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# Malaria and Agriculture

## A Global Review of the Literature With a Focus on the Application of Integrated Pest and Vector Management in East Africa and Uganda

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## INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

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# ABSTRACT

Malaria is one of the top five causes of death worldwide, and roughly half the world's population lives at risk of the disease. This health problem disproportionately affects the poor, particularly those in Africa south of the Sahara, where the disease is widespread. Many of those most afflicted are part of farming households; therefore agriculture, poverty, and health are intimately linked through malaria. Uganda has the highest malaria parasite transmission in the world and is an important case study due to the role agricultural development has played in increasing malaria transmission within the country, according to the literature reviewed here.

This review brings together current research from agricultural economics, environmental science, and epidemiology to provide a foundation for research directly addressing how malaria relates these fields to one another in malaria-endemic settings such as the East African highlands. While each field has addressed malaria within existing academic frameworks, this literature review should support further interdisciplinary research by providing a detailed and well-documented account of integrative work on malaria to date.

More than 280 published articles and reports were included in the final review, and many more were included in the selection process. Due to the massive volume of literature published on malaria, the selection has been limited to those articles found to fill particular gaps in interdisciplinary understanding.

Ambiguities on the causal relationships between malaria and poverty, climate change, irrigation, and land use changes are discussed in the light of high local variation in impact on malaria transmission. Integrated pest management is explored due to its utilization of farmers' vocational skills and success in reversing the pesticide resistance now threatening malaria interventions worldwide. In particular, integrated pest and vector management (IPVM) interventions are assessed as a potential option to reduce the malaria burden in agricultural communities. Farmer field schools and IPVM may provide a cost-effective and integrated solution for improving both health and poverty outcomes. Such programs can foster collaboration between the health and agricultural sectors, and draw on the expertise of each in contributing to rural development in malaria-endemic areas.



**Keywords: malaria, agriculture, health, ecology, integrated pest management, pesticide, farmer field school, extension, Uganda**

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## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AWDI | alternate wet/dry irrigation |
| CGIAR | Consultative Group for International Agricultural Research |
| DALYs | disability-adjusted life years |
| DDT | dichlorodiphenyltrichloroethane |
| FAO | Food and Agriculture Organization |
| FFS | farmer field school |
| GMEP | Global Malaria Eradication Program |
| IFAD | International Fund for Agricultural Development |
| IPM | Integrated Pest Management |
| IPVM | Integrated pest and vector management |
| IRS | indoor residual spraying |
| ITN | insecticide-treated nets |
| IVM | integrated vector management |
| KARI | Kenya Agricultural Research Institute |
| LLIN | long-lasting insecticidal nets |
| MAAIF | Ministry of Agriculture, Animal Industry and Fisheries |
| NAADS | National Agricultural Advisory Services Program |
| NGOs | nongovernmental organizations |
| UMCP | Urban Malaria Control Program |
| VMP | value of the marginal product |
| WHO | World Health Organization |
| WUAs | water user associations |

# 1. INTRODUCTION AND BACKGROUND

This paper reviews the environmental and agricultural context of malaria in East Africa and Uganda, presenting a range of land-, water, and pest-management mechanisms to reduce adverse impacts from malaria driven by these agro-ecological factors. Agricultural systems and malaria have a long history of interconnection, which has been documented in a number of histories of the disease (Packard 2007; Najera 2001; Oaks et al. 1991; Wernsdofer and McGregor 1988). The specific relationships that govern the interactions between agricultural systems, human populations, and the *Anopheles* mosquito populations that transmit the disease, however, are less well known.

The following sections provide a background and overview of malaria–agriculture interactions, and suggest policies and institutions that can help improve both agricultural and health outcomes.

## Basic Malaria Ecology: Plasmodia and *Anopheles* Mosquitoes

*Malaria* is a term commonly used for the four species of malaria plasmodia that infect humans. *Plasmodium falciparum* is the most dangerous form of the disease, accounting for 90 percent of malaria deaths in the world (WHO 2008b, viii). *P.vivax* is less virulent but significantly harder to eliminate by interrupting transmission between humans and mosquitoes because it can maintain itself in a dormant phase in the human liver for six months. *P.ovale* and *P.malariae* are the least virulent species of malaria but may also persist in the body for months or years.

The reproductive life cycle of these plasmodia requires transmission between human and mosquito hosts. Plasmodia sexually reproduce in the salivary glands of some species of *Anopheles* mosquitoes (Greenwood et al. 2008, 1268). Mosquitoes then transmit the infectious form of the malaria parasite (referred to as *sporozoites*) to human hosts, where they infect the liver. This infection leads to *blood-stage infection* and asexual reproduction of male and female gametocytes, during which humans experience symptoms of the disease. *Anopheles* mosquitoes taking a blood meal from a human with a *blood-stage infection* ingest the male and female gametocytes, which are then able to reproduce in the mosquito's salivary glands. Plasmodia can reproduce in the mosquito stage only when the external temperature is above 14°C, and ideally between 21°C and 27°C (Patz et al. 1998).

There are many species of *Anopheles* mosquitoes that act as vectors for transmitting human malaria. These species differ significantly in their transmission potential (or *vectorial capacity*) depending on behavior, lifespan, biting rate, and other factors (Ijumba, Mwangi, and Beier 1990). *Vectorial capacity* is the expected number of infectious bites that will eventually arise from all the mosquitoes that bite a single person on a single day (Smith, Smith, and Hay 2009, 111). *An.gambiae* is the most effective vector for transmitting *P.falciparum* and is present throughout much of Africa (Uneke 2007).

## Malaria in Uganda

Uganda is an important case study for malaria policy because it is representative of the challenges facing malaria control across Africa. Malaria is endemic in more than95 percent of the country, which has the highest malaria parasite transmission reported in the world (Okello et al. 2006); Uganda is also subject to the world's highest malaria incidence rate, with roughly 10 million cases per year in a population of 30 million (WHO 2009b).

Prior to the 1920s, malaria was not widespread in the East African highlands, which include much of Uganda. Lower humidity and cooler temperatures in the highlands have historically played a significant role in malaria mitigation and influenced human settlement patterns toward reducing exposure to the disease. Deforestation, agricultural expansion, new small dams, creation of borrow pits for road construction, and increased migration of infected individuals from the lowlands are cited as factors responsible for successive malaria epidemics as local populations of low acquired immunity have been introduced to the disease (Lindsay and Martins 1998;Reiter 2008). Uganda is now subject to 12 major *Anopheles vectors: arabiensis, brochieri, bwambae, coustani, funestus, gambiae, hancocki, hargreavesi,* *nili, paludis, pharoensis, and quadriannulatus*. Within Uganda these vectors transmit both *P.falciparum* and *P. vivax* (WHO 2009b).

The baseline transmission potential in Uganda has likely been increasing over the last 20to 40years due to the aforementioned human-induced changes (Lindsay and Martins 1998; MCP 2008, 12). Additionally, because Uganda has porous borders on all sides with countries in which malaria is highly endemic, temporary reductions in transmission from mass drug administration or bed net interventions are immediately reversed by population movements of infected humans and mosquitoes (WHO 2007, 41) unless the ecological relationships between humans and mosquitoes have been modified in some manner. Temporary reductions may even increase vulnerability of children upon reinfection, due to reduced immunity. This long-term vulnerability to re-establishment of malaria increases the value of measures that may reduce local baseline transmission potential. Understanding and managing the environmental and ecological conditions that foster reproduction of these vectors in close proximity to human populations is the primary task of environmental and ecological approaches to malaria control.

# 2. CLIMATE CHANGE AND MALARIA

Malaria is currently thought of as a tropical disease and has been associated with tropical climates since its elimination from Europe, Japan, the United States, and the former Soviet Union between 1945 and the end of the Global Malaria Eradication Program in 1969 (WHO 1969). The impact of climate change on malaria vector distributions has been examined by a number of studies over the years since increased vector-borne disease was identified as a potential impact of climate change in the mid-1990s (Patz et al. 1996). The broader climate change literature has also recognized vector-borne disease as an area of concern (Epstein and Ferber 2011).

An early series of such studies in the journal *Science* in 2000 and 2001 (Rogers and Randolph 2000; Dye and Reiter 2000; Clark et al. 2001) concluded that even under significant global warming scenarios, climate change was unlikely to expand the ecological ranges of malaria vectors. The studies highlight the limits to macro-scale ecological modeling of this type, given that many of the more direct relationships contributing to malaria ecology function at a more localized scale than gridded global temperature forecasts can capture.

A number of subsequent studies estimated the potential increase in malaria transmission due to climate change. Tanser, Sharp, and le Sueur (2003) concluded that increases in transmission would occur through extension of the transmission season in areas currently infected rather than expansion of those geographic ranges. These authors also emphasized that the small geographic changes that may occur will be related to altitude rather than latitude, a result consistent with other studies; this is particularly relevant to the East African context, where there are significant elevation gradients between the coast and the highlands (Loevinsohn 1994; McMichael et al. 1996; Epstein et al. 1998; Martens 1999; McCarthy et al. 2001).

More recent studies on the topic (for example, Gething et al. 2010) have reached similarly negative or ambivalent conclusions about any strong or direct relationship between climate change and malaria vectors. There is, however, consensus regarding the key role of the local and human vector ecology (mosquito varieties, livestock practices, deforestation, land use change, and irrigation, among others) for determining malaria risk (Reiter 2008).

In their recent analysis of climatic warming and the geographic recession of malaria from 1900 to 2007, Gething et al. (2010) provided robust empirical evidence for skepticism toward the link between climate change and increased malaria transmission expressed by researchers such as Hales and Woodward (2005). At the same time, studies continue to confirm a significant positive relationship between malaria and increased daily temperature minimums as well as a negative relationship with increased daily maximum temperatures (Paaijmans et al. 2010), with optimal transmission occurring at temperatures in the 32–33°C range (Parham and Michael 2010).

The analysis challenges inherent in downscaling from the global climatic level to local malaria risk were well articulated by Martens and Thomas (2005). There are two important points to keep in mind when considering the climate change–malaria relationship. First, global warming does not lead to uniform local warming across the globe; second, where local warming occurs, malaria transmission may increase only where minimum temperatures are the current constraint on reproduction and transmission of the parasite, which is highly dependent on local vector ecology (Reiter et al. 2004).

## Climate Change and Malaria in East Africa

The East African highlands have been the subject of numerous studies evaluating the role of climate change in the distribution of malaria vectors. Chaves and Koenraadt (2010) reviewed many of the previous studies and concluded that climate change is a statistically significant driver of changes in malaria distributions. However, the magnitude of its effect is negligible relative to human interventions, drug resistance, migration, and land use change (Patz and Olson 2006).

While mean temperatures are frequently used in climate change studies, Zhou et al. (2004) examined climate variability and annual minimum temperature as the climatic limitation on malaria vector distributions in the East African highlands. Alemu et al. (2011) used a similar set of time series meteorological records to show that monthly minimum temperatures were positively correlated with malaria *P. vivax* transmission, but monthly maximums are negatively correlated. Protopopoff et al. (2009) ranked epidemiological risk factors for malaria in Burundi and found that monthly rainfall and minimum temperatures were the top environmental predictors of malaria risk, reinforcing the conclusions of Alemu et al. (2011) and Reiter et al. (2004) that minimum temperatures are a primary constraint on transmission.

Hay and others (2002) and Hay, Shanks, and others (2005) challenged the association between malaria and climate change in the East African highlands as "overly simplistic." The authors claimed that rainfall, temperature, vapor pressure, and the number of months suitable for *Plasmodium falciparum* transmission had not changed considerably during the reported malaria resurgence.

Land use change, the El Niño–Southern Oscillation, health services decline, and malaria drug resistance are more plausible explanations for the resurgence of malaria in Kenya, Tanzania, and Uganda (Jones et al. 2007; Hay et al. 2002). Stern et al. (2011) used localized meteorological time series data to confirm that climate change has not played a significant role in malaria resurgence in East Africa. Over the last 40 years, periods of malaria intensification have not coincided with periods of warming, and conversely, periods of stable warming have coincided with declines in malaria prevalence (Stern et al. 2011). Bouma et al. (2011) and Alonso et al. (2011) address the debated impact of climate change on malaria in the East African highlands by emphasizing smaller-scale and finer-resolution studies rather than attempts to model impact at a regional level.

# 3. ECOLOGICAL MALARIA RISK IN EAST AFRICA

Within the medical literature are diverse publications on the prediction and modeling of malaria transmission using environmental data. Here we review a number of studies that have examined environmental and household risk factors for malaria in the East African highlands. Although this review is not exhaustive, it is representative of the diversity and detail available in current and past analyses.

Mouchet et al. (1998) performed one of the most comprehensive reviews of the environmental history of malaria in Africa south of the Sahara (SSA) since 1960, often cited by the more topically specific literature presented here. Importantly for the case of Uganda, these authors identify agricultural intensification of valley bottoms in the highlands and urbanization of smaller settlements as contributing to the 30-fold increase in malaria in the Ugandan highlands during the 1990s. This historical overview is particularly useful for the regional and historical context it provides on the changes to malaria transmission on the African continent.

Stresman (2010) reviewed existing literature on ecological risk factors for malaria, seeking to explain why climatic predictors such as temperature and precipitation are so inconsistent in their ability to explain local malaria risk. Stresman (2010) identified many local environmental factors that modify the effects of temperature and precipitation, such as the ability for water to pool and persist, water quality, elevation, deforestation, and agricultural systems.

## Land Cover, Topography, and Land Use Change

Many of the local conditions that moderate vector and parasite reproduction are driven by land cover and topography, which may moderate temperature and available moisture at the local/microclimatic level. While plasmodia reproduce optimally in the mosquito stage when the external air temperature is 21–27°C (Patz et al. 1998), mosquito larva development is fostered by warmer water temperatures of 32–33°C (Munga et al. 2006). Much of the literature on land cover and topography concerns how local microenvironments may create or inhibit these conditions.

Elevation has historically constrained malarious areas due to lower temperatures and a lower density of suitable breeding sites in highland areas. The elevation bounds of malaria usually occur between elevations of 1,200 m in Zimbabwe and 2,000 m in Kenya, Ethiopia, Rwanda, and Burundi (Lindsay and Martins 1998). The climate studies of Tanser, Sharp, and le Sueur (2003) and of others indicate that this elevation constraint may be relaxed by climate change, with malaria epidemics occurring more frequently at altitudes of up to 2,000 m, but malaria transmission has not been reported above 2,550 m (Lindsay and Martins 1998).

One explanation for the lower frequency of vector breeding sites in highland areas is the barriers to mosquito travel presented by ridges and hills. Many vectors have limited vertical flight of only a few hundred meters, which can limit dispersal in hilly areas. Wanjala et al. (2011) examined the contribution of landscape topography to the outbreak of malaria epidemics in the western Kenya highlands. They categorized five study sites as steeply incised, V-shaped valleys; shallower, U-shaped valleys; or plateaus. The flat bottoms of U-shaped valleys had 8.5 times higher rates of malaria infection, but this also meant that these populations had higher immune responses and were less vulnerable to precipitation-driven malaria epidemics. These authors' work indicates that while monthly fluctuations in temperature and precipitation may drive epidemic spikes in malaria, landscape terrain is a good predictor of which areas are more vulnerable to these epidemics.

In similar work, Cohen et al. (2010) dissected the relationship between land cover types and high-malaria foci by characterizing sites according to a topographic wetness index. The study affirmed correlations between malaria risk and agricultural land cover; however, its primary contribution was a finding that the topography and water accumulation of the sites provided predictive power in estimating malaria risk equal to or better than that of land cover alone. Consistent with this topographic research, Ernst et al. (2009) also identified flat topography as a risk factor due to poor hydrological drainage.

Kulkarni, Desrochers, and Kerr (2010) used Landsat 7 ETM+ 30m land cover data and maximum entropy software to predict the population distributions of the vectors *Anopheles* arabiensis, *An.gambiae,* and *An.funestusin* northeast Tanzania. Their work demonstrates the strong predictive power of elevation and landcover type, when combined with precipitation and temperature data, to explain vector selection in a given location. *An.gambiae* was found to be constrained by elevation but dominant in coastal plains. *An. arabiensis* could thrive at altitudes of 2,300 m and was associated with river valleys and irrigated rice production. And *An.funestus* was constrained to areas below 1,900 m elevation, but otherwise adaptable and similarly widespread to An.arabiensis. While this study demonstrated that the mosquito vectors may thrive at these higher altitudes, it did not indicate that transmission of the parasite is successful in this elevation zone.

Kelly-Hope, Hemingway, and McKenzie (2009) examined the influence of climate, vegetation density measured through normalized difference vegetation index remote sensing data, and elevation on the vector species An. gambiae, An. funestus, and *An. arabiensis* across 30 sites in southeastern Kenya using a geographically weighted regression. Their analysis showed that *An gambiae* and *An. arabiensis* tended to be associated with higher precipitation, lower temperatures, and less vegetation (open or sparse cover rather than forest). An. Gambiae was too widespread throughout the study region to determine any geographic clustering effects. This study provides important clarification on how different land covers can have variable effects on vector populations and malaria prevalence by selecting for vectors that breed more competitively based on vegetation density and sunlight availability.

A more detailed and controlled examination of the relationship between land cover and vector reproduction was provided by Munga et al. (2006), who examined habitat productivity of *An. gambiae* for 3 landcover types (farmland, forest, and natural swamp) on 16 sq. km over an elevation range of 1,420–1,580 m. Farmland was significantly more productive for An. gambiae than forest and swamp environments. The pupation rate of larvae was positively correlated with maximum water temperature, which was higher in farmland. Not only did farmland produce more mosquitoes, but it produced them more quickly than the cooler aquatic habitats found in the swamp and forest land cover types. Of particular interest for water management at such sites, the authors found that drainage ditches on agricultural land were the most common breeding site for mosquitoes because they are kept clear of vegetation, which increases their water temperature. Increased food sources providing nutrients to larvae were also shown to increase the population and individual growth of emerging adult mosquitoes. The authors suggested that maize pollen may be a possible contributor to this effect in agricultural land cover.

Also examining the microclimates of vector breeding sites, Ndenga et al. (2011) categorized larval habitats found in the western Kenyan highlands (Emuhaya and Vihiga districts) into puddles, natural swamps, cultivated swamps, river fringes, open drains, and borrow pits. Puddles were disproportionately the most productive habitats across all four vectors measured (*An.gambiae, An.coustani, An.funestus, and An.rhodesiensis)*. Cultivated wetlands/swamps were also highly productive of *An.gambiae and An.coustani*, a matter of particular concern to agro-ecological production of vector populations. Although puddles were considered the most productive, they are also far less stable than wetlands/swamps and therefore less suitable for intervention targeting with larvicidal source management in the opinions of the authors (Ndenga et al. 2011). Ernst et al. (2009) also identify wetlands as high-risk environments in western Kenya.

While land cover can play an important role in the micro-climatic contributions to vector reproduction, these effects are not uniform across vector species which leads to competitive selection pressures within local mosquito populations. Highlighting the central role of vector-selection in localized malaria-risk, Minakawa et al. (2008) examined how the 1.5m drop in the water level of Lake Victoria has affected vector populations. They found that on newly emerged land, *An.funestus* has benefited from new breeding sites during the high-water period, being better able to reproduce during flooded conditions. *An.gambiae* has been disadvantaged during the low-water period because it is far more sensitive to the drying out of habitats during the dry season. The authors also state that there is a risk that farmers may develop newly exposed land for agriculture and increase the small pools, which would favor *An.gambiae* and tip the balance in the vector population toward this higher-risk vector. The drop in water level has so far reduced malaria risk by shifting the composition of mosquito populations towards *An. funestus* (Minakawa et al. 2008). This study demonstrates the complexity of relationships between hydrology, vector populations, and malaria transmission.

Lindblade et al. (2000) specifically identified the impacts of land use change on vector populations and malaria transmission in the southwestern highlands of Uganda. Their work further supports the view that cultivation of wetlands in Uganda fosters vector reproduction through reduced vegetation cover, leading to warmer minimum temperatures in breeding sites. Based on the conclusions regarding elevation presented in this review as well as detailed local studies by the WHO in the 1960s, these southwestern highland areas, above 1,800m, should be well protected from high transmission, but the introduction of these warmer human-induced microclimates has allowed for serious malaria epidemics driven by *An.gambiae* since the late 1990s (Lindblade et al. 2000).

Patz et al. (2004) provided a comprehensive review of the pathways by which anthropogenic land use change, including agricultural cultivation, deforestation, road construction, dam building, irrigation, and wetland modification, may impact the transmission of infectious diseases such as malaria. Their review touched on a range of health effects from land use change. Ina particularly interesting example of such effects, Ghebreyesus et al. (1999) found a sevenfold increase in childhood malaria incidence in Ethiopian villages within 3km of micro dams for irrigation compared with children in neighboring villages, 8–10km from such dams. Throughout the literature on land cover and land use change, hydrological microclimates are recurrently identified as central to the malaria risk from different land uses or land covers. For this reason, water management is reviewed in finer detail in this review.

## Urbanization

Urbanization is a type of land use change that is generally treated separately from agricultural and rural development changes in the literature. While urban areas make up only 1.1 to 1.6 percent of land cover in SSA, these urban areas contain 200 million people at risk of contracting malaria and are rapidly growing (Keiser et al. 2004, 118–127). The demographic imperative—a projected doubling of Africa's population from2010 to 2050 coupled with rapid urban growth—means that urban malaria control will be of increasing importance to Africa in the 21st century.

It is worth noting that rural areas may have up to four times the rate of malaria experienced in these urban settings (Sabatinelli et al. 1986). Urban communities in SSA have far better health indicators than their rural counterparts, reflecting better socioeconomic and physical access to preventive and curative services (Hay, Guerra, et al. 2005).Another explanation for the disparity between urban and rural malaria risk was provided by Keating et al. (2003), who used a geographic grid sampling method to capture ecological information on humans and vectors in urban Kisumu and Malindi, Kenya. Their regression analysis included the interesting result that above a certain population density, urban construction precludes habitats suitable for mosquito reproduction.

Omumbo et al. (2005) reviewed published and unpublished literature along with 329 entomological surveys and found that in East Africa, rural areas generally had a 10 percent higher malaria prevalence than urban areas, but that in high transmission settings, such as central and northwestern Uganda, this difference rose to 18 percent.

Urbanization fosters selection of different vectors in much the same way as other land use changes. Okello et al. (2006) found that in rural sites in Uganda *An.gambiae* and *An.funestus* were the typical vectors, but in the studied peri-urban site, *An. arabiensis* was the dominant vector. This ecological selection effect is important for adapting control measures to address the specific vector concerned.

Caldas de Castro et al. (2004) described the success of the urban malaria control program in Dar es Salaam in the 1990s in reducing malaria within the city using remote sensing, malaria risk mapping, and larvicidal intervention at vector breeding sites, as well as indoor residual spraying (IRS) and environmental management (such as maintaining and clearing drains) to eliminate pockets of transmission within the city. They also noted the importance of *matuta* (ridges) used in urban agriculture for crops such as sweet potatoes, rice, and beans as vector breeding sites that may increase malaria risk. Their study includes cost-efficacy comparisons demonstrating the economic favorability of measures such as drainage and larviciding in preventing malaria relative to IRS and even distribution of insecticide-treated nets.

The CGIAR (Consultative Group for International Agricultural Research) System wide Initiative on Malaria and Agriculture released the Pretoria Statement on Urban Malaria in 2004 in order to emphasize that control strategies used in rural areas would not be easily transferred to urban malaria control efforts (Donnelly et al. 2005). Numerous studies have documented geographically clustered risk associated with urban agriculture, aquaculture, and proximity to wetlands (Klinkenberg et al. 2004; Julvez et al. 1997). More recently, Stoler et al. (2009) have found through regression analysis that women within 1 km of urban agriculture within Accra, Ghana, are at higher risk of malaria than other urban women despite higher socioeconomic status. These results confirm the views of the Pretoria Statement on Urban Malaria and reinforce the role of agriculture as a key element of malaria control.

Hay et al. (2005) firmly established that both behavioral changes and reduced ecological transmission potential are the key factors behind lower malaria prevalence in urban areas. Most encouragingly, they showed that in the case of Nairobi, malaria transmission within the urban area collapsed between 1950 and 2000, with new cases originating from outside the city. Although this bodes well for the increasing number of urban Africans, a vast majority of Africans still reside in rural areas.

## Agroforestry and Deforestation

Deforestation is another type of land use change that is frequently treated separately from generalized discussions of land use change. Yasuoka and Levins (2007) reviewed 60 case studies on how deforestation and subsequent agricultural land use may affect anopheline ecology. The review categorized case studies according to 31 *Anopheles* species and the conversion of forest into 14 categories:(1) general deforestation, (2) land exploitation and pollution, (3) cacao plantation, (4) cassava cultivation,( 5) sugarcane growing, (6) coffee plantation, (7) tea plantation, (8) rubber plantation, (9) rice cultivation, (10) irrigation system, (11) hydropower dam, (12) clearing of mangroves or swamps for fish ponds or charcoal, (13) mining, and (14) new settlements and urbanization, including highway construction.

Yasuoka and Levins (2007) concluded that the responses of individual *Anopheles* species to deforestation and rural development were highly divergent across species and across different locations. They provided valuable comparative evaluation of the many local studies on individual cases of deforestation. Furthermore, their focus on conversion of forest to agricultural uses is especially relevant to rural Uganda, where such land use changes are widespread.

Pattanayak and Yasuoka (2008) elaborated in further detail how malaria transmission shifts between species over time as part of a sequence of land use changes, documenting how a typical forest vector can be replaced by another vector species during the construction of irrigation works, and that successor can be replaced by others in the final cultivation phase. By way of example, *An.gambiae* breeds in small, sunlit puddles but does not breed well under a closed forest canopy; deforestation therefore increases breeding potential for this principally highland vector (Lindsay and Martins 1998).

Omlin et al. (2007) studied the role of specific tree species on *Anopheles* breeding patterns in urban and peri-urban areas of western Kenya (bordering Lake Victoria and southeastern Uganda). Their entomological survey indicated that *An.gambiae* uses tree holes as favored breeding sites rather than open water or puddles. The authors found that 19tree species harbor *Anopheles* larvae in urban environments, of which 13are nonnative tree species, such as eucalyptus, fig, avocado, mango, and acacia. This approach complements that of Yasuoka and Levins (2007), disaggregating by different tree species rather than by different *Anopheles* species.

Afrane et al. (2006) brought the established consensus on microclimate to bear on deforestation to explain its effects on malaria transmission. Their study compared houses shaded by forest with houses in deforested areas, lacking shade. They found that by raising the temperature of indoor breeding environments in the houses, deforestation contributes to the reproductive rate of mosquito populations, increasing malaria transmission in the western Kenya highlands. Ernst et al. (2009) also identified forest fringes as high-risk environments in western Kenya due to the lack of shade trees and vector preference for sunlit environments for breeding.

### Maize Cultivation

Maize has only recently been identified as a contributor to vector reproduction. Building on the initial work of Ye-Ebiyo et al. (2003), Kebede et al. (2005) demonstrated that hybrid maize cultivation had increased malaria incidence in the highlands of Ethiopia by a factor of 10over the past 20years. Specifically, Kebede and others (2005)found that adopting higher-yield, hybrid maize varieties such as BH660 led to pollination of mature maize plants later in the year (during August to September), which coincides with the ideal time for *Anopheles* breeding due to warmer temperatures and higher humidity. The authors also suggested that since pollination occurs later in the rainy season, pollen is less likely to be washed away from stagnant pools. They cited entomological studies showing that larvae fed on maize pollen survive to adulthood at higher rates and grow to larger sizes as adult mosquitoes. Larger adult body size contributes to greater longevity in these studies. BH660 therefore contributes to both the life expectancy of mosquitoes and the number of mosquitoes per human host. Ernst et al. (2009) corroborated these results in the western Kenya highlands, finding that cultivation of maize within 500m of a household was associated with higher malaria risk. This minor change in agroecology, a shift from conventional varieties to higher-yield hybrid seeds, is instructive of how small ecological changes can result in large, unanticipated effects.

### Livestock

Livestock is known to play a role as an alternative blood-meal source for vector populations; this characteristic has led to research on two contrary potential impacts on human malaria prevalence. Greater livestock density may reduce human malaria if vectors prefer livestock meals; or greater livestock density may increase human malaria if the larger food resource increases vector populations that continue to feed on humans (Mutero et al. 1999). Which of these trends prevails locally is dependent on the vector's meal/host preference. Seyoum et al. (2002) evaluated the effects of increased livestock keeping on the human biting rate of the vectors *An. arabiensis* and *An. pharoensis*. They demonstrated that keeping cattle in separate sheds outside of human dwellings can decrease the biting rate, but that greater cattle and goat density will increase human biting rates by these vectors (Seyoum et al. 2002). *An. arabiensis* is an important East African highland vector dominant in irrigation systems; it has a preference for livestock over humans (Mahande et al. 2007). Mahande et al. (2007) evaluated the effect of treating livestock with pesticide sprays in irrigated highland areas. A similar evaluation of livestock treatment was conducted in southern Ethiopia, where the vectors were known to have a preference for livestock meals and could thereby be eliminated or reduced at that intervention point (Habtewold et al. 2001). The research and programming on livestock and malaria are comparatively underdeveloped compared with those directed at land and water management, making it difficult to draw conclusions about the potential impact of livestock management on malaria prevalence.

Peterson et al. (2009) used multilevel analysis to calculate malaria risk at the individual and household levels in the peri-urban town of Adama in the Ethiopian highlands. The primary household risk factor across 310 households was living within 450m of a single vector breeding site, which accounted for 38.78 to 78.49 percent of variance in malaria outcome. This breeding site was a floodplain bordering the study site, used for cattle watering in the wet season and crop cultivation in the dry season. Additionally, this case study found that keeping 7or more livestock within 10m of the home also increased malaria risk for households from the vector *An. arabiensis*.

These disparate studies on the environmental malaria risk can inform local malaria management by identifying the root causes of baseline transmission potential. While certain environmental drivers of malaria transmission may be beyond the scope of intervention, many of the factors identified are readily modifiable through cost-effective means.

# 4. THE ECONOMICS OF MALARIA

Economic studies of malaria fall roughly along two lines of inquiry. The economic development literature generally focuses on the loss of labor productivity (Bleakley 2007; Nur 1993), land use changes such as shifting agriculture away from malaria-endemic areas and loss of investment in such areas (Wang'ombe and Mwabu 1993), and negative shocks to household finances due to malaria episodes (Shepard et al. 1991).

The second broad category of literature comes from the public health community. These analyses focus on the cost-efficacy of malaria health programs and measure macroeconomic costs that may justify investment in large-scale malaria control programs (Sachs and Malaney 2002; Wernsdorfer and Wernsdorfer 1988). At the macro level, it is an established fact that malaria is more prevalent in poorer regions of the world, especially Africa south of the Sahara (SSA) (Chimaet al. 2003; Gollin and Zimmermann 2007). Packard (2009) provided an in-depth critique of many such health–economics studies, arguing that since correlation and causation cannot be readily resolved in these studies, less focus should be given to economic justifications for malaria control.

Asenso-Okyere et al. (2009) have provided a broad overview of the literature roughly consistent with this division in the literature.

## Malaria and Socioeconomic Status of Households

At the micro level, a sizable body of literature has attempted to establish a relationship between malaria and the socioeconomic status of households and communities. Worrall, Basub, and Hansona (2003) used "material assets" as a proxy for socioeconomic status of households and found no positive relationship between asset ownership and reduced malaria incidence at the household level. At a more aggregate level, groups of lower socioeconomic status were found to have higher vulnerability to malaria, which may reflect lower access to malaria treatment. Among the most frequently cited barriers to access were the cost of treatment and distance to the nearest health center. Worrall, Basub, and Hansona (2003) mentioned that expenditure on prevention of malaria is more strongly correlated with income and socioeconomic status than is expenditure on treatment. Generally, rich households are more likely to use anti malaria drugs when the disease does occur.

According to Somi et al. (2007) and Goesch et al. (2008), contracting the malaria parasite is associated with reduced household socioeconomic status. Somi et al. (2007) included age, bed net use, household size, and household wall construction among their variables of socioeconomic status. Goesch et al. (2008) included living in a stone house, having running water in the house, hours of shower / flush toilet availability, ownership of a freezer, and belonging to the highest group in economic score.

Using household data from Tanzania, Dickinson et al. (2011) outlined a conceptual model of how socioeconomic status may influence malaria. This study found access to malaria prevention and treatment to be significantly associated with indicators of households' wealth. Dickinson et al. (2011) found demographic variables to be more closely related to reported malaria illness than socioeconomic status variables.

The study by Worrall, Basub, and Hansona (2003) showed differences in the types of care sought by wealthy and poor households, with the poor more frequently opting for care outside the "modern sector" and the wealthy more frequently opting for care inside it. The poor are both more likely to contract the parasite and less likely to be protected by bed nets or to receive appropriate treatment.

Mmbando et al. (2011), having analyzed spatial variations in the socioeconomic determinants of malaria infection in northeast Tanzania, found that rural areas were at greater risk than urban, that mud-walled housing posed a comparatively higher risk than brick, and that thatched roofing posed a higher risk than iron sheeting. Bed net coverage and socioeconomic status were both negatively correlated with malaria infection, as expected. The authors' geographic threshold of 1,500m for determining spatial effects reflected known dispersal ranges of typical vectors. The model's predictive power varied among the three vectors studied, but land cover types, seasonal precipitation, and maximum monthly temperature consistently contributed to predictive power. The paper also identified highland areas where these vector populations exhibited “anophelism without malaria,” a vector population that has the potential to transmit malaria but does not have any infection within the vectors. Anophelism without malaria is the goal of interrupting malaria transmission through malaria control measures. It is impossible to eradicate mosquitoes, but once the parasite is no longer present in the population, the vectors no longer pose a risk of disease transmission to humans. This paper is important because it demonstrated the ecological feasibility of this goal in the East African context. The authors also emphasized the utility of this form of risk mapping to identify foci of transmission as well as local tailoring of control interventions.

Messina et al. (2011) used a two-stage model with geographically weighted regression to analyze MEASURE DHS data from the Democratic Republic of Congo to model malaria prevalence at the national level. Their model predicted greater malaria prevalence in areas farther from urban centers; at higher elevation; and with lower community-level wealth, lower community-level bed net use, and lower individual wealth.

## Microeconomic Impacts of Malaria

Microeconomic impact studies mainly deal with the impact of malaria at the productive unit level. This can be a household or firm (Chima et al. 2003). Direct costs of malaria at the household or firm level include expenditures on prevention and treatment of malaria, while indirect costs include opportunity cost of the time lost as a result of the illness. Direct cost estimates suggest that households spend a lot of resources on prevention and even more on treatment (Chima et al. 2003).

Taking the case of rice farmers in Cameroon, Audibert (1986) assessed the effect of malaria on labor productivity. Audibert estimated a Cobb-Douglas production function and found no significant relationship between malaria incidence and rice production. Goodman, Coleman, and Mills (2000) cited Brohult et al. (1981), who looked into the impact of malaria on the working capacity of individuals in Liberia. They found no major differences between farmers living in areas where malaria is endemic and other workers living in areas where it is mesoendemic (that is, where the prevalence is between 11 and 50 percent).

The other microeconomic component is household expenditure, usually presented in two forms: prevention costs and treatment expenditure. In Malawi, preventive expenditures ranged between US$0.23[1] and $15 per household per month, while treatment costs ranged between $1.79 and $25 per household per month (Ettling et al. 1994).

Studies on the microeconomic impact of malaria need to be strengthened. Most provide evidence to affirm many microeconomic relationships with malaria but report problems in data (for example, de Bartolome and Vosti 1995). Many studies use inadequate data to calculate indirect costs, do not account for seasonal variations, fail to differentiate between average and marginal product of labor or fail to emphasize the different ways households and firms manage illness episodes (Chima et al. 2003).

## The Macroeconomics of Malaria

Gallup and Sachs (2001) mentioned that malaria and poverty are intimately connected, underscoring that in 1995 countries with malaria had only about one-third of the income level of countries without malaria, whether or not the countries were in Africa. However, malaria is geographically specific and malaria has more to with the ecological situations that create favorable conditions for the reproduction of malaria mosquito vectors. Intensive efforts to eliminate malaria in the most severely affected tropical countries have been ineffective, while countries that have eliminated malaria in the past half century have all been either subtropical or islands. The authors conducted cross-country regressions for the period from 1965 to 1990 to confirm the relationship between malaria and economic growth. Taking into account initial poverty, economic policy, tropical location, and life expectancy, countries with intensive malaria grew economically by 1.3 percent less per person per year, and a 10 percent reduction in malaria was

[1] All dollar amounts are in US dollars.

associated with 0.3 percent higher economic growth. Furthermore, Abdulla et al. (2001), cited by Chimaet al., (2003), demonstrated a significant negative relationship between growth in gross domestic product per capita and burden of malaria.

Gollin and Zimmermann (2007) pointed out the possibility for a country's economy to fall into a *malaria trap*, a situation of sickness begetting poverty and poverty making disease prevention unaffordable. Their model quantified the magnitude of the malaria trap, finding that malaria can reduce income per capita by about half. Comparing their results with those of Gallup and Sachs, who noted that "44 countries with intensive malaria burdens in 1995 had per capita income of $1,526, compared with $8,268 for the 106 countries without intensive malaria burden"(2001, 85),the Gollin and Zimmer (2007) model suggests that the disease alone could account for just under half of this income gap.

Ettling et al. (1994) investigated the economic impacts of malaria in Malawi, finding that expenditures for malaria varied with income levels: Very-low-income households spent 28 percent of household income on malaria treatment, while this amount was only 2 percent for the remaining households. Low-income households carried the biggest share of the economic burden of malaria. At a more macro level, Shepard et al. (1991) investigated the impact of malaria in Africa for 4case study countries (Burkina Faso, Chad, Congo, and Rwanda), deriving estimates for all of SSA from the averages of these 4countries. Estimated in 1987 US dollars, the per capita malaria cost was put at $9.84. Assuming that the average value of goods and services produced per day in Africa was $0.82 (in 1987); the authors equated this cost to 12 days of output.

A study conducted by Barofsky et al. (2010) evaluated the economic consequences of a malaria eradication campaign in a southwestern Ugandan district. The project was implemented during 1959 and 1960 through dichlorodiphenyltrichloroethane (DDT) spraying and mass distribution of anti-malaria drugs. The authors compared the project district with the rest of Uganda and found improvements in years of schooling, literacy, and primary school completion. In addition, the successful malaria eradication campaign had a significant impact in improving income levels.

Generally, studies indicate that malaria carries a major economic burden, especially for low-income households. Direct costs include money spent for malaria prevention and treatment, while indirect costs come through effects on labor productivity, land use, child school attendance, school performance, and cognitive development, among others (Goodman, Coleman, and Mills 2000).According to Shepard et al. (1991), 19 percent of total malaria costs in Africa are direct and the reminder indirect. Economic impact studies of malaria have generally failed to consider the specific nature of the malaria disease burden, the difference in coping strategies of households, and the effect of malaria on production incentives of households.

Although a variety of studies analyze the macroeconomic impact of malaria itself, these macroeconomic analyses are often complicated due to issues of endogeneity (Packard 2009).

# 5. ENVIRONMENTAL MANAGEMENT FOR MALARIA CONTROL

Historically, engineering- and environment-based interventions have played a major role in reducing malaria cases (Konradsen et al. 2002). Since the 1980s, pesticides have gained prominence as a tool for malaria control through the introduction of insecticide-treated nets (ITNs) and renewed use of dichlorodiphenyltrichloroethane (DDT) for indoor residual spraying (IRS). With the rapid development of resistance of mosquitoes to widely used insecticides, there is also renewed interest in environmental management–based approaches to fighting malaria (Konradsen et al. 2002).

Environmental management interventions for malaria control include the modification of land, water, vegetation, or human infrastructure to minimize vector propagation and human–vector contact (Keiser, Singer, and Utzinger 2005). Keiser, Singer, and Utzinger (2005) reviewed 40 case studies of environmental management interventions and their success or failure to reduce the local malaria burden. Their discussion highlights some of the important nuances to using environmental management, such as the local idiosyncrasy of successful programs, the long-term sustainability and cost-efficacy of environmental management, and the need for integration of environmental management within a larger malaria control strategy. These themes are repeated throughout the environmental management literature. Keiser, Singer, and Utzinger (2005) broke down the different applications of environmental management into 4eco-epidemiological settings: malaria occurring in deep forest and forest fringes, rural malaria attributable to irrigation and agricultural activity, rural malaria attributable to natural ecology, and urban malaria. While noting a publication bias toward including well-documented (and possibly therefore well-managed) programs in the review, the authors found that in many situations environmental management may reduce malaria risk by up to a factor of 10.

Another key review of environmental management was published by Lindsay et al. (2004), focusing on environmental management for malaria control in the East Asia and Pacific region. The local ecology–specific and vector-specific information is not directly transferable to the African or Latin American contexts in all cases, but the conceptual approach is. The authors document environmental management techniques that have controlled or could control vector populations: populating irrigation canals with larvivorous fish, applying bacterial larvicides[2] in urban vector breeding sites, building major subsurface drainage systems, making health planning a part of infrastructure development, and conserving mangroves to reduce coastal vector breeding at shrimp farm sites. The diversity of the cases outlined provides a broader approach to potential vector control options than much of the available literature.

Focused specifically on Africa south of the Sahara (SSA), Walker and Lynch (2007) reviewed the efficacy of larval control methods in malaria control. The interventions studied include removal of breeding habitats and larviciding with chemical and biological agents. These techniques have proven successful in urban environments when integrated into larger malaria control programs as demonstrated by the Urban Malaria Control Program in Dar es Salaam (Geissbühler 2008).

Killeen, Seyoum, and Knols (2004) provided an important framework for quantifying the contribution to vector control that environmental management has had in SSA. They developed a transmission model based on reproductive and food resource availability to vector populations. They tested their model against historical data from the pre-DDT era using an environmental management program from the Zambian Copperbelt in the 1930s and 1940s, which was also analyzed by Keiser, Singer, and Utzinger (2005) and by Utzinger, Tozan, and Singer (2001). The case study included modifying river banks to promote flowing water; screening windows, porches, and doors with mosquito netting; clearing vegetation; larvicidal oiling; and draining wetlands. This case study is one of the most empirically reliable due to the high quality of data available. Malaria incidence decreased by 75 percent in the first 2years of the program and remained at that level except for spiking each March with the onset of rains.

[2] Bacterial larviciding refers to the use of bacterial pathogens that attack insect larvae; the process was introduced as an alternative to chemical insecticides in the 1970s (WHO 1999).

Utzinger, Tozan, and Singer (2001) used historical budget records from the same Zambian Copperbelt program to evaluate the cost-efficacy of environmental management as one component of a malaria control strategy. Their work concluded that each death averted cost an estimated $858; each malaria case averted cost an estimated $22. According to the authors, these findings show environmental management to be comparable to ITN interventions in cost-efficacy terms, but only over decade-long intervention programs, wherein the benefits of high initial investments accrue to a greater number of persons over time.

The cost-efficacy of environmental management has to be weighed against the cost-efficacy of conventional interventions. Goodman, Coleman, and Mills (2000) evaluated conventional interventions in cost per disability-adjusted life years (DALYs) averted. DALYs are a standard public health measure of disease burden that measures the burden both from death (relative to life expectancy) and from illness. ITN programs (with an effective insecticide treatment lifespan of 2 to 5 years) cost between $19 and $85 per DALY averted; IRS programs cost between $16 and $29 per DALY averted, based on spraying twice a year; chemoprophylaxis programs cost between $8 and $41 per DALY averted, including the costs of setting up a distribution network. The study found that insecticide resistance led to a rapid reduction in cost-efficacy of both ITNs and IRS once resistance occurred in 25 to 75 percent of vectors (Goodman, Coleman, and Mills 2000). In contrast to these measures, the cost-efficacy of environmental management can be considered only over longer timer periods.

## Water Management Options

Water management is a critical topic within environmental management because of the central role that water plays in the reproduction of mosquitoes and its complex relationship to malaria transmission risk.

Asenso-Okyere et al. (2011) listed irrigation, wetland cultivation, and urban agriculture, among others, as water projects with the potential of causing malaria in Africa by expanding habitats for malaria-carrying mosquitoes, though these very activities would also increase the income of producers and thus their preventive capacities for malaria. Klinkenberg et al. (2002) conducted a field study on the rice irrigation system of Office du Niger, Mali, to investigate the water management options in general and their connection to malaria mosquito larval development in particular. They found that improper drainage after rice harvesting caused *Anopheles* gambiae to breed quickly and re-establish itself in fields where small water pools remained. Klinkenberg et al. (2002) recommended mosquito control by draining properly after harvesting the rice and through denser transplanting. Whether an individual water project triggers an increase in malaria transmission depends on the contextual determinants of malaria, including the epidemiologic setting, socioeconomic factors, vector management, and health-seeking behavior (Keiser, Singer, and Utzinger 2005).

Rice cultivation in West Africa and the Americas has a deep-rooted relationship with malaria transmission (Carney 2001). Ijumba and Lindsay (2001) examined the relationship among irrigation, rice, and malaria across SSA. In high-transmission areas, they found evidence that irrigation may actually have beneficial effects by displacing the vector *An.funestus* with *An.arabiensis*. *An. arabiensis* has a lower *vectorial capacity* for transmission but breeds more favorably in irrigated paddies than *An. funestus.* Displacing *An. funestus* with a less dangerous vector resulted in lower malaria transmission even though *Anopheles* was still present in large numbers. In contrast, expansion of irrigation into low-transmission areas may increase malaria transmission by introducing vector breeding sites. Villages with rice production will also tend to have improved income and be able to afford ITNs and anti-malarial drugs, a fact that complicates deciphering the relationship between irrigation and malaria.

For this review, we assess the evidence of alternate wet/dry irrigation (AWDI), wetland cultivation, and irrigation canals on malaria incidence as distinctive examples of water management activities with implications for malaria and malaria control.

## Alternate Wet/Dry Irrigation

In view of the growing competition for limited water resources and low rice yields in many developing countries, there is a renewed interest in finding better ways to grow more rice with less water (McHugh et al. 2003). Alternate wet/dry irrigation (AWDI) is one such method that can reduce water use with stable or increased yields. In AWDI, rice fields are intermittently dried instead of being kept continuously submerged (van der Hoek et al. 2001).

Van der Hoek et al (2001) summarized several studies on AWDI and its efficacy in terms of water saving and health impacts in different areas. Owing to the water-intensive nature of rice, more irrigated land is devoted to rice than to any other crop. While it is well known that AWDI saves water in the field, impacts on land productivity are less clear. AWDI reduces the potential of mosquito larvae to survive in the rice fields and thus reduces overall malaria incidence. However, the success of AWDI regarding improved health and increased water productivity is context specific. Van der Hoek et al. (2001) found that AWDI was effective against An.funestus in one case, but not against An.gambiae. In China, India, Indonesia, and Portugal, AWDI has been able to reduce mosquito larvae in rice paddies by as much as 75 to 90 percent (van der Hoek et al. 2001, 23). AWDI is suitable only where the main transmission vectors reproduce in paddy fields.

The most important factors that determine the success of AWDI are irrigation infrastructure, irrigation management capacity, and several natural factors such as rainfall and soil conditions (van der Hoek et al. 2001). The authors concluded that rather than mosquito control, the reason for AWDI adoption should be an effort to increase water productivity, particularly in water-scarce areas. They also stressed the criticality of land preparation as a precondition for the success of AWDI practices and malaria control. If land leveling is not done properly, numerous small puddles are left behind, which could increase the egg-laying potential of mosquitoes and thus increase malaria transmission if AWDI is practiced.

Similarly, Krishnasamy et al. (2003) reported on the health risk of AWDI as a result of pools of standing water left in rice fields in Tamil Nadu, India that were not properly leveled and drained, creating a breeding ground for mosquitoes that carry malaria. They concluded that although AWDI saved water locally while maintaining yields, it was not effective in suppressing mosquito breeding under the farmer-managed conditions encountered in the field, where frequent rainfall and inadequate field leveling confounded the intended drying effects of the AWDI water management regimens.

## Wetland Cultivation

Dixon and Wood (2003) analyzed wetland cultivation in the East Africa region with implications for short- and long-term wetland management policies. In view of the food insecurity prevalent in the region, wetland cultivation may serve as a remedial measure to offset production losses during periods of drought. However, this approach to food security raises long-term implications of the sustainability of wetland cultivation and maintenance of the benefits from wetland activities (Dixon and Wood 2003; Mulugeta 2004). In stark contrast to the very objective of wetland cultivation and its food security solutions, a study by Mulugeta (2004) on wetland use and its determinants in Ethiopia highlighted that it is the richest farmers who are practicing wetland cultivation. Mulugeta cited “greater legal and customary access to wetlands and more labor resources” as the main reasons for wetland cultivation by the “rich” rather than the “poor” as defined in the case study (2004, 110).

Dixon and Wood (2003) also highlighted the importance of the multiple uses of wetlands so as to sustain wetland benefits with little or no evidence for environmental degradation. This means placing drained and cultivated wetland areas alongside areas reserved for cattle and craft material collection. This is in contrast to complete wetland drainage and cultivation as well as to complete reservation of wetlands for grazing and other purposes. The paper also cites Denny and Turyatunga (1992), who reported that many wetland areas, in particular swamps, have suffered from intensive cultivation and drainage by the government in Uganda. The drainage and intensive grazing have accelerated water conveyance downstream, thus reducing the wetland’s ability to buffer peak flows and nutrient levels.

Lindblade et al. (2000) explored the role of wetland cultivation in the Ugandan highlands as an explanation of the introduction of malaria to this historically malaria-free region of SSA. Their study was based on entomological surveys of eight villages near the Rwandan border where land use patterns had recently changed. The cultivation of wetlands was linked to local temperature and humidity changes affecting vector reproduction in these areas. The authors argued that these wetlands were covered with natural papyrus, which limits the breeding of the *An.gambiae* mosquito because of the denseness of the vegetation and the natural oil layer. The elimination of the papyrus and the reclamation of the swamps have led to an increase in temperature, which promotes the breeding and survival of mosquitoes and increases malaria transmission. Lindsay and Martins (1998) also reported that the clearing of papyrus increased breeding potential because the natural oils of papyrus inhibit mosquito reproduction.

## Malaria and Canal Irrigation Systems

Ijumba and Lindsay (2001) conducted a review of recent literature of irrigation effects on malaria in Africa. They made a distinction between areas of "unstable transmission," where people have little or no immunity to malaria parasites, such as the African highlands and desert fringes, and areas of "stable transmission," which include most of SSA. In their comparison, increased numbers of vectors following crop irrigation have had little impact on malaria in areas of stable transmission.

Since rice dominates irrigation globally, Ijumba and Lindsay (2001) also made a distinction between rice and other crops. They found that development of rice irrigation programs in areas of stable malaria was associated with a decline in the prevalence of malaria in rice-growing communities compared with non-rice-growing areas due to improved socioeconomic status and higher adoption of anti-malaria protection measures. Based on these findings, Ijumba and Lindsay (2001) suggested that the economic gains from rice irrigation should be invested on anti-malarial measures.

Ijumba and Lindsay (2001) also found, based on an irrigation project in the Sudan that the increase in malaria incidence in the area was associated with the expansion of areas used for cotton and wheat, highlighting the change of the pattern of malaria transmission as the irrigation of wheat during winter months led to a second seasonal peak in malaria. Also, wheat irrigation occurred at a time when air temperatures were conducive for malaria transmission. They also showed that human factors (migration) exacerbated the problem of malaria.

Lokesha, Talawar, and Pol (2002) found that production of mosquitoes was higher in rain fed areas, where there was less water containing pesticides, than in irrigated areas, where pesticides contained in irrigation water reduce reproduction of mosquitoes drastically. Mukhtar et al. (2002) made an attempt to correlate malaria vectors with irrigation in South Punjab, Pakistan, and found that *Anopheles* breeding was "directly or indirectly" linked to the extensive canal irrigation system (2002, 42).

Senzanje, Hackenitz, and Chitima stated that irrigation has tremendous negative effects on health, especially for malaria, in the case of Zimbabwe (2002, 15). Depending on the control measures in place, 11–49 percent of the estate employees in the large-scale irrigation project studies suffered from malaria and 38 percent of total labor days were lost due to malaria. According to these authors, malaria control costs continue to increase, making irrigation unsustainable in view of the rising costs of chemicals and fertilizers.

Ijumba and Lindsay (2001) noted, however, a common problem in the general approach of measuring the impact of irrigation on malaria: Many irrigation-versus-malaria studies make their comparisons based on a few villages, comparing those with irrigation and those without. Such comparisons may overlook differences between these villages that existed before initiation of the irrigation project. For example, it is more common to irrigate rice in areas that retain water, and thus transmission of malaria may have been higher in the rice villages even before irrigation began (Ijumba and Lindsay 2001).

Importantly, blaming irrigation for aggravating the disease situation in local communities is "not evidence-based" in areas of "stable transmission" (Keiser et al. 2005, 394). Large numbers of mosquitoes do not necessarily coincide with large malaria incidence. This apparent paradox is explained by the fact that stable transmission areas are well prepared with bed nets and anti-malaria drugs. Keiser and colleagues (2005) suggested that as residents of the irrigation project area become wealthier due to income generated from agricultural production, some of the increased income should be diverted to protecting health. In areas around irrigation and dam sites, especially in "unstable" malaria-endemic areas, integrated malaria control measures and sound water management strategies are necessary to mitigate the burden of malaria (Keiser et al. 2005).Also, Ijumba and Lindsay (2001) reiterated that the irrigation costs need to be balanced against the gains of a more regular food supply and the possibility of greater wealth and nutrition.

De Plaen stressed the importance of an integrated approach to malaria and irrigation, calling it an "ecosystem approach to human health" (2002, 39). This approach considers the indirect impact of irrigation schemes through the natural environment, how irrigation affects the livelihoods of famers, and the effects of livelihood patterns on general human health and malaria in particular. De Plaen's (2002) study of northern Côte d'Ivoire confirms the hypothesis that irrigation effects are not limited to human–vector contact but function through the broader pathways of the farming system, socioeconomic structure, and gender relations.

## Malaria Control in Irrigated Areas

Several studies discuss the control and mitigation of the relationship between irrigation activities and malaria. Fernando (2002) mentioned that a periodic release of water from dams into the river helps reduce anopheline breeding. To minimize malaria risk in irrigation projects, Fernando recommended such intermittent flushing at dam sites especially during dry months (when the flow of the river below the dam is reduced to a level that could create vector breeding sites) as well as lining irrigation channels with cement (2002). Maintenance of irrigation channels and improved coordination between irrigation project authorities and anti-malaria campaigns also help reduce malaria risks (Rushomesa and Ndonde 2002). In the Sri Lankan Mahaweli irrigation project areas, a network of voluntary malaria treatment centers was established to provide free chemoprophylaxis to newly settled farming families for six months, which proved effective at controlling parasite introduction and transmission in the irrigated area.

Mini and Jyotishi (2002) highlighted the importance of institutions in the reduction of malaria transmission in irrigation systems. After comparing water systems managed by water user associations (WUAs) with those managed *centrally* in Karnataka, India they found that WUAs played an important role in both enhancing agricultural productivity and reducing malaria transmission through efficient water management policies.

Konradsen et al. (2002) reviewed three experiences of malaria vector control in engineered irrigation systems, examining historical cases from Punjab, Malaysia, and Sri Lanka. Mian Mir, now a suburb of Lahore, Pakistan, was a prominent experimental location for malaria control from 1901 to 1909. Malaria control measures included repairing the banks of the irrigation channels, clearing them of silt and vegetation to reduce overflow, leveling depressions next to channels, larvicidal oiling, and mass administration of quinine. Although the works were successful at reducing mosquito reproduction in the targeted environment, adult mosquito abundance was maintained through neighboring breeding sites. The MianMir case was also one of the first documented studies of "how to combine food production, livelihoods, and public health" (Konradsen et al. 2002, 8) and the source of much early debate on vector control. The Malaysian case study was also highly influential, with the subsurface drainage works experimented with at Klang and Port Swettenham becoming the basis for the drainage activities undertaken in the United States in the pre-DDT era following economic feasibility analyses funded by the Rockefeller Foundation in 1915–16 (Russell 1968). Surface drainage refers to water being carried off the land by systems of drains, generally through gravity. Subsurface drainage systems intercept water underground and carry it off to rivers and streams. Dadhich, Gupta, and Tejawat (2002) found that subsurface drainage cut down on waterlogged areas, thus decreasing the amount of standing surface water used as a breeding habitat by mosquitoes. The types of environmental engineering employed in early malaria control programs would likely not be feasible today, since they were conducted without the concern for the conservation of ecosystems that is now part of standard environmental impact assessments for major engineering works.

## 6. PESTICIDES, MALARIA, AND PESTICIDE RESISTANCE

Experimentation with dichlorodiphenyltrichloroethane (DDT) for mosquito control by the US military during World War II made elimination of malaria through vector control a highly cost-effective public health strategy. Use of DDT led to the elimination of malaria in Japan, Europe, North America, and the former Soviet Union by the late 1960s as part of the World Health Organization's (WHO's) Global Malaria Eradication Program (GMEP). In 1972, following the 1962 publication of Silent Spring by Rachel Carson, DDT use was banned by the newly created US Environmental Protection Agency. The subsequent drop in production led to a rapid increase in the international price, reducing the ability of low-income countries to continue using DDT in their malaria control programs (WHO 1975, 473). The 1995 Stockholm Convention on Persistent Organic Pollutants banned the use of DDT except for public health purposes (UNEP 2001; WHO 2004b).

While malaria control activities relied on targeted use of pesticides, agriculture practices involve widespread spraying and fogging over large areas, a method that fosters resistance in various insects, including *Anopheles* mosquitoes. During the 1960s, the Food and Agriculture Organization (FAO) and the WHO advocated for use of pesticides toward the goals of increased agricultural production and vector-borne disease elimination, respectively. Pesticide resistance arises as part of a cycle in which farmers continuously try to maintain yields by increasing application quantities as insects adapt to pesticides.

Since pesticide applications for agriculture are many orders of magnitude greater than those used in homes for public health purposes, rising resistance quickly eliminated the capacity of health departments to combat disease vectors such as *Anopheles* mosquitoes. Use of insecticides in agriculture has repeatedly been documented as contributing to the rise of insecticide resistance in *Anopheles* mosquitoes and subsequent erosion in the efficacy of malaria control. According to some analysts, this was a key contributor to the failure of the GMEP to succeed in Central America and the Indian subcontinent in the 1970s as cotton farmers applied large quantities of pesticides (Chapin and Wassertrom 1981; Cueto 2007). Sharma and Mehrotra disagreed (1986), suggesting that frequent pesticide supply chain interruptions were more to blame for malaria resurgence in India than pesticide resistance, but these two causes are complementary rather than exclusive.

Advocacy for pesticide use on crops in malarious areas, without coordination between the agricultural and health sectors, undermined malaria control ecologically and financially (Chapin and Wasserstrom 1981, WHO 1976).The financial cost of switching to second-and third-line pesticides in response to resistance was and remains prohibitive for many malaria control programs (Yekutiel 1980). In response to rising pesticide resistance, the FAO developed integrated pest management (IPM) strategies and guidelines in the early 1970s, but these programs started only after malaria programs declined due to the rising cost of DDT and second-line pesticides (Smith and Calvert 1976). More recently, a similar process has been documented in Burkina Faso and Peru, where application of pesticides on cotton created pyrethroid resistance in *Anopheles* mosquitoes, undermining the efficacy of insecticide-treated nets (ITNs) (Diabate et al. 2002; Kroeger et al. 1995). It is notable that over 40 years, cotton cultivation has been linked to insecticide resistance across 4continents.

As donor interest in malaria control has increased in recent years, pesticide resistance has once again become of concern to the public health sector. Current malaria control strategies rely heavily on indoor residual spraying (IRS), ITNs, and mass drug administration or chemotherapy. Two of these three tools are at risk of diminishing efficacy due to the development of insecticide resistance on the part of *Anopheles* mosquitoes. Insecticide-resistant malaria vectors have been documented in most malaria-endemic countries. Table 6.1 presents information on insecticide resistance by country. The problem of insecticide resistance is increasingly acknowledged and accepted within the public health sector; the impending rise of resistance across Africa might well threaten the gains in malaria control made in recent years (Kelly-Hope, Ranson, and Hemingway 2008).

**Table 6.1—Countries with documented anopheline insecticide resistance**

| Africa | Reference | Asia / Europe | Reference | Latin America | Reference |
|---|---|---|---|---|---|
| Benin | N'Guessan, R., V. Corbel, M. Akogbéto, and M. Rowland. 2007. | Bangladesh | Mittal, P. K., P. Wijeyaratne, and S. Pandey. 2004. | Belize | Dusfour, I., N. L. Achee, I. Briceno, R. King, and J. P. Grieco. 2010. |
| Burkina Faso | Diabate, A., T. Baldet, F. Chandre, M. Akoobeto, T. R. Guiguemde, F. Darriet, C. Brengues, et al. 2002. | Burma | Kyi, K. M. 1972. | Colombia | Fonseca-González, I., R. Cárdenas, M. L. Quiñones, J. McAllister, and W. G. Brogdon. 2009. |
| Burundi | Mouchet, J. 1988. | Cambodia | Verhaeghen, K., W. Van Bortel, H. D. Trung, T. Sochantha, and K. Keokenchanh. 2010. | Ecuador | Brogdon, W., and J. McAllister. 1998. |
| Cameroon | Chouaïbou, M., J. Etang, T. Brévault, P. Nwane, C. K. Hinzoumbé, R. Mimpfoundi, and F. Simard. 2008. | China | Kang, W., B. Gao, H. Jiang, H. Wang, T. Yu, P. Yu, B. Xu, et al. 1995. | El Salvador | Mouchet, J. 1988. |
| Chad | Kerah-Hinzoumbé, C., M. Péka, P. Nwane, I. Donan-Gouni, J. Etang, A. Samè-Ekobo, and F. Simard. 2008. | Greece | Mouchet, J. 1988. | Guatemala | Brogdon, W. G., and A. M. Barber. 1990. |
| Côte d'Ivoire | Girod, R., E. Orlandi-Pradines, C. Rogier, and F. Pages. 2006. | India | Mittal, P. K., P. Wijeyaratne, and S. Pandey. 2004. | Haiti | Brogdon, W. G., J. H. Hobbs, Y. St. Jean, J. R. Jacques, and L. B. Charles. 1988. |
| Egypt | Mouchet, J. 1988. | Indonesia | Mouchet, J. 1988. | Mexico | Penilla, R. P., A. D. Rodríguez, J. Hemingway, J. L. Torres, J. I. Arredondo-Jiménez, and M. H. Rodríguez. 1998. |
| Equatorial Guinea | Moreno, M., J. L. Vicente, J. Cano, P. J. Berzosa, A. de Lucio, S. Nzambo, L. Bobuakasi, et al. 2008. | Iran | Zahirnia, A. H., H. Vatandoost, M. Nateghpour, and E. Djavadian. 2002. | Panama | Caceres, L. 1999. |

**Table 6.1—Continued**

| Africa | Reference | Asia / Europe | Reference | Latin America | Reference |
|---|---|---|---|---|---|
| Ethiopia | Mouchet, J. 1988. | Iraq | Akiyama, J. 1996. | Peru | Perea, E. Z., R. B. León, M. P. Salcedo, W. G. Brogdon, and G. J. Devine. 2009. |
| Gabon | Pinto, J., A. Lynd, N. Elissa, M. J. Donnelly, C. Costa, G. Gentile, A. Caccone, et al. 2006. | Laos | Verhaeghen, K., W. Van Bortel, H. D. Trung, T. Sochantha, and K. Keokenchanh. 2010. | Venezuela | Molina, D., and L. E. Figueroa. 2009. |
| Gambia | Betson, M., M. Jawara, and T. S. Awolola. 2009. | Malaysia | Reid, J. A. 1955. | | |
| Ghana | Yawson, A. E., P. J. McCall, M. D. Wilson, and M. J. Donnelly. 2004. | Nepal | Mittal, P. K., P. Wijeyaratne, and S. Pandey. 2004. | | |
| Kenya | Stump, A. D., F. K. Atieli, J. M. Vulule, and N. J. Besansky. 2004. | Pakistan | Rathor, H. R., G. Toqir, and W. K. Reisen. 1980. | | |
| Mali | Tripet, F., J. Wright, A. Cornel, A. Fofana, R. McAbee, C. Meneses, L. Reimer, et al. 2007. | Papua New Guinea | Keven, J. B., C. N. Henry-Halldin, E. K. Thomsen, I. Mueller, P. M. Siba, P. A. Zimmerman, and L. J. Reimer. 2010. | | |
| Mozambique | Casimiro, S., M. Coleman, P. Mohloai, J. Hemingway, and B. Sharp. 2006. | Sri Lanka | Kelly-Hope, L. A., A. M. Yapabandara, M. B. Wickramasinghe, M. D. Perera, S. H. Karunaratne, W. P. Fernando, R. R. Abeyasinghe, et al. 2005. | | |
| Nigeria | Oyewole, I. O., A. A. Ogunnowo, C. A. Ibidapo, H. I. Okoh, T. S. Awolola, and M. A. Adedayo. 2011. | Syria | Akiyama, J. 1996. *Report to WHO East Mediterranean Regional Office, Alexandria.* Alexandria, Egypt: WHO. | | |

**Table 6.1—Continued**

| Africa | Reference | Asia / Europe | Reference | Latin America | Reference |
|---|---|---|---|---|---|
| Rep. of Congo | Koekemoer, L. L., B. L. Spillings, R. N. Christian, T.-C. M. Lo, M. L. Kaiser, R. A. I. Norton, S. V. Oliver, et al. 2011. | Thailand | Somboon, P., L. A. Prapanthadara, and W. Suwonkerd. 2003. | | |
| Senegal | Trape, J.-F., A. Tall, N. Diagne, O. Ndiath, A. B. Ly, J. Faye, F. Dieye-Ba, et al. 2011. | Turkey | Akiyama, J. 1996. *Report to WHO East Mediterranean Regional Office, Alexandria.* Alexandria, Egypt: WHO. | | |
| South Africa | Hargreaves, K., L. L. Koekemoer, B. D. Brooke, R. H. Hunt, J. Mthembu, and M. Coetzee. 2000. | UAE | Ladonni, H., and H. Townson. 1998. | | |
| Sudan | Himeidan, Y. E., H. Chen, F. Chandre, M. J. Donnelly, and G. Yan. 2007. | Vietnam | Verhaeghen, K., W. Van Bortel, H. D. Trung, T. Sochantha, and K. Keokenchanh. 2010. | | |
| Tanzania | Kulkarni, M. A., M. Rowland, M. Alifrangis, F. W. Mosha, J. Matowo, R. Malima, J. Peter, et al. 2006. | | | | |
| Uganda | Verhaeghen, K., W. Van Bortel, P. Roelants, P. E. Okello, A. Talisuna, and M. Coosemans. 2010. | | | | |
| Zambia | Norris, L. C. 2011. | | | | |
| Zimbabwe | Munhenga, G., H. T. Masendu, B. D. Brooke, R. H. Hunt, and L. K. Koekemoer. 2008. | | | | |

Source:  Compiled by authors from sources cited within.

A number of studies address the rise of pesticide resistance in *Anopheles* mosquitoes, implying a threat to the sustainability of ITN/LLIN (long-lasting insecticidal nets) programs as well as IRS programs. Unfortunately, such studies usually lack any methodological framework to support assertions regarding the impact on health and economics (Greenwood et al. 2008). Nonetheless, resistance is now widespread and looms as a threat to public health achievements against malaria.

### Integrated Pest Management

IPM is an environmentally sensitive approach to pest management that takes advantage of a variety of appropriate pest management options including, but not limited to, the judicious use of pesticides. According to Wiebers (1993) and Krishna, Byju, and Tamizheniyan (2009), benefits of IPM include (1) lower production costs at farm level;(2) reduced pesticide imports and subsidies for pesticide use;(3) lower environmental pollution and improved soil and water quality;(4) reduced farmer and consumer risks from pesticide poisoning and related hazards; and (5) increased ecological sustainability by conserving natural enemy species, biodiversity, and genetic diversity. Moreover, IPM helps consumers enjoy abundant and relatively inexpensive, unblemished foods (Fernandez-Cornejo, Jans, and Smith 1998). Application of IPM requires advanced technology, skilled human power, and high-level organizational procedures. Another cost of IPM is the time it requires for monitoring systems for pests and insect predators (Wiebers 1993).

Fernandez-Cornejo, Jans, and Smith (1998) cited several econometric studies that showed mixed results for microeconomic impacts of IPM. IPM led to a significant decrease in pesticide expenditures for cotton growers in California, led to an increase in pesticide use among cotton farmers in 14 US states, and showed no effect on pesticide expenditures for cotton farmers in the US state of Georgia. Fernandez-Cornejo (1996, 1998) also found that the impact of IPM is consistent with farmers' profit-maximization objectives. IPM adopters use fewer insecticides and fungicides (taking the example of tomatoes and grapes); Fernandez-Cornejo and Jans (1996) showed that IPM had no significant effect on pesticide use for orange growers in Florida and California. By and large, cotton is the commodity most studied in relation to the effects of IPM.

What is most neglected in IPM economic impact analysis is the aspect of pesticide quality? In a study of grape producers in six US states, Fernandez-Cornejo (1998) showed that IPM adopters applied significantly less insecticide and fungicide than non-adopters. Fernandez-Cornejo and Jans (1996) showed that the average toxicity and the index of potential environmental impact of insecticides (Kovach et al. (1992) decreased slightly with adoption of IPM. However, toxicity and the potential environmental impact index of fungicides remained about the same for adopters and non-adopters of IPM for disease control.

In Asia in the early stages of the Green Revolution (the 1970s), pesticides were heavily subsidized and their use was especially high. This practice disrupted natural enemy populations, leading to the resurgence of primary pests and to secondary pest outbreaks. An example is the rice brown plant hopper (Nilaparvata lugens), a pest linked to early-season insecticide sprays, which widely threatened rice production in Asia. Despite scientific evidence, regional policymakers in Asia were still skeptical or simply unaware of the fact that a pest outbreak could actually be caused by the subsidized pesticides (Gallagher, Ooi, and Kenmore 2009). Therefore, an important aspect of the IPM program was to demonstrate to decision makers that the yields from fields sprayed with the subsidized insecticides were lower than those of the non-sprayed fields. Gallagher, Ooi, and Kenmore (2009) emphasized that with each new generation of decision makers, there is a danger of resurgence of subsidized pesticides since the widespread view is that pesticides increase yields.

In 1985–86, many Asian countries adopted IPM as the overriding agricultural and crop protection policy. Indonesia, the Philippines, Malaysia, and India were among the first countries to declare IPM a priority for agricultural research and extension in rice. Efficiency of IPM practice was investigated and compared with the conventional method in Asia (Lee 2003). Taking the case of South Korea, the production efficiency measures showed that plots using IPM methods were more efficient than plots using conventional methods. Studies in Vietnam (Chi, Hossain, and Palis 2004) showed that IPM resulted in the reduction of insecticide use per crop season. In Indonesia, Mariyono (2008) used panel data from 1990 to 1998, the period when IPM technology was disseminated, to estimate the demand for insecticides in soybean farms on Java and analyze the impact of the IPM technology on insecticide use. Results showed that the IPM technology significantly reduced the use of insecticides in soybean farming. The IPM success was attributable to the elimination of the insecticide subsidy and the dissemination of IPM technology. IPM in rice-based cropping systems has been most successfully practiced in Indonesia (Oudejans 1999; Mariyono 2008). According to Soejitno (1999), the success in Indonesia was due to the farmer-centered application of IPM, with IPM field schools enhancing farmers' abilities. IPM had broad-based policy support, and a breakthrough in rice IPM research was also instrumental in its success. Moreover, IPM helped famers to learn and become more innovative. The economic impact of the IPM program from 1991 to 1999 in Indonesia suggests that farmers reduced the use of pesticides by approximately 56 percent and yields increased by approximately 10 percent (Mariyono 2008).

To illustrate the impact of the policy shift from pesticide subsidies to IPM on government expenditures, Gallagher, Ooi, and Kenmore (2009) considered the case of Indonesia. In 1986, pesticide subsidies amounted to 0.17 percent of gross domestic product and 0.8 percent of total government expenditure. In the period 1986–89, direct subsidies on many pesticides were phased out and some rice pesticides were banned. As a result, more than $100 million in government expenditures were saved per year, without adverse effects on rice production and with positive effects on the environment and public health.

In Malaysia, national IPM in rice lacked political support and its role was limited to rice farmers in the large-scale rice irrigation systems of Peninsular Malaysia (Oudejans 1999).In Thailand, IPM implementation in rice has not reached farmers due to lack of funding commitment (Oudejans 1999).

### Integrated Pest Management Costs and Returns to Agriculture

Few studies assess the longer-term costs and returns of pesticide use in agriculture. Fernandez-Cornejo, Jans, and Smith (1998) reviewed the empirical evidence of the potential health effects and environmental concerns associated with the use of pesticides. One of the principal approaches, according to them, is the estimation of "marginal productivity "of pesticide use. Citing Campbell (1976), they argued that marginal productivity estimates provide an indirect measure of the cost "in terms of forgone agricultural output" of reducing pesticide use to protect human health and the environment; this would mean that the extent of pesticide reduction needed to "protect human health and the environment depends in part on the extent to which food and fiber production would fall" (quoted in Fernandez-Cornejo, Jans, and Smith 1998, 466). In line with classical microeconomic theory, a producer would maximize profits by increasing pesticide use up to the point where the expected marginal return (value of the marginal product, or VMP) equals the pesticide's marginal cost. The authors point to mixed results from several authors in relation to marginal productivity of pesticides across years and regions. The general consensus is, however, that the VMP of pesticide application is falling (Fernandez-Cornejo, Jans, and Smith 1998). For US agriculture, the authors concluded that the VMP of pesticide use is higher than the pesticide price, implying that pesticides are economically viable options. Consequently, Campbell's (1976) conclusion that "the marginal costs of reducing pesticide use for health and environmental considerations are relatively high" is still valid (quoted in Fernandez-Cornejo, Jans, and Smith 1998, 470). However, other studies indicate that the VMP of pesticides is declining, suggesting that the marginal costs of reducing pesticide use may be declining as well (Fernandez-Cornejo, and Jans. 1995).

Application of IPM techniques and the use of improved pesticides are preferred practices in reducing the health and environmental threats associated with pesticide use (Fernandez-Cornejo, Jans, and Smith 1998). The success rate of such methods, however, depends on the profitability of the methods. Fernandez-Cornejo, Jans, and Smith (1998) cited Gianessi's (1993)assertion that more research is needed to identify alternatives to the health-threatening chemical products, and that public and private funding must give priority to such research programs.

### Integrated Pest Management Yield Compared with Conventional Pesticide Application

Wetzstein et al. (1985) found that yield and total variable cost increased as the degree of producer participation in IPM increased, whereas pesticide expenditures and net returns remained constant. They also stated that an IPM program may not always decrease the level of pesticides for individual producers. These results imply that IPM has the capacity to increase yields while at least maintaining the same level of pesticide expenditures as a non-IPM approach. Therefore, continuing IPM programs and educating farmers with regard to new IPM technology may be beneficial for agriculture as well as society.

Fernandez-Cornejo (1996) developed a methodology to study the impact of IPM on pesticide use, yields, and profits, and applied it to tomato growers in eight US states. He further made a distinction between IPM application for insects and IPM application for diseases. Results showed that fresh market tomato growers who adopted IPM for insects and diseases applied significantly less insecticide and fungicide, respectively, than did those who did not adopt IPM. Fernandez-Cornejo (1996) further noted that IPM adoption had an insignificant effect on yields and a small effect on profits. The adoption of IPM for insects and IPM for diseases did not have a significant effect on yields. Pesticide prices, farm location, contractual arrangements for the crop, and farm size were found to be important determinants of pesticide demand and the adoption IPM.

Fernandez-Cornejo, Jans, and Smith (1998) showed that yields and profits generally increased as a result of IPM. Because losses vary by crop, soil, and weather, estimates of crop yield losses that might result without the availability of pesticides are difficult to obtain (Fernandez-Cornejo, Jans, and Smith 1998). Yields may also vary yearly because of technological developments (new plant varieties and new pesticides), weather, and development of pesticide resistance by certain pests; thus estimates are highly variable. However, econometric techniques for impact analysis such as propensity score matching and difference-in-difference would capture this variation (Wooldridge 2010).

### Integrated Pest Management and Reduced Environmental Toxicity

There is a rich literature on the positive impact of IPM techniques on pesticide exposure and poisoning, a major health risk to farmers who lack knowledge about the safe use of these toxic chemicals. This topic received high levels of attention in the 1970s from initiatives such as the FAO and United Nations Environment Programme (UNEP) global program on IPM, which was a response to insecticide resistance among agricultural pests and disease vectors such as anopheline mosquitoes and to the growing awareness of the occupational health risks of injudicious pesticide use by poorly educated farmers (Smith and Calvert 1976).

A number of more recent studies have analyzed how IPM has addressed these relationships in the agro-ecological contexts of concern for malaria control. Maumbe and Swinton (2003) evaluated the agricultural benefits and health costs associated with pesticide use in cotton farming in Zimbabwe, a case study of particular relevance to the cotton-growing areas that may be at higher risk for development of pesticide resistance on the part of *Anopheles* mosquitoes. Their study indicated that farmers lost an average of two days of labor per season due to avoidable pesticide poisoning that could be readily addressed by IPM programs. Antle and Pingali (1994) analyzed the health and production trade-offs of policies to restrict pesticide use in rice-growing areas of the Philippines, another crop of high interest to malaria control. Their analysis found a negative impact on farmer productivity due to health declines attributed to intensive pesticide use; this lends additional support to the potential of IPM to simultaneously improve both income and health outcomes for farmers.

Mancini et al (2005) and Mancini, Jiggins, and O'Malley (2009) documented both the occupational health risks to farmers, particularly in cotton-growing areas, and the positive impact on farmer health of reduced pesticide exposure through farmer field school (FFS) training in IPM. Their analysis of pesticide poisoning among Indian cotton farmers highlighted the high risk of acute poisoning to female farm laborers responsible for mixing pesticide concentrations and filling tanks, reduced through FFS training in IPM. Davis et al (2010) found that FFS participation improved the health outcomes of female-headed households in Uganda, a result that may be explained by this exposure pathway. Konradsen et al. (2003) highlighted the need for greater education among farmers of lower socioeconomic status in lower-toxicity alternative pesticides to reduce poisonings. They suggested IPM and dissemination of new biotechnologies as ways to reduce self-exposure to these chemicals.

Van der Hoek and Konradsen (2005) analyzed pesticide poisoning in Sri Lanka, an important addition to the literature on the success of IPM FFSs in Sri Lanka in collaborating with the health sector to reduce vector-borne disease (van den Berg et al. 2006). The relationships between pesticide poisoning, IPM, and farmer health form complementary pathways by which IPM can improve health outcomes beyond those associated with vector-borne disease.

### Integrated Vector Management and Health

Integrated vector management (IVM) is a rational decision making process for the optimal use of resources for vector control, emphasizing a range of interventions used in combination based on local suitability (WHO 2004a). IVM is similar to IPM but has different objectives. IVM's objective is to reduce or eliminate targeted disease vector species. IPM, in contrast, seeks to reduce losses and protect the yield of an agricultural crop species from damage by pests while minimizing pesticide input costs. An important contribution of the IVM system is to reduce (though not eliminate) the use of interventions at locations where they may prove ineffective, with associated cost savings (Beier et al. 2008).

A number of vector-borne diseases are present in Uganda: malaria and lymphatic filariasis (elephantiasis) transmitted by *Anopheles* mosquitoes; yellow fever, dengue fever, and chikungunya transmitted by Aedes aegypti mosquitoes; trypanosomiasis transmitted by tsetse flies; onchocerciasis(river blindness) transmitted by black flies; schistosomiasis (snail fever orbilharzia) transmitted by fresh-water snails; and leishmaniasis transmitted by sandflies (WHO 2010b;CDC 2012; Powers and Logue 2007;Amarasinghe et al. 2011). All of these diseases can be addressed through integrated vector management (WHO 2009a; Hotez et al. 2007; Dumont and Chiroleu 2010; Hopkins et al. 2002; WHO 1995). IVM has a broad and deep potential to sustainably reduce the burden of these diseases in rural Uganda, and the WHO now recommends implementation of IVM at the national level to reduce all such vector-borne diseases (WHO 2004a).

Beier et al. (2008) provided a comprehensive description of the IVM framework and its application to national malaria control efforts. They emphasized that IVM may complement the conventional biomedical interventions of ITNs/LLINs and IRS with additional control methods without imposing additional costs because IVM is a more efficient, evidence-based management of interventions and resources than uniform national application. Beier et al. (2008) built on the IVM experiences of Tanzania in the 1990sand of Zambia and Sri Lanka in the first decade of the present century to provide practical guidance on its successful implementation.

Chanda et al. (2008) provided one of the most comprehensive and current accounts of national-level IVM implementation. Their case study evaluated progress of the Zambian IVM program from 2002 to 2007 in relation to the five key elements of IVM described by the WHO (2004a): (1) advocacy, social mobilization, and legislation;(2) collaboration within and across sectors;(3) integrated approaches;(4) evidence-based decision-making; and(5) capacity strengthening. With the backing of the national government, district-level environment officers and a vector control group within the Ministry of Health have effectively implemented IVM to control malaria, schistosomiasis, and trypanosomiasis. A key outcome of the National Malaria Control Program of Zambia was that the IVM program increased coverage and utilization of IRS and ITN interventions, with significant benefit to malaria morbidity and mortality (Chanda et al. 2008).

Geissbühler (2008) documented the IVM experience of the Urban Malaria Control Program (UMCP) in Dar es Salaam from 2006 to 2007. Bacterial larvicides were used to supplement the ITN program because local vectors (*Anopheles* gambiae sensu stricto, An.arabiensis, An.funestus, and An.merus) had adapted to ITNs by feeding during the day rather than at night (Geissbühler 2008, 107). The UMCP hired and trained a community member from each ward of the city to take responsibility for managing and applying larvicides within the ward. Participatory mapping was used to identify mosquito breeding grounds. Anopheline larval abundance was reduced by 96 percent in the intervention wards compared with controls, which resulted in a reduction of 31 percent of malaria transmission by An. gambiae ($p = 0.04$).The larviciding was associated with a 40 percent reduction ($p < 0.001$) of *Plasmodium falciparum* infection in the population. In addition, the majority of infected mosquitoes in Dar es Salaam were found during the dry season, which also coincided with maximum larval control success (Geissbühler 2008, 140). The dramatic success of this IVM program in an urban environment demonstrates the potential for IVM beyond farms as urban populations continue to grow.

### Integrated Vector Management, Pesticide Resistance, and Drug Resistance

The health sector has been effective at raising awareness regarding the threat that pesticide resistance presents to the health of rural communities (Curtis et al. 1998). Programmatic solutions that can address resistance are documented and promoted by the agricultural sector as well, but with a focus on agricultural pests rather than human disease vectors.

FAO, the Insecticide Resistance Action Committee, the International Water Management Institute, and other prominent agricultural organizations have advisory programs on how to address pesticide resistance using monitoring systems and IPM practices that integrate nonchemical control methods, rotation and combination of pesticides, and targeting and rationing of pesticide application (IRAC 2006; Overgaard 2007). Unlike public health agents such as the WHO, these agricultural organizations have direct experience in implementing IPM programs in rural communities through their core activities of extension and FFS programs (WHO 2010a).

IVM may enhance the cost-efficacy and longevity of current interventions by counteracting the development of drug and insecticide resistance. A prominent example of this counteraction is the use of bacterial larvicides in the West African Onchocerciasis Control Programme to control the main vectors (black flies). By using these larvicides in rotation with chemical insecticides, the program reversed the emerging problem of organophosphate insecticide resistance in the main vector (WHO 1999, 2). In West Africa, IVM has been suggested as a way to address the emerging resistance of *Anopheles* mosquitoes to the pyrethroid insecticides used on ITNs (Curtis et al. 1998).

IVM of mosquitoes may be able to slow emerging drug resistance as well through similar larval control effects. Based on research conducted in Uganda on the genetic spread of chloroquine resistance, ineffective vector control may contribute to the spread of drug resistance in *P.falciparum* (Talisuna et al. 2007). The diminishing returns of mass drug administration and insecticide usage that arise from resistance imply that IVM can extend the cost-efficacy life spans of current drugs and insecticides.

### Integrated Pest and Vector Management

Integrated pest and vector management (IPVM) is a program recently developed by FAO and UNEP that addresses the dual role of agricultural systems in producing food as well as fostering or reducing disease vectors (van den Berg et al. 2006). IPVM engages communities through FFSs in a rational decision making process to simultaneously achieve the goals of IPM and IVM. Since the integration of IPM and IVM into a joint IPVM program is a relatively new programmatic approach, there is relatively little literature specifically on the IPVM approach. Van den Berg and Knols (2006) have identified and advocated for ways that the FFS approach can be adapted to train communities in IPVM rather than IPM. The only well-documented project to implement IPVM through FFS was a pilot program conducted in Sri Lanka from 2002 to 2006 that built on the existing IPMFFS to reduce malaria and Japanese encephalitis (van den Berg et al. 2006).

IPVM intervenes at the confluence of agriculture and vector-borne disease to address the common agro-ecological basis of the agricultural and health sectors. IPVM fosters improvements in agricultural income, production inputs costs, pesticide resistance in agricultural pests and disease vectors, pesticide poisoning, vector-borne disease, efficacy of ITN and IRS interventions against malaria, health-related expenses at the household level, and health-related labor losses.

# 7. THE FARMER FIELD SCHOOLS APPROACH

Key principles for farmer field schools (FFSs) are universally known to include the following elements (David et al. 2006; Gallagher 2003):

1. A farmer-centered approach that identifies and focuses on farmers' problems and then involves farmers in solving their own problems through experiential learning in small groups that facilitate individual participation and contribution, as well as discovery of how things work and why
2. A focus on learning rather than on a technology or message, which encourages farmers to experiment so that they can discover new knowledge and new ways of solving field-based challenges; this has to be based on a curriculum specific to the local crop and on topics that are collectively identified and pursued
3. Competent facilitators who guide the farmers in all the major processes of the school through asking the right questions, helping in the design of farmer experiments, and following up on the outcomes of the experiments
4. Empowerment, which as a key principle is the fundamental capacity the FFS leaves with the farmers, an ability to make their own decisions and confidently reach their targets as well as engage in partnerships that are deemed useful
5. Use of a systems approach whereby the farm and the whole agro-ecosystem is considered a learning field
6. Self-help, which promotes total participation and collective action by all members rather than reliance on outsider help, except if outside help is properly demanded

These FFS principles can be complemented by four integrated pest management (IPM) principles, namely, grow a healthy crop, conserve natural enemies of insect pests, monitor the fields regularly, and become IPM experts through participation in FFS (Bartlett 2005; David et al. 2006; Braun, Thiele, and Fernandez 2000).While the processes of FFS for IPM vary and can be adaptable from one enterprise to another, there are fundamental steps that have been universally followed and are responsible for the impacts realized where the approach has been used successfully.

The key processes of the FFS methodology begin with planning or groundwork conducted mainly to identify collaborators and target communities, needs assessment, and sensitization of the community about the FFS and the problem to be solved. These steps are followed by selecting participants and initiating the FFS. The FFS involves steps such as capacity needs assessment; training of trainers; and then the start of the learning cycle, which normally follows the crop or livestock life cycle, with weekly or biweekly meetings (every two weeks) depending on the enterprise. In each FFS session, an agro-ecosystem analysis is conducted by small groups of about 5 members, who also present their findings to the larger group of 20–30 farmers. The larger team consents on a topic to experiment with, such as a way to control a pest or manage the crop. This latter process involves basic experiments with a treatment and a control field, the latter representing the farmers' conventional practice for comparison purposes (Braun, Thiele, and Fernandez 2000; David et al. 2006). However, in all these processes and principles, innovation and flexibility are exercised.

## Cases of Farmer Field School Programs in Integrated Pest Management around the World

The FFS approach to solving agricultural challenges, particularly pest management, has been widely applied since its introduction in Indonesia in the late 1980s. In Indonesia and the nearby rice-growing countries of Southeast Asia, the main challenge that triggered the widespread use of FFS for IPM was the problem of the rampant brown plant hopper (Nilaparvata lugens) in rice. This pest outbreak was a result of heavy and indiscriminate use of broad-spectrum chemical pesticides in irrigated rice fields, causing pest resistance to pesticides, death of pest predators, environmental damage, pesticide poisoning, and serious health risks to millions of people (Praneetvatakul, Waibel, and Meenakanit 2007). The spread of the IPM FFS approach in other regions, however, has had varying motivations and intensity. This section explores the key goals that were pursued by various FFS efforts globally and the institutional setup under which FFSs were implemented. We also look at the key process factors that contributed to the successes and those that were limiting. Finally we draw key lessons for the agriculture and health partnership to improve agriculture-based livelihoods and health in relation to malaria control in a country like Uganda.

FFSs have been proven to be an effective extension methodology to improve both crop and livestock productivity under various national and agricultural problem contexts. In Peru, FFSs for coffee were started to provide a learning structure focused on good agricultural practices, certification, and market access (den Belder, García, and Jansen 2006). In the Cajamarca department of Peru, FFSs were introduced in 1998 by the International Potato Center, one of the CGIAR (Consultative Group for International Agricultural Research) centers, to tackle the challenge of late blight, the fungus responsible for the great Irish potato famine of 1845 (Godtland et al. 2004). In Ethiopia, FFSs were introduced to address the challenges of coffee wilt disease (Babur 2009), while in Benin; IPM FFSs were introduced to address the problem of pests and misuse of pesticides for cowpeas (Nathaniels 2005). In Kyrgyzstan, FFSs seem to have been started due to the extension service vacuum that existed following the collapse of the Soviet Union (Muller, Guenat, and Fromm 2010). Crops like cotton, cucumbers, potatoes, and tomatoes were the target for the Kyrgyz FFS program. In southern India, IPM FFSs were introduced for cotton to reduce the massive use of highly toxic pesticides that were seriously affecting farmers' health and livelihoods, including a risk of cancer for young children who consumed food with pesticide residues (Dhawan, Singh, and Kumar 2009; Mancini et al. 2006).

The process adopted particularly the entry point; the type of stakeholders involved and the nature of their involvement; staff skills; and institutional and organizational factors influence the effectiveness and sustainability of FFSs. Several case studies, including the FFS for vegetables that followed the FFS for cotton in the Gezira Irrigation Scheme in Sudan (Khalid 2002), the livestock FFS in Vietnam, and the IPM FFS in Nepal, illustrate these points (Bartlett 2005; Dalsgaard et al. 2005; Khalid 2002). In the case of Sudan, while a national policy for using FFSs to control cotton pest problems in the irrigation project area was recommended, institutional bottlenecks and self-interest of some organizations, including the pesticide companies that wanted to keep a market for their pesticides, interfered with the IPM FFS. In addition, uncoordinated actions and disagreements among high-level officials, as well as replacement of the well-trained human resources with less qualified but politically correct ones, affected the success of the program (Khalid 2002). Such sets of institutional and organizational factors were well explained by Bartlett (2005) as key to success or failure in the scaling up of FFS activities. The culture of the Kyrgyz farmers, who shunned keeping records or sharing their financial status—or if they did, tended to be unreliable—also affected the progress of the FFS.

Successful IPM FFS programs, such as the one in Nepal, were accredited with the presence of champions and committed leaders who believed in the FFS approach and had political and donor community connections, young and enthusiastic staff, and cooperative and interested farmers and community leaders. FFS graduates in Nepal formed an FFS trainer association and also expanded into what is presently known as community IPM (Bartlett 2005).

Success in Nepal can also be attributed to incorporation of lessons from other Asian countries into the FFS design and implementation. For example, there were IPM activities in Indonesia and also lessons from the Philippines prior to the large-scale use of IPMFFSs in Nepal (Bartlett 2005). Existing groups can also be a building block for an FFS, as was the case with the potato IPMFFS in Peru (Godtland et al. 2004). In Sudan the existing IPM FFS work for cotton and vegetables was not fully exploited during the up scaling process. Competent and well-trained facilitators from the extension system were replaced by less trained supervisors of the irrigation system—a reflection of institutional intrigue and competition. All of the existing FFSs collapsed due to this change (Khalid 2002).

The farmer livestock school (FLS) in Vietnam is another case illustrating institutional and social culture challenges that can be met when promoting nontraditional FFS programs (Darlsgaard et al. 2005). While Vietnam had a successful IPM FFS for rice, the livestock FFS was not that smooth. The first challenge arose from the traditional, production- and export-focused, centrally directed, and top-down extension approach that was being used in the livestock sector. This approach was the opposite of the new FLS approach, which targeted poorer livestock farmers with small livestock, used participatory methods, had extension workers as facilitators, and encouraged microfinance instead of subsidized inputs (Darlsgaard et al. 2005). Small livestock were generally looked down upon by policymakers, bureaucrats, and technocrats alike (Joensen 2002). There were philosophical differences between an export-led livestock system and a pro-poor livestock support system that the FLS was designed to help, yet the implementers were more oriented toward export-led thinking.

Support for the FLS was obtained at the government and policy level, albeit after intense lobbying by international donors and nongovernmental organizations (NGOs) who argued for more pro-poor policies; still, challenges remained with the implementation agencies at ministry and district levels. The IPM FFS for crops had been implemented by the Plant Protection Department through the central and provincial governments. The agricultural extension service, a parallel institution, was not involved. While the IPM FFS for crops was successful, the extension department never recognized it as a way to reach farmers since the two institutions competed for the same resources and rarely collaborated nor shared any lessons. The next stage of challenges was realized when developing the FLS curriculum. The entire process of introducing and operationalizing the FLS reveals key bottlenecks, including difficulties in relinquishing traditional extension approaches; poor attitudes toward alternative, pro-poor extension methods; conflict between institutions that are often competing for resources and do not share learning experiences; and the culture among farmers, who expect subsidies and payments for attending meetings, for example. However, the resilient leadership team of the FLS in Vietnam exercised flexibility, lobbying capacity, financial endowment, and patience, permitting the country team to be able to slowly adjust while maintaining ownership.

Some of the notable impacts of FFS projects have been a clear reduction in the amount of pesticide use, up to between 30 and100 percent in rice, for instance; an increase in agricultural yields of up to 4–14 percent; and improved health conditions among FFS participants (van den Berg and Jiggins 2007). Increased productivity was observed with IPM for FFS in the potato farmers of Peru (Godtland et al. 2004). In the cotton IPM FFSs in southern India, team-building efforts within the FFS processes led farmers to form an alumni group after the conclusion of the schools to continue experimenting and also to meet social needs of members that required collective action (Mancini et al. 2006). There were gendered benefits in this specific effort, with women increasingly participating more in farmers' meetings, engaging constructively with policymakers, and contributing their knowledge and expertise in subsequent pest management causes.

Mancini et al. (2006) also reported reduced use of pesticides in cotton production in the Dharwad and Warangal districts of India, increased savings due to reduced purchase of pesticides, and increased sales from increased yields. There was increase in social and human capital in terms of the post-FFS farmers' clubs that addressed other community issues such as marriage and neem tree seed collection for use in pest management. Knowledge of the cropping systems of cotton had increased, and women felt uplifted, with their knowledge of the crop and its ecology having been used during the process—resulting in self-fulfillment. Changes in knowledge, attitudes, and skills have been notable outcomes of the FFS efforts, as was the case with Peruvian potato farmers in the Andes region and with the sugarcane FFS in Pakistan (Habib et al. 2007). Significant increase in IPM knowledge on pests, fungicides, and resistant varieties was observed among Peru potato farmers (Godtland et al. 2004).Other notable impacts have included empowerment as farmers gain skills in communication, experimentation, leadership for collective action, and facilitation. This meant that they could carry on similar activities and initiate new ones by themselves (van den Berg and Jiggins 2007). Many FFS graduates have been taken on as expert trainers of trainers. IPM FFSs have often resulted in community IPM, alumni associations, cooperative societies, marketing groups, networks, associations, and nonagricultural focal community groups including those for HIV/AIDS control (Bartlett 2005; van den Berg and Jiggins 2007; Winarto 2003).

The FFS approach is influencing change in the extension policy of several countries because of its empowering potential among farmers as well as its ability to educate farmers through the experiential learning processes. The methodology has attracted inter-sectoral efforts such as joint agricultural and public health programs to deal with vector-borne diseases such as malaria (van den Berg and Knols 2006). The environment has also been protected from further damage, for example, due to excessive use of chemicals (van den Berg and Jiggins 2007). Most importantly, health risks for farmers have been reduced while opportunities for health improvement have also been made possible through increases in yield and income that can be spent on better living conditions.

### Sri Lanka Farmer Field Schools for Integrated Pest and Vector Management and Health

Building on the IPM FFS experience, an FFS for integrated pest and vector management (IPVM) was started in Sri Lanka in 2002 and by 2006 had established 67 FFSs, involving more than1,000 farm households in 11 locations (van den Berg et al. 2007).The project had the following inter-sectoral partners: the Plant Protection Service of the Department of Agriculture from the Ministry of Agriculture, which was responsible for overall project coordination; the district departments of agriculture and the district authorities, which controlled the irrigation systems and implemented the FFSs; and the Department of Public Health's anti-malaria campaign, which helped with curriculum development and with the monitoring of mosquito populations (van den Berg et al. 2007). After proper institutional coordination and community empowerment, the first field activities that involved farmers included conducting a survey of their perceptions and knowledge of vector-borne diseases, specifically malaria, which was followed by exploring the life cycle of the malaria-transmitting mosquito in the early stages of the rice season, which coincides with the mosquito breeding season. This activity guided the second step of developing a curriculum for addressing the breeding and life cycle of the mosquito. The third step, implementation, included conducting agro-ecosystems analysis (AESA), studying mosquito breeding sites (rice fields, canals, wells, open cement tanks, ornamental cisterns, tires, coconut husks), sampling of mosquitoes, studying their life cycle, distinguishing between mosquito species, identifying predators, analyzing the disease cycle, identifying agricultural practices that suppress mosquito breeding, reducing the source of mosquitoes, and mapping. Farmers easily adapted to the study of mosquito behavior during this time given their experience with AESA under the IPM FFS. Mosquito developmental stages and aquatic predators were sampled during weekly meetings both at the beginning of the planting season and at the end, when larvae were most prevalent. Mosquito behavior and development stages were observed and studied daily in transparent, water-filled containers. Leveling/grading and alternate wet/dry irrigation were implemented in study plots to manage mosquitoes, and farmers learned to practice source reduction through filling, draining, or manipulating water bodies in their environment. A role-play was used to teach the farmers how the disease was transmitted from the mosquitoes to humans (van den Berg and Knols 2006, 5; Yadav 2007).

Key outcomes of the IPVM FFS in Sri Lanka included these:

- FFS alumni gained the ability to distinguish between beneficial and harmful insects and to identify larvae and adults of three vector mosquito genera (*Anopheles*, Culex, and Aedes).
- Alumni acquired skills for analyzing the agricultural and mosquito ecologies to be able to make locally appropriate decisions to address identified vectors, pests, and crops.
- Application of rice pesticides was reduced due to increased awareness of the pesticides' health effects.
- Vector control methods, such as eliminating breeding sites, rearing fish for household use, cleaning surroundings, applying mineral oil to water bodies, covering water containers, and using bed nets were promoted, contributing to reducing local malaria risks.
- There was an increase of up to 60 percent in the use of bed nets (Yasuoka et al. 2006).

A key success factor was the willingness and motivation among the FFS alumni to participate in the vector management activities. Another important factor was the readiness and willingness of the anti-malarial program to recognize the contribution of agriculture and its openness to working and learning together (van den Berg et al. 2007; van den Berg and Knols 2006; Yadav 2007).

### Farmer Field Schools in East Africa

The FFS approach was first introduced in East Africa in 1995 under the FAO Special Program for Food Security in western Kenya, which ended in 1998 (Braun, Masai et al. 2006;Okoth et al. 2006;Davis et al. 2010). Since then, various external donor–funded FFS projects have been implemented in the region. FFSs have been used to disseminate a range of technologies in the region, including integrated production and pest management, land and water management, self-sustainability for refugee communities, integrated crop management, promotion of farmer innovations, livestock, social forestry, and control of banana wilt. Over the last decade, the approach has been successfully adapted from a typical rice mono-crop farming system, where it originated in Asia, to a highly diverse, resource-poor, smallholder farming system with strong interactions between crop and livestock components (Okoth et al 2006). There are indications that mainstream government institutions are beginning to embrace the approach. For instance, the adaptive research program of the Kenya Agricultural Research Institute (KARI) has adopted FFS as an up scaling approach for its promising technologies. By the end of 2003, KARI had initiated more than60 FFSs and trained more than 800 farmers (Bunyatta et al. 2006). In addition, the FFS approach has now been embraced by Kenya's Ministry of Agriculture as a promising participatory extension method to be scaled up in its national program (Bunyatta et al. 2006).[3] In Uganda, the implementation guidelines for the second phase of the National Agricultural Advisory Services Program (NAADS Phase II) lists FFSs among the key participatory approaches to be used for promoting market-oriented and commercial agriculture among small-scale farmers (NAADS 2010).Below we discuss experiences from several cases of FFS projects in East Africa, pointing out indications of effectiveness, identifying challenges, and drawing lessons.

Bunyatta et al. (2006) used a survey with an ex-post facto design to determine the effectiveness of the FFS approach in knowledge acquisition, adoption, and dissemination of soil and crop management technologies developed by KARI among small-scale farmers in Kenya. A comparison of FFS and non-FFS farmers revealed that the former fared better, with a significant difference in knowledge acquired, adoption, and dissemination capacity. Onyango et al. (2003) documented experiences of using FFSs to disseminate new technologies by the soil management project of KARI's National Agriculture Research Centre at Kitale in Keiyo district in 2002. In order to have a holistic approach, the curriculum was integrated, covering crop and livestock husbandry, horticulture, and land husbandry together with ecology, economics, sociology, and education. Problems confronted in the field and farmers' needs formed the integrating principle (Onyango et al 2003). In this case, a key challenge was a high participant dropout rate. Initially, attendance was high due to high expectations of free production inputs. However, numbers dropped to below minimum requirement levels when expectations were not met. Low and fluctuating farmer attendance during sessions negatively affected the FFS process. Men often gave the excuse of not being around while women were too busy with housework. Sessions were also interrupted by sociocultural community functions. The second problem was high turnover of school officials due to inability to identify reliable leaders, which disrupted the learning process. For more effective FFSs, farmers need training in leadership and basic financial management. It is also important to link FFS participants to service providers who can address the expectations that are beyond the scope of the school.

The East African Sub-regional Integrated Production and Pest Management Project, funded by FAO and the International Fund for Agricultural Development (IFAD) (probably one of the largest FFS projects in both scope and duration within the region), was implemented in Busia, Bungoma, and Kakamega districts of western Kenya; Busia, Kaberamaido, and Soroti districts in Uganda; and Bukoba,

[3]For further information, see this national report: ICARRD (2006).

Muleba, and Missenyi districts in Tanzania during the period 1999 to 2002 and 2005 to 2008 (Davis et al. 2010). With integrated production and pest management (IPPM) as the primary focus, the FFS curriculum for this project incorporated several sustainable livelihood aspects over time, including HIV/AIDS issues, reproductive healthcare, nutrition, gender issues, malaria control, child immunization, environment management, basic financial management, simple credit management, farming as a business, and many more. This responsiveness to farmer needs has transformed the FFSs into popular community forums where farmers discuss problems under the local context and seek solutions with minimal external influence.

The overall goal of the FAO–IFAD IPPM project was to assess the effectiveness of the FFSs in addressing poverty issues. The long-term objective was to expand the capacity of governments, NGOs, and the private sector to respond to the needs of resource-poor farmers for knowledge and access to agricultural information. In addition, goals included the development of networking capacity for the exchange of FFS experiences within and between countries, and contributing information on the replicability and effectiveness of FFSs as an alternative and sustainable mechanism for extension delivery (Braun, Jiggins, et al. 2006). Davis et al. (2010) used longitudinal impact evaluation with quasi-experimental methods (propensity score matching and covariate matching) together with qualitative methods to study farmer participation and the impact of the IPPM FFS in the FAO–IFAD project. The study found that overall, participation in FFSs significantly increased incomes in all three countries. FFSs were found to be especially beneficial to farmers with medium land holdings and categories of people who usually do not access extension via other methods, namely, women and people with low literacy levels. Female-headed households benefited significantly more than male-headed households in Uganda. For enhanced effectiveness, use of FFS’s as a communication channel would need to address identified barriers to farmer participation, namely, lack of time and information. There is also a need to conduct studies to understand the needs of groups found not to engage with FFSs, such as the well-to-do and educated, and devise mechanisms to involve them.

The FAO–IFAD IPPM project tested several innovations geared toward sustainability of the FFS, which have since become part of FFS programs in many other organizations in and outside the region (Okoth, Khisa, and Thomas2002a). The innovations included the foci model, and semi-financing and self-financing of FFSs. The foci model literally means growing from a nucleus outward, whereby successive FFSs are established in the immediate neighborhood to form a cluster. This method enhances interaction and sharing, and fosters coordination within the cluster, reducing overall implementation costs. Under the semi-financing arrangement, a grant system is used whereby farmer groups write simple proposals for grants to run their FFS. IPPM FFS participants arrange their own field study plot devoted to educational activities as well as larger, commercial plots that the group manages together to raise more funds. Self-financed FFSs, which emerged over time, involve transforming the grant into an educational revolving loan. The cases reveal the following key lessons for effective use of FFSs in the East African context.

Close engagement of farmers in the FFS decision-making process so as to harness local knowledge and priorities, and build farmer commitment to change is critical. At the start of the FFS farmers should identify their problems and opportunities, and map out resources available as a basis for selecting relevant activity areas and topics in the season-long training and post-FFS follow-up activities (Okoth et al. 2006).

Although by design, the FFS approach was not intended for creating long-term organizations, providing for post-FFS institutional arrangements contributes to the sustainability of FFS achievements. A key lesson is the need to make provisions for continued networking of FFS graduates. It has become apparent that after the season-long FFS process most of the groups continue working together to address problems in their community. For instance, the FFS graduates of the FAO–IFAD project wanted to carry on after the initial field training, and they formed networks in 2000 (Busia) and 2001 (Bungoma and Kakamega). FFS networks now exist in 10districts in Kenya. Most of the networks also act as intermediary or apex organizations linking farmers to service providers, markets, and information (Braun, Masai, et al. 2006, 96).Critical factors identified as necessary for sustaining the FFS networks in western Kenya included leadership and access to financial and technical resources. According to Okoth et al

(2006), only 4.3 percent of the alumni FFS groups established between 1999 and 2002 under the FAO–IFAD IPPM project disintegrated. By May 2006, all the other groups were still functional and were accessing services as a group from various institutions and service providers. This staying power is due to the inherent attributes of the FFS approach of cultivating cohesion and a willingness among farmers to learn together while solving problems that affect them as a community.

Post-FFS activities are effective mechanisms to build on group development. Empowered FFS groups are good partners for activities such as soil conservation and new crop introductions. The groups are also becoming more involved in social issues such as HIV/AIDS through a process called farmer life schools in which field ecology is extended to human ecology (Okoth, Khisa, and Thomas 2002b).

FFS curricula that have been most useful to farmers, resulting in self-sustaining post-FFS institutional networks, were broad, addressing farmer needs along the entire agricultural value chain. Small-scale farmers in East Africa produce mainly for subsistence and are unable to access more profitable markets due to, among other factors, lack of know-how and skill in value addition, poor understanding of supply and demand dynamics, limited financing and credit facilities, poor access to market information, lack of effective organizational and managerial capacity, and poor communication among members of field schools. In order to address these issues and broaden impact, FFSs that were initially formed to address agricultural production concerns had to strengthen their agribusiness linkages to enable farmers to meet these new challenges and opportunities, and sell their extra output. It was realized that there is a need to broaden the FFS curriculum to include new critical focus areas, including farming as a business, marketing, resource mobilization, agribusiness development, and farm management (Braun, Masai, et al. 2006).

### Agricultural Extension and Health Access in Rural Uganda

Structurally, agricultural extension and health services are offered under two different ministries in Uganda, namely, the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) and the Ministry of Health. The Local Government Act of 1997 affected both ministries, transferring responsibility for service delivery from central ministries to local governments (Bashaasha, Mangheni, and Nkonya 2011). The act devolved to local governments far-reaching powers and responsibilities in such areas as finance, legislation, politics, planning, and personnel matters. The devolution of powers, functions, and responsibilities to local governments was intended to achieve the following objectives:

- Transfer real power to the districts, thereby reducing the workload of remote and under-resourced central government officials
- Bring political and administrative control over services to the point that they can actually be delivered, thereby improving accountability and effectiveness, and promoting people’s ownership of programs and projects executed in their districts
- Free local managers from central government constraints and, as a long-term goal, allow them to develop organizational structures tailored to local circumstances
- Improve financial accountability and responsibility by establishing a clear link between payment of taxes and provision of the services they finance
- Improve the capacity of local councils to plan, finance, and manage the delivery of services to their constituents (Asiimwe 1989)

Generally, it was envisaged that decentralization would bring political power closer to local communities so as to respond to local needs, build local capacity, and improve accountability. Specifically, for the health sector, improvement was expected in the form of increased utilization of health services, better access to health services, more coverage of the population with basic services, better quality of healthcare, and ultimately, a decline in the rate of illness and death (Jeppsson and Okuonzi 2000).

However, existing data show no improvement in social services or people's quality of life following the reform. In fact, many indicators have either remained the same or worsened (Jeppsson and Okuonzi 2000; Komakech 2005), a scenario some have attributed to, among other factors, flawed financial resource allocation and management at the local level, as well as personnel quality and management issues at these levels (Foster and Mijumbi 2002; Akin, Hutchinson, and Strumpf 2005). In addition to resource allocation at the local level, the actual total resources allocated to the sector are inadequate. Uganda is still heavily dependent on external support, with insufficient internal commitment of resources to the health sector; this is reflected in the precarious sustainability status of the services (Jeppsson and Okuonzi 2000). Despite the program goal of Uganda's Health Sector Strategic Plan II 2005/06–2009/10 (Ministry of Health 2005) of "reduced morbidity and mortality from the major causes of ill health, premature deaths, and reduced disparities therein" (p8), the Uganda National Household Survey 2005/06 (UBOS 2007) found that 40 percent of the population had fallen sick in the 30 days preceding the date of the survey; this was significantly higher than the 2002/03 survey figure of 29 percent. The proportion of people in rural areas that reported an illness (42 percent) was higher than that in urban areas (33 percent). Regional variations showed that the highest percentage of persons that fell sick was reported in the Eastern region (49 percent), followed by Central and Northern (at 41 percent each), Western (34 percent), and Kampala (26 percent). About half (50 percent) of the study population that fell sick in the 30 days preceding the survey experienced malaria/fever symptoms. The Western region was the most affected by malaria, with 57 percent, followed by Eastern (51 percent) and Northern (36 percent). Rural areas reported higher incidence of malaria (53 percent) compared with urban areas (49 percent). There was a notable decline in malaria prevalence among the urban population, from 61 percent in 2002/03 to 49 percent in 2005/06.

With regard to agricultural extension services in Uganda, decentralization was implemented in tandem with other reforms, including privatization; liberalization; and changes in the mode of funding, organization, and management of government extension programs. Liberalization of service delivery led to a proliferation of private companies and NGOs operating at the grassroots level, providing channels for agricultural technology and information service delivery to farmers (Friis-Hansen and Kisauzi 2004). In 2001, Uganda embarked on a process of transforming its public extension system to conform with the rest of its economic transformations. Under the National Agricultural Advisory Services (NAADS) Act of 2001, the public extension system was gradually phased out and replaced by a privatized contract system implemented by NAADS, a new statutory semiautonomous body under the MAAIF, and implemented within the broader policy framework of a multi-sectoral Plan for Modernization of Agriculture, involving decentralization, liberalization, and privatization (Mangheni 2007).The major features of the NAADS program include private delivery of publicly funded services; a demand-driven and farmer-owned, decentralized service delivery approach; and poverty and gender targeting (Mangheni 2007). Private extension service providers, who operate as either individuals or firms, are contracted by sub county farmers' forums to deliver enterprise-specific services to specific groups of farmers over a period of three to six months. In order to foster farmer articulation of needs, ownership, and control over the program, NAADS used the farmer institution development process to facilitate the establishment of farmers' forums from parish to district level. The performance rating of the program is mixed. Benin et al. (2008) found that farmers participating in the NAADS program had better access to extension and other rural public services, were more organized in groups, had better capacity to demand improved technologies, and had experienced welfare gains. For example, 41–58 percent of the NAADS participants perceived that their average wealth, their access to adequate food, the nutritional quality of their food, and their ability to meet basic needs or overall well-being had improved between 2000 and 2007, as compared with 27–44 percent of their nonparticipant counterparts. These impacts were found to vary by region, with the largest impact occurring in the Central and Western regions.

Data from the Uganda National Household Survey 2005/06 (UBOS 2007) showed that at the national level, only 7.3 percent of the respondents indicated having been visited by an extension worker during the 12 months preceding the survey. Out of those reporting access, the Western region recorded the highest number (about 35 percent), followed by the Eastern region (about 29 percent). The Northern region had the smallest percentage of households visited (14 percent), probably due to the insurgency in the region at the time. Only 9 percent of the households reported having participated in a training program organized by the NAADS program, while only about 5 percent reported having a household member involved in a NAADS farmers' group. The Western region had the highest percentage of agricultural households (about 32 percent) that reported having a member involved in the farmers' groups under this program. The Central and Northern regions had the least, at about 21 percent each. The survey also sought information from agricultural households regarding adoption of selected agricultural technologies, including crop protection and disease control measures. The Central region reported the highest number of agricultural households that practiced disease control, at about 40 percent. The Northern region recorded the smallest rate of adoption for all technologies.

# 8. CONCLUSIONS

This literature review has sought to bring together a comprehensive and interdisciplinary set of research papers on the various relationships between malaria and agricultural environment as they apply to East Africa and Uganda specifically. Both climate change and agricultural land use can facilitate warmer local microclimates, which lead to more mosquitoes with faster reproduction and longer life spans, increasing malaria transmission potential. But agro-ecological factors such as hybrid maize adoption, wetland papyrus clearing, deforestation, and livestock density regulate baseline transmission more locally. The health and agriculture sectors are both deeply dependent on the efficacy of pesticides but have no formal coordination mechanism to ensure that agricultural pesticide use does not diminish the efficacy of malaria control in the rural communities where both sectors are working to improve the socioeconomic welfare of households. This review may offer concerned stakeholders a sound knowledgebase on the key historical and empirical research on how malaria epidemiology relates to the local environment and rural agricultural economy.

This review has attempted to provide focused background information, including cost-efficacy evaluations on the most promising avenues of intervention and collaboration for addressing malaria and agriculture linkages: integrated pest and vector management (IPVM), agricultural extension services, and in particular the farmer field school (FFS) approach. FFSs and IPVM in particular may provide a cost-effective and integrated solution for improving both health and poverty outcomes in rural agricultural communities. Investment in IPVM offers a unique opportunity to simultaneously reduce vector-borne disease, increase agricultural yields, and preserve the efficacy of pesticides by combating the development of pesticide resistance. The FFS methodology facilitates the participatory and collective decision-making required for successful inter-institutional cooperation between the agricultural and health sectors. Due to its responsiveness to the needs of farmers, FFS has demonstrated itself to have many positive spillovers by delivering information on the needs prioritized by participants, such as nutrition, malaria control, environment management, and on-farm livelihoods. The Ugandan health and agriculture sectors can easily build on the lessons from programs such as the IPVM FFS in Sri Lanka and the post-FFS farmer life schools, which built on community empowerment to educate about human ecology.

Designing a broader policy framework to support collaboration between the agricultural and health sectors highlights many institutional challenges. There are broad gaps in expertise between the agricultural and health sectors on how each may contribute to mutual objects linked through poverty, health, and the environment. Time and resources need to be invested in designing a curriculum that fits the needs and capacities of the farmers and community members, and that stimulates experimentation to address the interdisciplinary challenges of agriculture, malaria, and pest management. To succeed, all stakeholders will need to exhibit openness to new knowledge, skills, and methods in order to develop a common vision and joint strategy for working with rural farmers through collective learning and action.

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