deaths, mostly of children, attributed to this disease. Every 40 seconds a child dies of malaria, resulting in a daily loss of more than 2,000 young lives worldwide. These estimates render malaria the pre-eminent tropical parasitic disease and one of the top three killers among communicable diseases.

Beyond mortality, malaria causes morbidity through fever, weakness, malnutrition, anemia, spleen disorders, and vulnerability to other diseases. Malarious patients also experience asymptomatic parasitemia, acute febrile, chronic debilitation, and pregnancy complications (Bremen, 2001). Malaria's global impact on human health, productivity, and general well being is profound, with joint mortality and morbidity impacts estimated to be 45 million disability adjusted life years (DALYs) in 2000, an amount equal to nearly 11% of all infectious diseases (Guerin et al. 2002). Moreover, as with other diseases, the malaria burden is experienced disproportionately by some of the most vulnerable populations, in particular children and pregnant women.

Social scientists, especially economists, have studied malaria's social and economic impacts at several scales, peering inside families, looking across households and communities, and comparing entire nations and continents. What these researchers have found is remarkably consistent—malaria imposes substantial social and economic costs and impedes economic development through several channels, including quality of life, fertility, population growth, savings and investment, labor productivity, premature mortality, and medical costs (Sachs & Malaney, 2002).

Economists have sought to put a monetary value on this burden by measuring the impacts on households, health systems, and national economies. At the household level, malaria imposes both direct and indirect costs. Direct costs include time lost from work as well as the cost of medical treatment (including transportation and medical care). Indirect costs, which are typically harder to measure, include

loss of work efficiency and time and work reallocation within the household. For children in particular, indirect costs also include nutritional deficiencies, cognitive and educational disabilities, and physical retardation. Pain and suffering are clearly substantial costs of malaria, but are perhaps most difficult to quantify and monetize. In general, long-term effects, such as child development and compromised immunity, are unknown (Hutubessy et al. 2001).

At the level of health-care systems, economists typically focus on treatment and medication costs. In most economies, households are subsidized for treatment and medication and other expenses are borne by the health system. There are also opportunity costs for displaced or delayed treatment and medications for other family members, while caregivers lose workdays.

These direct and indirect impacts can collectively impede economic development and growth. Malaria is estimated to decrease annual per capita GNP growth by 0.25-1.30% in tropical countries, after accounting for initial endowments, overall life expectancy, and geographic location (Guerin et al. 2002; Sachs & Malaney, 2002). To the extent that slow economic growth limits malaria-control funds, there is a vicious cycle of poverty and malaria that diminishes economic opportunities for huge numbers of people.

Societal and Individual Responses

Societies respond to the malaria burden in several ways, broadly grouped into preventive (control) and curative (treatment) approaches. The efficacy of both approaches is affected by ecological and behavioral factors at the individual, community, and regional levels.

Malaria prevention focuses on controlling the mosquito vector or reducing contact between humans and vectors. Predominant strategies include insecticide-treated bed nets (ITNs) and indoor residual spraying of insecticides (IRS). Environmental management is another option that is gaining support, particularly in light of growing resistance to insecticides and antimalarials (Lindsay & Birley, 2004). Utzinger et al. (2001) argue that despite a wide variety of efforts to combat malaria, including engineered malaria-resistant mosquitoes and new vaccines, these will take time and may not succeed. In the interim, the best option may be environmental management for vector control, including vegetation clearance and management of water bodies (e.g., modification of river boundaries, drainage of swamps, reduction of standing water, and application of oil to open water bodies). Further support for environmental management comes from Keiser et al. (2005), who review 24

studies and find that environmental management decreases the malaria risk ratio substantially (88% reduction in the risk ratio for environmental modifications and 79.5% for human habitation modifications).

Malaria vaccines represent another prevention strategy that could prove very beneficial over the long run. Vaccine research has made substantial progress recently—one vaccine (RTS,S/AS02A) appears very promising—but an effective agent is unlikely to be available for widespread use for at least ten years (Greenwood et al. 2005).

Besides vector control and other preventative strategies, case management (treatment) is the other major plank in efforts to combat malaria. Indeed, prompt and effective treatment using chemophrophylaxis is widely recognized as the most cost-effective malaria control strategy (Goodman et al. 1999). Because the rate of infectious contact is critical in disease transmission, prompt individual treatment is an important form of population-level prevention (Wilson, 2001).

Despite the importance of disease treatment for both individuals and society, several important barriers impede effective treatment on a broad scale. First, people in endemic areas often lack access to treatment beyond inferior drugs. Second, accurate and consistent diagnosis is critical for successful treatment (Greenwood et al. 2005). Ideally, interventions should be predicated upon laboratory-based diagnosis involving some form of “bloodwork” through microscopy, dipstick, or test strip. Unfortunately, most individuals do not avail themselves of these tests and treatment is mostly limited to clinical or self-diagnosis. These diagnoses are often inaccurate because signs and symptoms of malaria are nonspecific and overlap with other febrile infectious diseases and because the subjective sensation of fever is unreliable. As a result, society engages in unnecessary and inappropriate treatment and drug use that can have toxic side effects, impose unnecessary costs for individuals and health systems, and increase parasitic resistance (Guerin et al. 2002).

Resistance of mosquitoes to insecticides is an additional barrier to malaria prevention.¹ Multiple economic factors may cause inappropriate use of drugs and pesticides, shortening the useful life of these substances and hindering long-term malaria prevention and treatment (Reed et al. 2002).

Finally, an essential ingredient of almost all prevention and treatment packages is local awareness of

malaria-control alternatives. For example, high mortality from severe malaria (which can result in organ failure, cerebral malaria, and acute anemia) continues because patients arrive in an advanced state, although home or village-based rectal administration of artesunate is a promising approach (Guerin et al. 2002). Individuals can also minimize exposure to the vector by limiting activities in the early morning and evening hours, using repellents, and maintaining and using ITNs.

The public-health responses discussed in this section—vector control, case management, and vaccine development—represent the mainstream in malaria control [see for example the recently completed reviews by the Roll Back Malaria program (WHO & UNICEF, 2005) and the Working Group on Malaria (Teklehaimanot et al. 2005)]. These approaches are predominantly supply-side; for example, officials from national health ministries might identify, choose, and target an indoor residual spraying regimen in a place and time of their choice, rather than on the basis of household demand for and participation in such treatment. Such strategies gloss over the behavioral basis of malaria transmission, particularly the modifications and adaptations by individuals, households, and communities to their disease exposure, which in turn is affected by the natural and psychosocial environments (Pattanayak et al. 2006). Given that the host is not a passive agent in the “agent-host-environment” framework, the human ecology approach and the more recent eco-epidemiology framework are vital for understanding how humans modify and adapt to their environment, including their disease environment (Wessen, 1972; MacCormack, 1984; Parkes et al. 2003). The following review of the role of deforestation in malaria transmission seeks to establish the basis for this proposition.

Deforestation Impacts on Malaria

An ecological perspective on the life cycles of parasitic microorganisms and their associated infectious diseases is critical to understanding and controlling these diseases (Wilson et al. 1994; Wilson, 1995).² Moreover, infectious diseases are part of a larger human ecology in which “human social systems, economic activities, interactions with the environment, and lifestyles represent some of the key domains of interaction that affect infection and disease risk” (Wilson, 2001). Each environmental change, whether occurring as a natural phenomenon

¹ Resistance is more likely to emerge when background immunity is weak, parasite numbers in individuals are high, transmission is low, and insecticide and drug pressure is intense. *P. falciparum* has become variably resistant to all drug classes except the artemisinin derivatives.

² Our understanding of the ecological basis for disease dates back at least as far as Hippocrates’ “On Airs, Waters, and Place,” written in 400 BC.

or through human intervention, alters the ecological balance and context within which disease hosts, vectors, and parasites breed, develop, and transmit diseases (MacCormack, 1984; Parkes et al. 2003).

In general, vector-borne anthroponoses such as malaria are strongly affected by environmental factors influencing the abundance and survival of the vector. Indeed, Smith et al. (1999) attribute 70-90% of the risk of malaria to environmental factors. The variety and magnitude of environmental influences on malaria are enormous (Wilson, 2001). Abiotic elements such as precipitation and temperature affect the abundance of mosquito vectors and the development of parasites within the vectors. In addition, biotic factors operating through deforestation, agriculture, and housing construction may also influence vectorial capacity. Furthermore, the impact of deforestation and other land-use changes on temperature, precipitation, and vegetation reveals the interacting and correlated nature of these environmental influences.

While a number of anthropogenic land-use changes have the potential to affect the emergence, reemergence, and spread of infectious diseases, the relationship between deforestation and malaria is particularly important (Lindsay & Birley, 2004; Patz et al. 2004). As Patz et al. (2004) note, deforestation has accompanied increases in malaria in Africa, Asia, and Latin America. Widespread felling of trees is often a precursor to other important land-use changes such as agricultural expansion and intensification. Deforestation has also attracted substantial policy attention and innovation, with potential cross-effects on malaria control. While we recognize the importance of other processes—for example urbanization—in the evolution of malaria, we focus here primarily on deforestation. In particular, a review of the literature reveals five potential pathways through which forest management and deforestation can affect malaria infection and disease transmission (Walsh et al. 1993, Patz et al. 2000; Wilson, 2001; Molyneux, 2003; Patz et al., 2004).

First, deforestation changes the ecology of a disease vector and its options for hosts. Whereas primary growth forest floors tend to be heavily shaded and littered with a thick layer of organic matter that absorbs water and renders them quite acidic, cleared lands, generally more sunlit and on flat terrain, are prone to the formation of puddles with more neutral pH that can favor specific anopheline larvae development (Patz et al. 2000).³

³ Molyneux (2003) points out that forest loss may also lead to the elimination of certain vectors that are specially adapted to the forest ecosystem, thereby decreasing the disease burden. The ex-

Second, deforestation can affect climate at local, regional, and even global scales (through impacts on the global carbon cycle). Where the scale of deforestation is large, such as in the Amazon basin, the effects on temperature and moisture and, therefore, on vector habitats, could be quite significant (Wilson, 2001). Higher temperatures can increase the pace at which mosquitoes develop into adults, the frequency of their blood feeding, the rate at which parasites are acquired, and the incubation of the parasite within mosquitoes (Walsh et al. 1993). For example, deforestation and its related activities have produced new habitats for *Anopheles darlingi* mosquitoes and have been correlated with malaria epidemics in South America (Walsh et al. 1993). The different species complexes in Southeast Asia (*A. dirus*, *A. minimus*, *A. balabacensis*) have been differently affected by forest clearance with varied impacts on malaria incidence (Walsh et al. 1993).

Third, deforestation is often just the first step in a chain of land-use changes. These modifications may involve agriculture and livestock, plantations, human settlement, forest regeneration, road construction, and water-control systems (i.e., dams, canals, irrigation systems, and reservoirs). Networks of irrigation ditches, canals and impoundments, as well as puddles from road construction, can improve vector habitats. Livestock can change vector ecology and vectorial capacity, influencing malaria-transmission patterns.⁴ Rubber plantations in Malaysia encourage *A. maculatus*, whereas in Trinidad erythrina (with their bromeliads) encourage *A. bellator*. Insecticide use in subsequent agricultural activities on cleared land can increase vector resistance (Wilson, 2001).

Fourth, deforestation is accompanied by migration and other behavioral changes that may enhance the spread of malaria. In the case of gold mines in the Brazilian Amazon, migrants typically have little previous exposure and therefore lower immunity (Castilla & Sawyer, 1993). Moreover, migrants introduce additional complications associated with administering health services to transient populations—inadequate medical follow-up and possible side effects. Although incomplete treatment can relieve fever, the underlying malarial infection persists as the

amples provided do not include malaria vectors, but this is at least theoretically possible.

⁴ For example, certain *Anopheles* species are zoophilic, preferring to feed on livestock rather than humans. The introduction of livestock may thus decrease the human-malaria burden by providing mosquitoes with an alternative source of bloodmeals, a process known as zoophylaxis. However, it is also possible that the introduction of livestock will expand vector abundance, leading to an increase in malaria. The direction of the effect is likely to vary, and depends on factors such as vector mortality, the ratio of humans to livestock, and proximity of livestock and humans to breeding sites (Saul, 2003).

migrant moves and potentially transmits the disease to other locations, often on the deforestation frontier.

Finally, ecosystem change such as deforestation can play a role in the antibiotic resistance that has become a major concern for several plasmodium species. Resistance evolves through processes of selection and evolution, responding to diverse factors such as extent of treatment, nature and site of antibiotic action, and genomic complexity of the parasite (Wilson, 2001). Greater virulence results from genetic changes that occur by chance mutation and subsequent drift of selection. While ecological change permeates the process, it is difficult to delineate the roles of specific forms of modification such as deforestation. However, it is possible that deforestation will increase the genetic diversity of parasite populations and increase the rate at which resistance evolves.

Reviewing Poverty, Deforestation, and Malaria Linkages

To this point, we have enumerated the potential benefits of reducing malaria incidence, choices for public-health interventions, and pathways by which deforestation may influence malaria. This is important within the cross-sectoral perspective we are advocating because deforestation is a significant development-policy issue (Deacon, 1994; Angelsen & Kaimowitz, 1999; Wunder 2001; Wood & Porro 2002; FAO 2005; Sunderlin et al. 2005; Sills & Pattanayak, 2006). Research on deforestation's causes and consequences, including income and poverty, has identified many public interventions to promote forest conservation (by slowing or reversing deforestation). Both forest and health policies ultimately aspire to enhance human welfare, as do policies that directly promote economic development of forest frontiers. Unfortunately, it is unclear which of these policies complement each other and which conflict because of the complex and dynamic relationship between deforestation, malaria, and poverty (see Wolman, 1995 for similar concerns). We consider it critical to incorporate deforestation and forest management into malaria research, not only because of the potential linkages enumerated earlier, but also because of linkages through the human causes and consequences of malaria and deforestation. Moreover, the tactics that can be employed to control malaria through forest conservation are clearly different from more traditional clinical, or even community medicine, approaches. We present four reasons why it is important to understand how malaria is linked to economic development via deforestation.

First, deforestation is not merely the exogenous (remote control) removal of forest cover (Patz et al.

2000). As discussed above, it is the beginning of an entire chain of activities, including forest clearing, farming, irrigating, livestock raising, and non-timber forest product collecting, that all have ecological (vector habitat) and behavioral (exposure and transmission) consequences for malaria.

Second, millions of rural households depend directly on a wide variety of forest products and services (Byron & Arnold, 1999). By lowering the natural wealth of local populations, deforestation can reduce household capacity to invest in health care and pay for malaria prevention and treatment. At the same time, deforestation may increase the wealth of other households that will then be better able to avoid and cure malaria.

Third, deforestation is an integral part of life and the landscape in many malaria-infested regions (Wilson, 2001; Donohue, 2003). Consequently, sustainable-forest management has become an important policy goal as donor agencies and local policymakers take a more integrated view of people in natural settings. The resulting land-cover changes, as well as modifications in how people interact with forests, have implications for malaria. Thus, conservation policies aimed at slowing deforestation affect malaria (Walsh et al. 1993; Ault, 1994; Taylor, 1997).

Finally, malaria and deforestation are central elements of the vicious poverty cycle in the rural areas of many developing countries. In simplistic terms, malaria could be considered to "cause" deforestation, because malaria can make people poorer and poverty can "cause" deforestation under some conditions. In reality, the linkages are, of course, more complex and context-specific. For example, Sawyer (1993) argues that high rates of malaria encourage men to work as day laborers (in logging or ranching) rather than establish family farms. This adaptive response allows women and children to live in towns with relatively lower malaria incidences. While it is often difficult to disentangle causality in such situations, it is clear, as Smith et al. (1999) observe, that "many of the most critical health problems in the world today cannot be solved without major improvement in environmental quality."

Empirical Evidence on Malaria-Deforestation-Poverty Links

The previous sections advanced several hypotheses regarding possible relationships among deforestation, malaria, and poverty. We now ask two important questions in light of these contentions. First, what do existing data tell us about deforestation-malaria-poverty linkages? We consider both macro-level and micro-scale analyses and draw lessons from each

Box 1 A Macro Viewpoint

We test the hypothesis that deforestation is a causal factor for malaria using country-level data on deforestation, malaria risk, and geographic and socio-economic control variables. Data on forest loss at the country level between 1990 and 2000 was collected from the World Development Indicators, while data on malaria risk at approximately the same time period (1994) and pre-determined covariates come from Kiszewski et al. (2004). In total, 160 countries are represented, although several countries had missing values for one or more variables.

Nonparametric tests for correlation show that **change in forest cover is negatively associated with malaria risk** ($\rho=-0.5$). That is, countries that experience negative forest-cover change (deforestation) have higher rates of malaria. Regression analysis was used to probe this correlation in more detail to test whether or not the data could support a causal relationship between malaria and deforestation, controlling for other explanatory variables. In the most basic model involving no control variables, malaria risk is negatively correlated with deforestation rates. However, **once we control for a number of control variables in the analysis** (geographical location, quality of institutions, per capita income), **deforestation is no longer a significant correlate of malaria risk**. The one variable that is consistently significant in these analyses is the proportion of land area in the tropics. This variable's strong correlation between with both deforestation rates and malaria seems to be driving the observed correlation between malaria and deforestation. However, this should not be taken as proof that no such relationship exists. **This cross-sectional macro data set does not allow us to identify any causal link between deforestation and malaria.**

	Deforestation (P-value)	Controls	R Sq	N
Malaria risk	-0.07(<0.01)	--	0.06	160
Malaria risk	-0.01(>0.01)	location, gdp, institutions	0.67	142

of these perspectives. Second, what are the current gaps in our knowledge regarding the relationships among deforestation, malaria, and economic development, and what kinds of research could help to address these deficiencies?

Reviewing Evidence from Macro- and Micro-level Studies

Existing data sources provide two options for examining the links between deforestation, malaria, and economic development. The first approach uses national-level data to look for consistent macro-level correlations. For example, is deforestation consistently correlated with malaria risk, even when we control for other explanatory variables? Box 1 summarizes results from a macro-level analysis of the links between deforestation and malaria. Evaluation of these cross-national data suggests that malaria and deforestation are correlated at the national level. However, this relationship disappears when regression analyses include other factors such as tropical location.

A second approach uses individual- or household-level data to look for micro-level relationships. Such data sets allow us to identify detailed causal relationships in specific settings and to avoid some of the statistical problems (e.g., high correlation among explanatory variables, aggregation of local heterogeneity) that can undermine our ability to detect causal relationships. Box 2 summarizes the results from two micro-level studies of the links between ecosystem change and malaria in Indonesia. Both studies report a negative association between the extent of primary-forest and malaria. This finding is consistent with the notion that primary forest conservation can reduce malaria incidence.

Comparing macro- and micro-level studies reveals the benefits and drawbacks associated with each approach. Research on national-level data, particularly cross-sectional data, does not capture complex local and regional phenomena. Data available at the national level for several countries often lack sufficient detail to test more subtle hypotheses. For example, the two micro-level studies cited here found that more *primary* forest cover is associated with lower malaria rates, but the national-level data sets used in the macro-scale analysis record only *total* forest cover without distinguishing between primary and secondary forest. Conversely, micro-level studies are an excellent source of detailed knowledge about particular areas, but it is often hard to generalize these results across different settings. This observation is especially germane to informing policy decisions. The contrast between micro-level and macro-level studies, not unique to the deforestation-malaria problem, requires a multi-faceted research strategy that optimizes the relative advantages of each type of study.

Knowledge Gaps

Despite the previously described emerging body of knowledge about the economic and ecological causes and consequences of malaria, our understanding of these complex issues remains incomplete and inadequate (McMichael et al. 1998; Lindsay & Birley, 2004; Patz et al. 2004; Wilcox & Colwell, 2005). In particular, no study has comprehensively related deforestation to malaria incidence and burden by analyzing a longitudinal (panel) data set. Panel data allow the researcher to combine the best features of cross-sectional and time-series analysis while being able to control for population characteristics,

Box 2 A Micro Perspective

Malaria is highly contextual, with incidence and transmission depending on local conditions, perturbations, and catastrophes. Thus, **individual-level multi-factor research** is perhaps best suited to incorporate the diversity and heterogeneity of the ecological, epidemiological, and economic phenomena surrounding malaria. Two recent micro-level studies from rural Indonesia provide examples of this kind of research, and reveal linkages between deforestation and malaria.

In remote areas of developing countries, people's lives are closely intertwined with the condition of the natural environment particularly in rural areas that lack hospitals, doctors, and other public services. A household-production framework (Berman et al., 1994) can be used to specify econometric models to evaluate the links between ecosystem change and the incidence of malaria. Data from a survey of households residing near protected areas in Flores and Siberut Islands in eastern and western Indonesia are used to estimate multivariate logit regression models. These models test the correlations between the forest protection and malaria, controlling for individual, household and community characteristics. The Flores case study focuses on child malaria (Pattanayak et al. 2005) and the Siberut case study focuses on adults (Ginwalla et al. 2005). In both cases the results indicate **statistically significant correlations between village-level forest protection and the incidence of malaria**—the extent of primary forest is negatively associated with malaria. Other significant factors related to malaria include gender, caregiver's age, household wealth and house quality, village area and elevation, and level of public-health infrastructure. The statistically significant correlation between the forest-cover variables and child-malaria rates suggest that **forest protection may offer health benefits to nearby communities**.

	Primary forest (P-value)	Secondary forest (P-value)	Controls	Pseud RSq	N
<i>Siberut (adults)</i>	-(<0.01)	+(>0.10)	demographic, SES, physiographic	0.20	501
<i>Ruteng (under 5)</i>	-(<0.10)	+(<0.05)	demographic, SES, physiographic, public health	0.15	337

temporal dynamics, and unobservable variables to rigorously test causal relationships.

We believe that an interdisciplinary approach integrating economics, epidemiology, and ecology could address many of the knowledge gaps distilled below.

- Malaria is highly contextual, with incidence and transmission depending on local conditions, perturbations, and catastrophes. Any attempts to evaluate the relationship between forest conditions and malaria should adopt an individual-level, multi-factor approach to incorporate the diversity and heterogeneity of the ecological, epidemiological, and economic phenomena surrounding malaria incidence in particular locations. Nevertheless, the modeling of heterogeneity and diversity seems to be the exception rather than the rule in research on malaria's behavioral dimensions.
- The incomplete understanding of the human ecology of malaria is exemplified by the insufficient and partial modeling of behaviors—at societal, community, household, and individual levels—including a wide variety of observable and unobservable activities related to exposure, prevention, and treatment. Behavioral response is complex, and mechanistic behavioral models do not fully account for human responses to changing ecological and economic conditions. In particular, typical cost-of-illness estimates based on lost productivity ignore behavioral response altogether and thereby grossly under represent socio-economic impacts on individuals and households.
- Policy evaluations of malaria control have typically overlooked the full range of ecological factors in parasite life cycles. Several aspects of malaria, such as acquired immunity, vectorial and parasitic resistance, child development, and cumulative well being, involve long gestation periods. As far as we have discerned, no existing study fully incorporates these dynamic processes or measures the long-term benefits of malaria control.
- Forests are one of the primary ecological factors influencing malaria transmission. Yet, there is only a thin empirical literature on malaria in forest regions, at least in terms of research that considers socio-economic factors, including behaviors. Most critically, to date no research has comprehensively considered the role of forests in contributing goods and services and thereby changing household and individual wealth.
- Malaria control is an example of a real-world program that produces non-random (non-experimental) data with the associated problems of reliable inferences and conclusions. Evaluation science has made significant strides in data-collection and analysis methods that can address the concerns of heterogeneity, diversity, and dynamics (see, e.g., Singer, 1989; Ezzati et al. 2005). Unfortunately, malaria-control evaluations seem not to have fully incorporated this methodological gain into relevant analyses, and few long-term field studies have collected repeated cross-sectional, cohort, and/or panel data

on malaria's social and behavioral dimensions that could complement classical laboratory experiments.

Building a Comprehensive Strategy to Link Research and Policy

This paper highlights the need for further exploration of the complex relationships linking malaria, deforestation, and poverty. Understanding these relationships is critical for informing policies to decrease the burden of malaria, protect forest resources, and promote economic development. We propose that a carefully designed, integrated approach linking research and policy can address this need and, over time, lead to improved knowledge and outcomes. In particular, we contend that an overarching decision-analysis framework can facilitate both policy-relevant research and evidence-based policymaking.

A Decision-Analysis Framework

Decision analysis provides a framework for evaluating the factors that influence malaria and informing choices among different policy options (Kramer et al. 2006). The general approach underlying decision analysis involves mapping out a set of relationships to show how policy decisions interact with factors outside of the decision maker's control to generate a set of (potentially interrelated) outcomes (Clemen, 1996). In this case, decision makers must choose a set of policies affecting malaria, deforestation, and poverty. While these three kinds of policies are usually viewed separately, we emphasize the need to consider them simultaneously, as has been advocated in sustainability science (Kates et al. 2001), eco-epidemiology (Parkes et al. 2003), and human ecology (MacCormack, 1984). The policies implemented will interact with several factors outside of the decision makers' control to produce a joint set of malaria, deforestation, and poverty outcomes.

The decision-analysis framework provides the basis for an integrated and dynamic strategy linking research and policy. Figure 3 depicts this strategy visually and shows how the framework, research, and policymaking interact, with each drawing lessons from and providing inputs to the other two.

Policy-Relevant Research

The process of developing a preliminary decision-analysis framework will highlight gaps in our understanding of the relationships between malaria, deforestation, and poverty. Such an approach will also help us to set a research agenda that could remedy these deficiencies and better inform policy choices. The framework should reflect the collective initial understanding of the "knowns" and "un-

knowns" by a team of ecologists, economists, and epidemiologists. While this paper identifies some potential pathways, more work is needed to generate plausible and testable hypotheses and to suggest the variables for inclusion in testable models. Meta-analysis and literature review are two important tools for developing the decision-analysis framework and identifying key hypotheses (see, e.g., Eisele et al. 2000).⁵

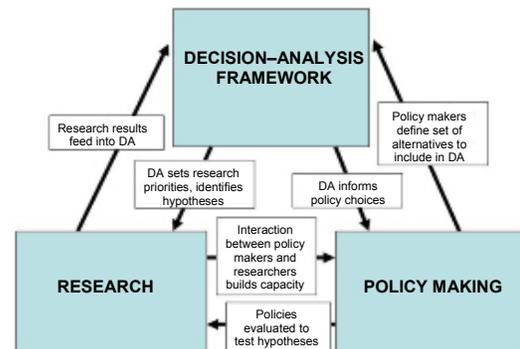


Figure 3 A comprehensive strategy to link research and policy

After constructing the initial decision-analysis framework and identifying key hypotheses, the next step is formulating empirical strategies to test these hypotheses. These strategies must address two inter-related issues: data collection and analytical methods.

The decision-analysis framework identifies which outcomes are of interest, as well as the various causal and confounding factors generating these outcomes. In this context, outcomes include indicators of health, wealth, and environmental quality. Extent of forest cover and forest condition are among the key explanatory variables. Other variables include socio-economic status, demographic composition, environmental quality, health status, and public-health policy. The challenge in empirical work is to identify robust measures of these variables and to separate independent and dependent variables. The multiple channels for feedback between malaria, deforestation, and poverty suggest that these variables would be dependent in some specifications and independent in

⁵ Meta-analyses can be structured and effective mechanisms for identifying gaps in the literature (Stanley, 2001). When the phenomenon or process is similar enough across the studies, meta-analysis is also helpful in generating hypotheses. In addition to meta-analysis of all empirical studies on the economic and environmental determinants of malaria incidence in forest regions, the decision-analysis framework can benefit from a more general review of different relevant bodies of literature, including socio-economic evaluation of disease-control policies (Singer, 1989; Ezzati et al. 2005) and ecology of infectious diseases (Wilson et al. 1994; Wilson, 2001).

other specifications and data sets. Although researchers can employ an array of sophisticated techniques to remedy defects in available data, clearly “prevention” in the form of careful data collection is superior to “cure” in the form of *ad hoc* statistical fixes (Heckman et al. 1999). Longitudinal data sets—and particularly panel data sets—are key to addressing at least three critical issues in the types of research proposed here: heterogeneity, endogeneity, and dynamics or mobility (Cebu Study Team, 1992; Ezzati et al. 2005). Data should ideally be collected at several scales, ranging from individual-level health and demographic data, to household-level economic information, to community- and regional-level environmental statistics and policy factors. Geographical information systems (GIS) can integrate data layers across space and time (Jacquez, 2000).

To ensure that the empirical work is policy relevant, it is critical to collect data on both the “treated” (participants in a clearly defined program or policy) and comparable “controls” (non-participants that represent the counterfactual scenario). Given that deforestation and diseases are potentially large-scale phenomena, it is important to consider ways to minimize contagion bias and/or measure “macro effects of treatments” on the controls or nonparticipants (Miguel & Kremer, 2004).

The goal of data analysis is to disentangle the effects that different mixes of health and forest policies, different target groups, and different environmental settings have on people’s health and wealth. This calls for a range of parametric, non-parametric, and semi-parametric methods. Key lessons for empirical evaluations can be gleaned from Ravallion (in press). There are many parameters of interest in evaluating deforestation impacts on malaria and poverty, partly because of the heterogeneity of impacts. For this reason, analysts should use a variety of comparison groups and estimation methods and should highlight and explain the differences that emerge from the multiple approaches.

Because the prospective research program begins with the policy environment, results from these studies will provide parameter estimates that can be fed into the decision-analysis model to help identify optimal policies. The availability of better estimates related to policy outcomes will improve the confidence of decision makers in their choices. In addition to facilitating more informed policies, the experience of working with researchers and using decision-analysis tools can play an important capacity-building role.

Conclusion

The foregoing account describes the burden that malaria places on human development, provides pre-

liminary empirical evidence on the role of deforestation as a causal factor, and proposes a framework for a transdisciplinary and policy-relevant research agenda. We argue that understanding the role of deforestation is essential to combating the growing global burden of malaria on human health and wealth. To this end, we propose decision analysis as the framework for linking research and policy to better comprehend and address this important challenge.

By bringing researchers and policymakers together, the decision-analysis framework will foster collaborations with important benefits for both sides. For researchers, coordinating with policymakers can improve the quality of their study designs and research results. For example, data collection can be timed to coincide with policy implementation, allowing “before” and “after” comparisons. Researchers can inform policymakers on how to integrate data collection and impact evaluation into policies. When resources are scarce and do not allow for immediate comprehensive policy implementation, some aspects may be randomized (e.g., the order in which regions receive the benefits of a policy that must be implemented incrementally). More fundamentally, collaboration between policymakers and researchers should lead to clearly stated, well-defined, and consistently implemented rules governing policy implementation. Any of these collaborative outcomes would facilitate testing hypotheses and identifying the effects of different interventions. Working with policymakers also gives researchers a sense of what matters “on the ground” by helping them to identify key variables and to build more policy-relevant models and analyses.

From a resource-allocation standpoint, the infrastructure for performing and disseminating this type of multi-disciplinary research should be developed in countries where the malaria burden is most pronounced. International organizations can foster the capacity for this work through in-depth technical assistance and training that provide individualized assistance to specific stakeholders such as local researchers, national policymakers, local government officials, and nongovernmental organizations. In general, a well-designed research program will allow researchers in developing countries to build skills in meta-analysis, cross-disciplinary research, publication for scientific peers and policymakers, and proposal-writing for long-term funding.

The proposals put forth here respond to several recommendations of the Working Group on Land Use Change and Disease Emergence as outlined in Patz et al. (2004). These include developing a conceptual model that links land-use and public-health policy; promoting research on deforestation and in-

fectious disease; engaging in health-impact modeling; developing location-specific decision-support tools; implementing research and policy programs; and assessing and addressing trade-offs among environment, health, and development. The issues we raise, and the comprehensive research and policy strategy we promote, clearly complement these goals and may be important in implementing the Working Group's recommendations. These efforts can, in combination, give public-health officials, environmental agencies, and economic policymakers a better chance of effectively countering the threat of malaria while also promoting better land use and forest management, thereby improving the condition of millions of people worldwide.

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