The Economics of Malaria Vector Control

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A dissertation submitted in partial
fulfillment of the requirements for the degree
of Doctor of Philosophy in the Department of
Environment in the Graduate School
of Duke University

2011

Background and Summary

THE HISTORY OF SPECIAL ANTIMALARIAL CAMPAIGNS IS CHIEFLY A RECORD OF EXAGGERATED EXPECTATIONS FOLLOWED SOONER OR LATER BY DISAPPOINTMENT AND ABANDONMENT OF THE WORK.

- League of Nations: Second General Report of the Malaria Commission (1927)

Malaria is one of the most persistent infectious diseases of humans, and by some measures the most deadly. The disease has had a dramatic impact on human economic systems for millennia, having been implicated in the decline of the Roman Empire (Sallares, Bouwman et al. 2004). In modern times, intensive malaria within a given country has been linked to a 1.3% penalty in economic growth rates, controlling for other factors (Gallup and Sachs 2001).[1]

The twin discoveries in the late 1800s of the malaria-causing pathogen *Plasmodia* and the *Anopheles* mosquito responsible for its transmission inaugurated an era of large scale malaria control programs. The strategy of these programs was to eliminate malaria via reductions in *Anopheline* densities, reduction of human contact with these mosquitoes, and via the "sterilization" of infected patients' blood through the use of drug therapies (Nájera 1999).

For the most part, these programs were aimed at immediate disease reductions, with little concern for sustaining initial successes over the long-term. The quote at the top of the page suggests that this problem was recognized at the time. However, as I show below, the sustainability of malaria control programs remains an open—and looming—question. This dissertation is aimed at addressing specific aspects of sustaining the positive impacts of malaria control programs.

[1] The causal relationship between malaria and economic growth has proven to be a Pandora's box. See Acemoglu, D. and J. Robinson (2001). What is clear is that malaria and poverty in modern times are strongly correlated.

The success of early malaria control projects hinged on the scale of support they enjoyed. Elimination of malaria from the area surrounding the Panama Canal was the most lauded success, and was accomplished principally through mosquito reduction efforts (*ibid.*). However, a similar vector control program around the same period at Mian Mir, Pakistan failed (Bynum 1994). Nájera (1999, pp 15-16) implicates differing financial commitments, in particular "the immense sums spent [in the Panamanian case] on the sanitation of the zone ten by forty miles," as the source of these programs' distinct outcomes.

Discovery of the insecticidal properties of dichlorodiphenyltrichloroethane (DDT) completely changed the approach to malaria control. The U.S. military pioneered the use of this chemical as an insecticide for malaria vector control in the 1940s, and by the 1950s it had become a mainstay of the World Health Organization's Global Malaria Eradication Program, or GMEP, which was launched in the 1950s (Nájera 1999).

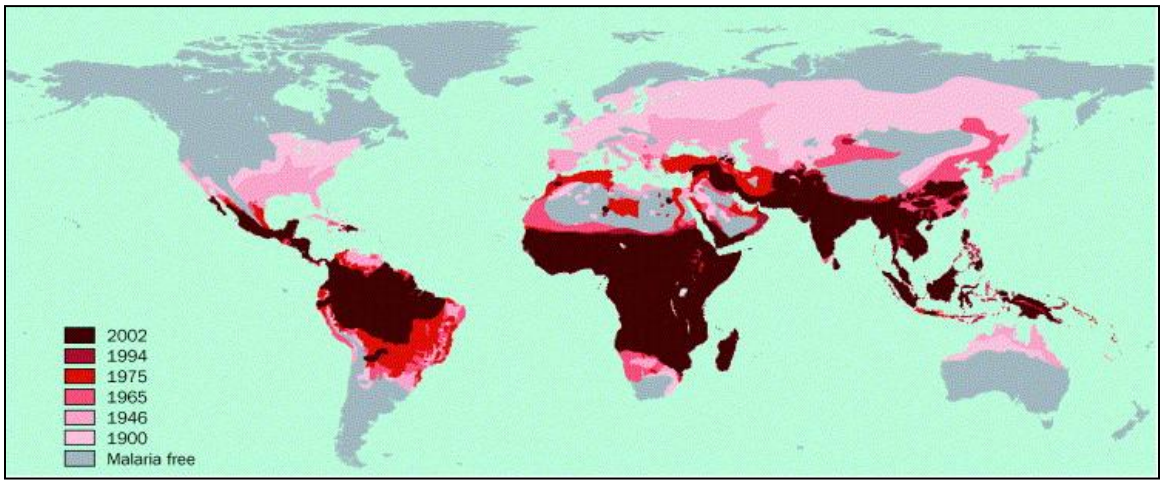

FIGURE I: GLOBAL DISTRIBUTION OF MALARIA OVER TIME. © *Reproduced from Hay, Guerra, et al. (2004) with permission from the copyright holders.*

The GMEP was as ambitious as its name suggests. With malaria having been eliminated in most temperate areas of the world, the architects of the GMEP saw eradication (i.e. worldwide elimination) as a feasible goal given sufficient financial resources. The remaining malarial areas

of the world at that time were concentrated in tropical and subtropical areas (Figure I), and these areas became the focus of GMEP efforts. GMEP operations were funded through a special account with the World Health Organization (WHO), the contributions to which are shown in Figure II for the period 1956-1996.

The majority of GMEP funding through the mid 1970s was from the United States, and when the U.S. commitment waned so did the health impact of the GMEP.

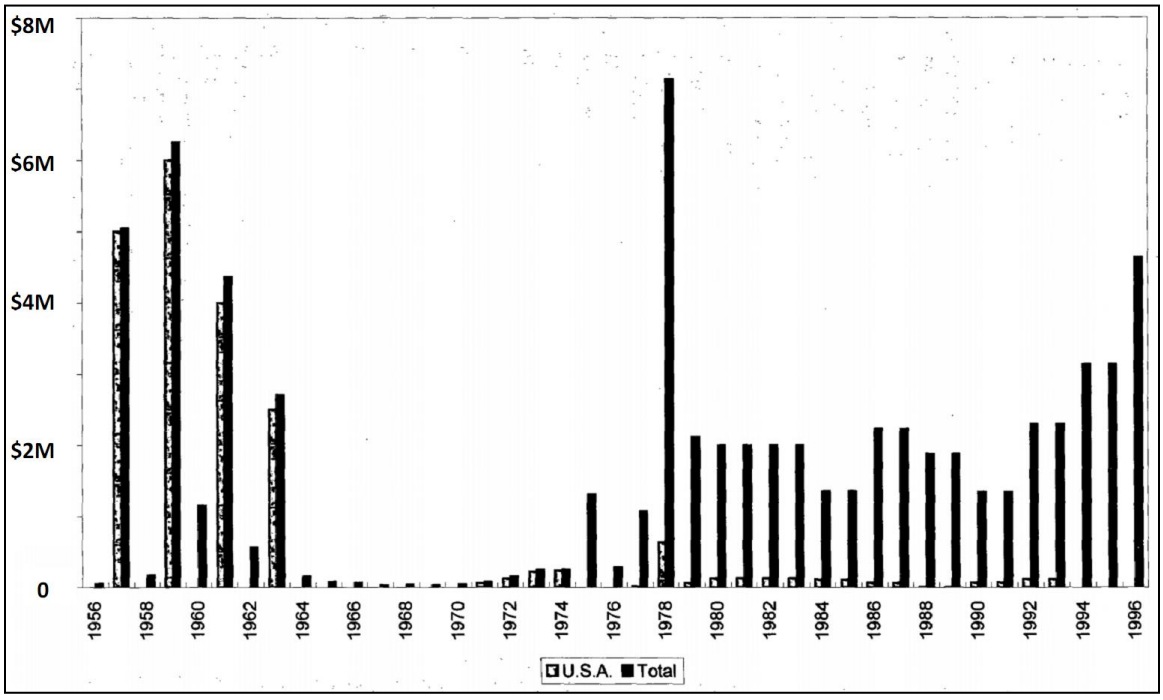

FIGURE II: CONTRIBUTIONS TO THE WHO FOR THE GMEP, 1956-1996. *Reproduced from Nájera (1999) with permission from the WHO.*

The resulting trend, not surprisingly, was that malaria was effectively reduced and eliminated in many areas for as long as GMEP resources were available, but rebounded severely when these resources dwindled. Numerous examples of this trend can be found in government documents and the published academic literature. Nájera (1999) illustrates this for Gezira, Sudan, in which a control program was launched in force in 1974 and subsequently abandoned in the mid 1980s. Figure III shows dramatic declines in malaria prevalence in this region when the program began. An even more dramatic rebound of malaria followed cessation of the program in the 1980s.

Large rebounds in disease burden are commonly observed in such situations, and is predicted by a variety of theoretical models of infectious disease transmission.

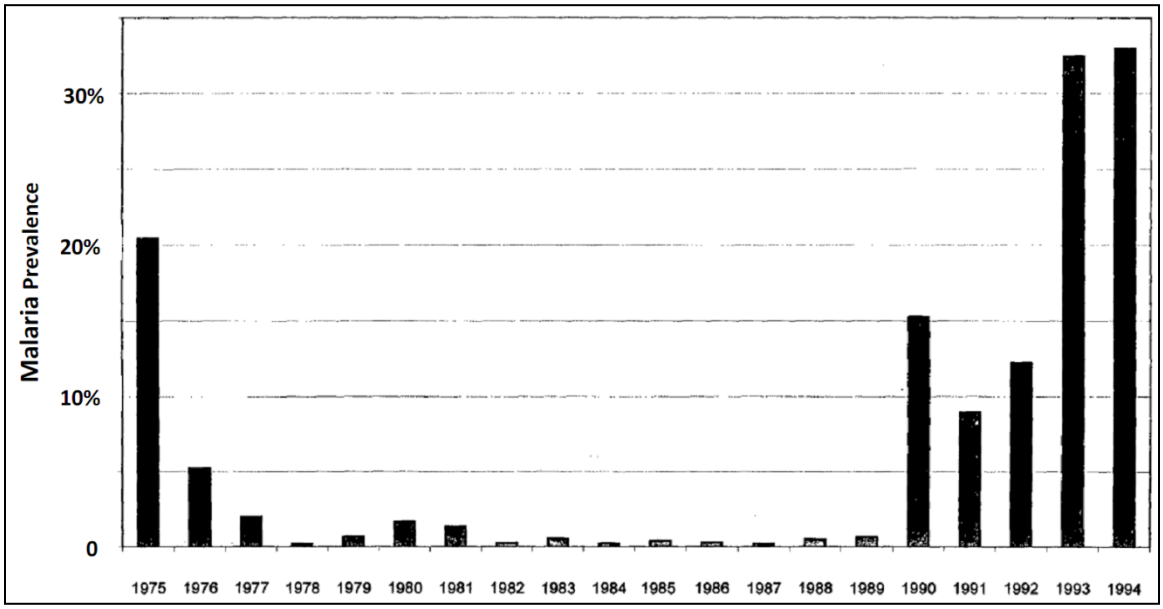

FIGURE III: MALARIA PREVALENCE (PARASITEMIA) AMONG 2-9 YEAR-OLDS IN GEZIRA, SUDAN. *Reproduced from Nájera (1999) with permission from the WHO.*

As Figure II illustrates, GMEP funding (from non-U.S. sources) did return in fits and starts beginning in the 1970s. But the successes of the GMEP in the 1950s were not mirrored in this renewed funding. Over time it was recognized that the goal of eradication could not be achieved with the GMEP's available resources. Much of the area targeted by the GMEP remained highly endemic in 2002 (Figure I). Indeed, in 2000 an estimated 800,000 African children died from malaria (Rowe, Rowe et al. 2006), hardly equating to success of the GMEP.

Thus was situation at the beginning of the 21st century, when the Bill and Melinda Gates Foundation (BMGF) and the Global Fund to Fight AIDS, TB, and Malaria (GFATM) declared earnest commitments to halting the disease's spread. Global development assistance for malaria control changed from less than $50 million in 1990 to nearly $800 million in 2007 (Figure IV).

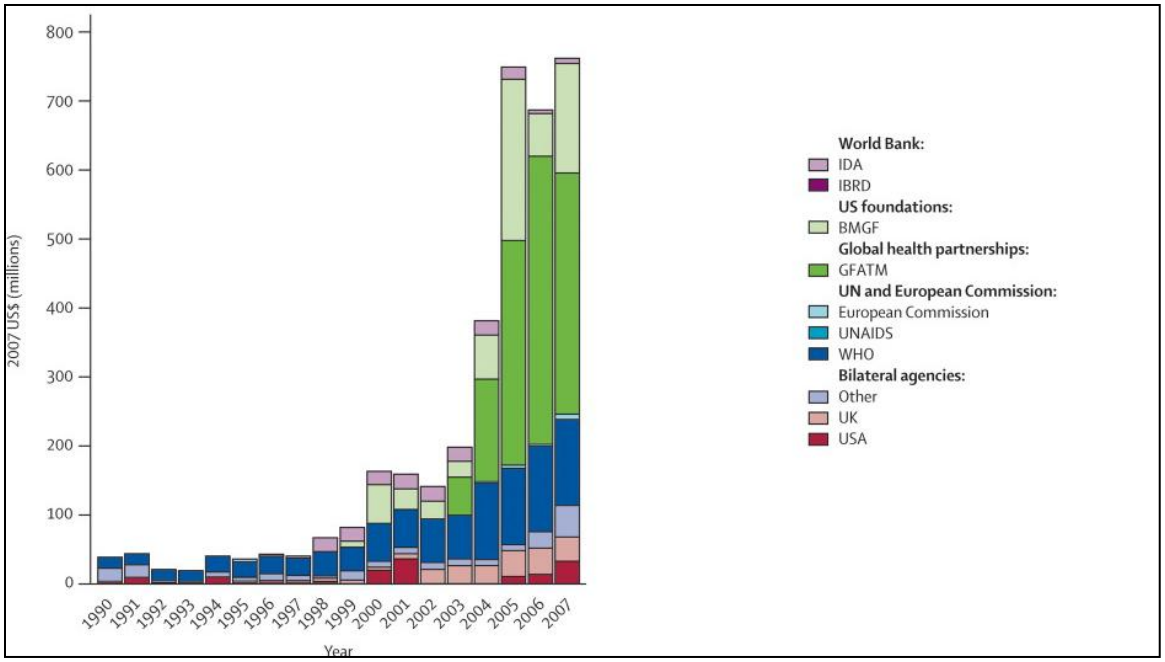

FIGURE IV: DEVELOPMENT ASSISTANCE FOR MALARIA IN USD2007. © *Reproduced with copyright holder's permission from Ravishankar, Gubbins et al. (2009)*

Recognizing the failure of the GMEP of the 1950s and 1960s—at least in accomplishing its primary goal—raises questions about the sustainability of the current wave of malaria control support. Although remarkable progress has been made in developing new methods of malaria vector control and in crafting a viable malaria vaccine (Rowe, Rowe et al. 2006), the current tools for malaria control remain only slightly improved versions of what was available at the incipience of the GMEP: effective drugs, effective insecticides, the elimination of mosquito habitat, and the erection of barriers (including distance) between humans and mosquitoes. Past experience therefore warrants a multilevel research agenda investigating how we can sustain and add to humanity's accomplishments in reducing malaria and thereby improve households' welfare throughout the world.

The explanations for the failure of the GMEP have included economic and biological factors that contributed to rebounding malaria levels across endemic areas. Biological factors included the spread and increasing frequency of malaria parasites that were resistant to

antimalarial drugs (Laxminarayan 2004; Laufer, Abdoulaye et al. 2007), and mosquitoes resistant to both DDT and pyrethroids (Reimer, Fondjo et al. 2008). In the background were also complex population-level dynamics resulting from individual-level immune responses to malaria exposure. Many populations living in the areas targeted by the GMEP had been subject to high levels of stable malaria exposure for thousands of years. Biologists have identified an array of immunity mechanisms, acquired through individuals' repeated exposure (Doolan, Dobaño et al. 2009) or through millennia of evolutionary pressure on human populations (Kwiatkowski 2005), adding nuance to our understanding of how malaria exposure translates into malaria episodes. It is impossible to know with certainty how changing immunity dynamics impacted the outcomes of the GMEP.

Economic factors implicated in contributing to the stalled progress of malaria control include the macro-level relationship between malaria control financing and reduction in global burden of disease (a relationship touched on above), as well as a number of micro-level factors. Such factors include the behavior of households in deciding whether or not to commit their own resources (e.g. time, money, or assets) to the public good of malaria prevention or to seek effective treatment. Analysis of such behavior constitutes an active area of research among development economists (Whittington, Pinheiro et al. 2003; Cropper, Haile et al. 2004; Dupas 2009). Moreover, quantifying the economic value of reducing malaria, as perceived by exposed households, provides information for improving priority-setting in development assistance.

This dissertation focuses on four specific challenges for improving the sustainability of malaria control, principally focusing on the control of the *Anopheles* vector. Chapter 1 addresses theoretical aspects in the economic management of insecticide resistance in vector control programs. The chapter begins with an overview of how the general problem of biocide

resistance (e.g. insecticide resistance in agriculture and public health, antibiotic resistance in infectious diseases) has been treated by economists. It then lays out a biological model embodying the tradeoff between increasing insecticide-usage to reduce current malaria levels and tempering current usage to maintain lasting—if less dramatic—disease reductions. After constructing an empirically motivated cost measure, this biological system is then subjected to standard optimal control procedures, enabling an analytic characterization of the optimal steady states and numerical analysis of the transition paths to these steady states. The primary contribution of the first chapter is the identification of a specific biological detail—the mechanism(s) leading to evolutionary fitness tradeoffs in insecticide-resistant populations of vectors—that qualitatively affects the economically optimal policy for managing resistance. Identifying the economic relevance of this biological detail makes for a more nuanced perspective on how to manage insecticide resistance in malaria vectors, and more generally how to manage biocide resistance in a variety of bioeconomic systems.

Chapter 2 approaches the problem of sustainable malaria control policies by treating the policymaker's problem as one of dynamic profit-maximization. In this setting, "avoided malaria burden" is produced using a set of conventional, time-invariant malaria interventions which comprise the inputs in the production function. The research aim is first to identify "profit" maximizing packages of inputs, i.e. malaria interventions, under a range of specifications for the production function. By allowing for multiple, simultaneous epidemiological and biological dynamics that have been alleged to be important for malaria control programs, I am able to explore the properties of this production function in more realistic settings. These dynamics include malaria infection, incubation, and recovery in humans and mosquitoes; evolutionary selection for drug resistance in parasite populations and insecticide resistance in vector

populations; and lastly acquired immunity to malaria and age-structure in the human population. The bulk of the work in this chapter thus consists of the construction and analysis of this production function, and relies heavily on numerical and simulation methods.

Not surprisingly, the epidemiological and biological dynamics considered in the model generate nonstandard properties in the production function, such as increasing marginal product of particular interventions (e.g. the distribution of insecticide-treated nets). As a result, the package of malaria interventions that maximizes net benefits often lies at the boundary of the feasible space of controls, e.g. with all infected patients being administered antimalarial drugs and/or all households being sprayed with insecticides. The most striking result from this analysis is that, under realistic conditions, increasing the level of one input (e.g. use of insecticide-treated nets) can flip the production function from exhibiting decreasing to increasing marginal product of another input (e.g. widespread use of antimalarial drugs), causing a discontinuous jump in the benefit-maximizing package of interventions.

Chapter 3 shifts the focus of analysis to households' expectations and preferences about vector control programs, the research aim being to investigate how households' support for these programs could change under future epidemiological conditions (e.g. lower malaria risk). I econometrically estimate households' perceived costs from malaria infection and perceived benefits of insecticide-spraying campaigns in northern Uganda, accounting for transactions costs in these programs. Using a stated-preference, experimental approach (namely a discrete choice experiment), I am able to circumvent the potential endogeneity between households' decisions to participate in spray programs, the expected malaria reduction gains from spraying, and actual levels of malaria risk. The estimation permits the prediction of households' participation in a

given spray program as a function of the private risk reduction that a household can expect from the program.

I find that households place significant value on reductions in malaria risk, with a willingness to forego an average 14% increase in the value of nonproductive, household assets for a permanent 1% decrease in the perceived monthly malaria risk per person. This estimate falls within the range of those reported in other stated-preference and cost-of-illness studies (Whittington, Pinheiro et al. 2003; Cropper, Haile et al. 2004; Russell 2004). On the other hand, participation in these spray programs is predicted to be relatively inelastic to the expected malaria reduction gains from spraying. This inelasticity is caused by transactions costs, which limit participation even when high reduction in malaria risk can be expected from participation. As one validity check of the econometric results, I find that the predicted participation rates of 75%-85% fall in the range of participation rates observed in the one previous round of spraying that was done in the study area.

Chapter 4 returns to the endogeneity between spray program participation and malaria risk (perceived and actual). The research aim of this chapter is to identify the potential efficiency gains from providing additional incentives for spray program participation. It is well-known that one household's decision to participate in a given spray program has positive spillover effects on neighboring households (e.g. Chitnis, Schapira et al. 2010). Even when spray programs are offered free-of-charge, the presence of transactions costs will lead to an under-provision of the mixed public-private good of insecticide-spraying (setting aside possible negative health consequences from spraying). To quantify the extent of this under-provision and the magnitude of a cash incentive aimed at alleviating it, I construct an individual-based simulation model of malaria transmission, allowing for heterogeneous participation decisions of

households. Using estimates from the epidemiological literature, I parameterize the simulation model to reflect the type of malaria transmission present in northern Uganda, as well as the spatial structure observed in each of the surveyed villages in the Chapter 3 study. I subsequently derive estimates of the private and public malaria reduction gains from spraying for all 15 villages in my survey.

Coupling these epidemiologically-derived estimates to the econometric estimates of preferences in the third chapter, I find that a welfare-maximizing set of cash incentives for spray program participation could reduce the incidence of malaria episodes by 10%-15%. In the case where the system of cash incentives is self-financing, with subsidies for participating households being funded by levies on nonparticipating households, the economic value of the incentive program is estimated to be negligible, at less than 1% of the value of a household's nonproductive assets. However, this economic estimate does not account for additional external benefits of malaria reduction, such as decreased exportation of malaria cases to population centers, and decreased congestion of the health system. Future work will address these external benefits and consider how such an incentive scheme could be implemented jointly with a development aid program, thereby creating a system of conditional cash transfers (CCTs) tied to spray program participation.

Returning to the question of the sustainability of current and future malaria control programs, the chapters of this dissertation lay out four broad lessons for the epidemiologists, economists, policymakers, and technicians responsible for formulating the strategies of these programs. First, as illustrated in Chapter 1, the biological details of any scientifically-grounded model used to formulate such strategies can dramatically (i.e. qualitatively) affect the recommended policy. Second, taking an economic approach to coordinating vector control and

drug therapy strategies—that is, embedding the epidemiological details into a malaria reduction "production function"—can significantly enhance the net benefits of such programs, by taking advantage of complementarities between malaria prevention and drug therapy. Third, households place significant economic value on malaria reduction, adding credibility to previous estimates of the economic value of malaria reduction. Scientifically-rigorous estimates of this value can be used in cost-benefit analysis of malaria control programs to maintain and elevate the priority of these programs in aid budgets. Finally, there is a role for incentive schemes to promote malaria prevention behaviors, to maintain public support for these programs, and to increase the efficiency of malaria control over the long-run, or until we finally reach a point where the disease is eradicated.

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