ECOSYSTEM CHANGE AND PUBLIC HEALTH

A Global Perspective

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Malaria and Global Ecosystem Change

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Malaria, a potentially lethal parasitic disease once in decline and targeted for global eradication, afflicts hundreds of millions of people annually, and its impact is growing in many parts of the world. Malaria demonstrates the importance of the broad ecosystem concept of interactions between living organisms and nonliving elements. The transmission of malaria is directly affected by environmental conditions external to the human host because the infection is transmitted by mosquitoes. Environmental conditions, in turn, are affected by human activities. The purpose of this case study is to generate awareness of how global changes in the growth and movement of populations, patterns of economic development, and climate are changing the risk of exposure of human populations to malaria parasites. The forces underlying the spread of malaria are growing as populations with little or no immunity are infected more frequently by malaria parasites that are increasingly difficult to treat effectively (see Box 12.1).

Malaria is caused by a protozoan parasite that completes its complex cycle of development alternating between human hosts and mosquitoes of the genus *Anopheles*; the biting of human hosts by mosquitoes is the mode of contact that permits transmission from human to mosquito and back to human (see Chapter 10). Malaria reveals the relationship between ecosystem change and human health in several ways (see Fig. 12.1). Changes in land use, manipulations of water use, and variation in climate influence the distribution and abundance of the mosquito vectors of this disease. Also, the development of the malaria parasites within the mosquito vectors depends upon climatic conditions, particularly temperature. For example, ambient temperatures that are too cold or too hot inhibit the development of all *Plasmodium* species that infect humans; for *Plasmodium falciparum*, which is the species of malaria parasite that causes the most se-
The Emergence of Drug-Resistant Malaria

Chloroquine is a synthetic antimalarial drug that was made generally available in the late 1940s. Chloroquine became popular because it was cheap, relatively safe, and highly effective. However, its dual use, both for treatment after infection and for suppressive chemoprophylaxis before infection, and its uncontrolled distribution through private markets set the stage for the emergence of resistance to the drug. Doses that may be adequate to relieve symptoms are often not large enough to wipe out entire populations of parasites, so that resistant parasites are left to be transmitted to mosquitoes and then other people (see Chapter 10). During the 1950s, chloroquine-resistant *Plasmodium falciparum* became a major operational problem for malaria control in some areas; during the ensuing decades, chloroquine-resistant *P. falciparum* spread around the world (Wernsdorfer and Payne 1991; Wernsdorfer 1994). *P. falciparum* is of particular concern because it causes the most severe form of malaria.

Other antimalarial drugs have been introduced, but these alternative drugs are typically more expensive, more difficult to administer, and more likely to have adverse side effects than is chloroquine. Moreover, in some areas, *P. falciparum* parasites have already developed resistance to some of these drugs. There is evidence of cross-resistance in which resistance to one drug also creates resistance to other drugs, limiting the period during which new drugs can be effectively used (Olliaro et al. 1996). Approaches for dealing with cross-resistance include the administration of combinations of drugs and research for new drugs that target different biochemical mechanisms of parasite infection. Some new drugs are under development, although they are few in number (Olliaro et al. 1996). Vaccines are an additional line of active biomedical research, although the prospect of a safe and effective vaccine for general use seems unlikely in the near future.

vere illness in humans, the estimate of the minimum temperature required ranges from 16°C to 19°C and the maximum temperature for viable parasites is about 35°C (Lindsay and Birley 1996).

The growth and movement of human populations may bring more people into contact with mosquito vectors and malaria parasites. For example, resettlement of people without prior exposure to malaria may place them in malarious zones without the partial immunity acquired through years of exposure. In addition, genetic characteristics expressed in the blood cells of local populations may make them more or less susceptible to infection by malaria parasites (Livingstone 1984; Allen et al. 1992). Activities related to economic development—agriculture, irrigation, deforestation, and the construction of roads and buildings—modify the use of land and water, sometimes augmenting the number of possible aquatic breeding sites for the mosquito larvae and altering local or regional climate. Less directly, activities associated with economic development release into the atmosphere greenhouse gases that may accelerate global warming and affect patterns of global climate (see Chapter 7).
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The relationship between ecosystem change and malaria at the global level is not divorced from conditions that operate on regional and local scales (see also Table 2.2). One particularly important issue is the diversity of anopheline species and their associated larval habitats, ranging from puddles in small, ephemeral depressions to swamps, marshes, and even brackish water (see Box 12.2). The geographic distribution of anopheline species is the main feature affecting the regional classification of the epidemiology of malaria (Rubio-Palis and Zimmerman 1997).

A better scientific understanding of the long-term changes in the global ecosystem could lead to the development of new strategies for the prevention of malaria. Decisions in the joint management of health issues and ecosystems involve complex tradeoffs (Wolman 1995; Graham and Wiener 1995). For example, the application of the insecticide DDT to kill vector mosquitoes is in conflict with a campaign to eliminate the dispersal of DDT and other persistent organic pollutants (United Nations Environment Programme 2000; World Health Organization [WHO] 1999; Hooper 1999). Any global program should also review successful approaches to the environmental management of malaria at local and regional scales. A traditional type of environmental management is the implementation of programs to manage water resources so as to eliminate the breeding sites of anopheline mosquitoes. Intermittent raising and lowering of water levels, alternately flushing and drying out breeding sites, has been used for larval control by the Tennessee Valley Authority in the United States and the Blue Nile Health Project in the Sudan (WHO 1995). Environmental management can also reduce the contact between humans and mosquito vectors by locating settlements away from breeding sites, by constructing housing with barriers to mosquito entry, and by the programmatic use of bednets...
Box 12.2

Swamp Fever

The diversity of aquatic habitats associated with malaria may be surprising to speakers of European languages, whose names for the disease reflect only the European and Mediterranean experience of an association with swamps and marshes. The English word derives from *mala aria* in Italian, meaning "bad air." *Paludisme* and *paludismo* in French and Spanish, respectively, derive from *paludis* in Latin, meaning "of the marsh." In traditional English usage, malaria has been called *swamp fever* or *marsh fever,* analogous to *Sumpffieber* in German.

...treated with pyrethroid insecticides, which are less stable than DDT. Environmental management contributed to the successful control of malaria in some areas, such as the Pontine marshes in Italy and the Hula swamps in Israel.

This chapter provides examples of malaria as a public health problem in selected countries. In all examples, local factors interact with global changes in population growth and movement, economic development, or climate or some combination thereof. The examples also demonstrate that countries at very different levels of risk are affected by ecosystem change on a global scale.

Zimbabwe, Gambia, and Niger are selected as countries at high risk for malaria. Zimbabwe is in the southern portion of central Africa and is part of the Southern African Development Community, while Gambia and Niger are in West Africa. Variations in rainfall and temperature are major influences on the transmission of malaria in these countries. In Zimbabwe, the El Niño/Southern Oscillation (ENSO) climatic anomaly generates interannual variability in rainfall (see Chapter 8), and zones at higher altitudes are markedly cooler than zones at lower altitudes. In Gambia and Niger, fluctuation in rainfall from year to year is also important, although the pattern of climatic variability is different in West Africa. Global changes in climate are therefore likely to affect the transmission of malaria. Gambia and Niger illustrate how the pressures of population growth and associated economic development are creating new breeding sites for mosquito vectors and hence facilitating greater transmission of malaria. Migration is also an important regional factor, as demonstrated by the past movement of refugees from Mozambique to and from Zimbabwe.

Sri Lanka and Brazil are selected as countries at intermediate risk for malaria. The transmission of malaria in Sri Lanka is affected by major projects that manage water resources as well as interannual variability in rainfall subject to the influence of ENSO. In addition, the migration of population has contributed to malaria as a public health problem, since the development of water resources includes plans to resettle people from nonmalarious areas to malarious areas. The migration of population has...
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been central to the resurgence of malaria in Brazil for similar reasons. Brazilians are encouraged for economic purposes to move into the malarious Amazonian region out of established cities and towns that are free of malaria. The transmission of malaria is further exacerbated by extensive deforestation associated with new settlement. Patterns of rainfall are also important as an environmental determinant of the transmission of malaria in Brazil. Amazonian deforestation is projected to alter regional climate, adding to the possible effects of global climate change.

The United States is selected as a country at low risk for malaria. Since there is no sustained transmission of malaria in the country, international movement of infected people is the critical factor in the small number of outbreaks that have occurred in recent years. Outbreaks have also been favored by weather conditions that were hotter and more humid than usual. Therefore, global warming would likely increase the risk of the transmission of malaria whenever the malaria parasite is introduced into the population.

Malaria in Africa

Malaria in Africa deserves special regional attention because over 90 percent of an estimated annual global total of 300–500 million clinical cases of malaria and 1.4–2.6 million deaths are among Africans (WHO 1995). The disproportionate burden of malaria in Africa can be largely attributed to the abundance of three species of mosquitoes that are very efficient at transmitting malaria—Anopheles gambiae, Anopheles arabiensis, and Anopheles funestus (Gillies and Coetzee 1987). The ability of malaria vectors in sub-Saharan Africa to breed in temporary pools without vegetation, such as a footprint filled with rainwater, is key to the exceptional persistence of malaria on the continent (Coluzzi 1994). The deadly importance of the African species of malaria vectors was demonstrated when An. gambiae from West Africa was accidentally introduced into Brazil, where South American vectors were already transmitting malaria. Anopheles gambiae is such an effective vector that, in 1938, only eight years after it had arrived in Brazil, it caused a major epidemic of malaria with 14,000 deaths (Soper and Wilson 1943; Walsh et al. 1993). Fortunately, Fred Soper and the Rockefeller Foundation responded and were able to eradicate An. gambiae from Brazil by intensive antimosquito operations. Unfortunately, eradication of An. gambiae from its native habitat in Africa would be infinitely more difficult or outright impossible.

Despite common regional concerns in Africa, understanding the relationship between ecosystem change and malaria requires an appreciation of local variation in ecology, geography, climate, and human activity. The countries selected illustrate the diversity of issues arising within the region.
Malaria in Zimbabwe
Malaria control has been in operation in Zimbabwe since the end of World War II, but, on April 17, 1996, the Panafriican News Agency reported that Zimbabwe had already experienced 828 deaths due to malaria and more than 300,000 cases of malaria since the beginning of the year. During the same period in 1995, the number of deaths had been reported to be 130 and the number of cases of malaria had been more than 100,000. The change in one year was clearly alarming and newsworthy. The primary cause was a significant increase in rainfall. Secondarily, the combination of rainfall and bad roads hindered the distribution of antimalarial drugs to affected areas, contributing to over a sixfold increase in the number of deaths due to malaria.

In southern Africa, the amount of rainfall is highly variable from one year to the next; heavy rainfall in 1996 had been preceded by five years of drought (Fig. 12.2a). Zimbabwe has a distinct rainy season characterized by monthly rainfall that begins to increase in October, peaks from December through March, and declines in April (Unganai 1996). The transmission of malaria peaks from February through May (i.e., toward the end of the rainy season) (Taylor and Mutambu 1986). Years with wetter rainy seasons are more favorable for transmission. In southern Africa, an increase in the incidence of malaria may also be one of the effects of a major flood episode (see Chapter 14). Years of heavy rainfall in the region tend to be associated with the La Niña phase of the ENSO climatic anomaly, which is the best-understood source of climatic variability on a seasonal to interannual time scale (see Chapter 8). Improvements in seasonal climate forecasting are gaining greater attention in Southern Africa Malaria Control (SAMC) and the larger public health community (SAMC 2000; Jury 2000; Kovats et al. 1999; Liverpool School of Tropical Medicine 2000; National Oceanic and Atmospheric Administration [NOAA] 2000).

A major uncertainty for the future is accelerated global warming as a consequence of emissions of carbon dioxide (CO₂) and other greenhouse gases (see Chapter 7). Projections of rainfall under conditions of accelerated global warming are not consistent from one climate model to another (see Chapter 9). Although historical analysis of the twentieth century’s rainfall in Zimbabwe shows an average drop of 10–16 percent, climate scenarios projecting the effect of doubling CO₂ in the atmosphere allow for an increase or a decrease of 10–15 percent (Unganai 1996; Hulme 1996). The effect of accelerated global warming on ENSO fluctuations is also unclear (Unganai 1996; Hulme 1996). Increased interannual variability in precipitation would cause increased fluctuations in the transmission of malaria, very likely limiting the development of natural immunity to malaria that results from repeated exposure. The effect of environmental change is influenced by human action or inaction. In the epidemic of
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Figure 12.2  a: Rainfall in southern Africa, 1900/01–1995/96. The rainfall year is from
July to June. Source: Redrawn with permission from Hulme 1996, Figure B. b: Altitudi-
nal classification of Zimbabwe. mS, meters elevation in the southern region; mN, met-
ters elevation in the northern region; 1200 m+, more than 1,200 meters elevation.
Source: Redrawn with permission from Taylor and Mutambu 1986, Figure 1.
malaria in Zimbabwe in 1996, the death toll was probably increased because of shortages of antimalarial drugs in clinics in outlying areas as well as the unexpectedly high demand for treatment. One hopes that assessments of the consequences of climate change over several decades may be greatly reduced if the public health community is able to use seasonal to interannual climate forecasts to prevent morbidity and mortality due to malaria (see Chapter 5).

Temperature in Zimbabwe varies from the cooler central plateau, where the major population centers are located, to the warmer low-lying areas (Fig. 12.2b). Within Zimbabwe, malaria is much more common at lower altitudes (Taylor and Mutambu 1986). According to Leeson (1931), seasonal transmission of malaria at higher elevations is caused by the progressive migration of mosquito vectors from lower altitudes where transmission is perennial; seasonal transmission of malaria at higher elevations is interrupted when cool, dry weather kills off the populations of mosquitoes that grow during the warm, rainy weather. The potential for an increase in the transmission of malaria above an elevation of 900 meters is particularly sensitive to a projected increase of 2°C due to global climate change (Lindsay and Martens 1998).

Nevertheless, it is difficult to obtain clear empirical evidence of an effect of temperature changes alone on the incidence of highland malaria. An analysis of yearly variation in temperature in Zimbabwe suggests that, over the twentieth century, years of higher incidence of malaria have been associated with higher temperature (Freeman and Bradley 1996). However, that study is quite limited because it uses only the September temperature in Harare on the high central plateau, where malaria is not present, to compare to the incidence of malaria in the rest of the country. Over the twentieth century, the annual mean temperature for Harare has increased, probably because of the effect of an urban heat island, while the annual mean temperature for the country has decreased slightly (Unganai 1996).

Studies of Rwanda and Ethiopia, two East African countries at risk for malaria in highland areas, have examined an association between increases in the number of cases of malaria observed at higher elevations and increases in minimum temperatures (Loevinsohn 1994; Tulu 1996). However, multiple factors are responsible for the spread of malaria to highland areas (Mouchet et al. 1998; Lindsay and Martens 1998). For example, the El Niño phase of ENSO, which generates warmer and wetter conditions in East Africa, seemed to trigger an epidemic of highland malaria in Uganda in 1997–98, although only an association between excessive rainfall and the density of vectors proved to be statistically significant in the analysis of that epidemic (Lindblade et al. 1999). Interestingly, the rainfall of that same El Niño event was associated with a reduction in the incidence of ma-
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laria in highland Tanzania (Lindsay et al. 2000). Understanding these di-
dent effects will require a close examination of environmental differences
in altitude, weather, and vector ecology as well as differences in study de-
sign that affect the measurements of increases and decreases in incidence.

A historical perspective also demonstrates the need for caution in in-
terpreting the effect of climate change. The apparent burden of malaria in
England during the Little Ice Age (a period of unusually cold weather start-
ing in the middle of the sixteenth century and lasting approximately 150–
200 years) underscores the importance of examining temperature in con-
junction with other factors, including limitations in diagnostic accuracy
(Reiter 2000; Martens 2000). Despite the fact that the central plateau of
Zimbabwe is considered too cool to support the transmission of malaria,
Leeson (1931), in a classic study of the anopheline vector mosquitoes in
Zimbabwe, reported that “there are people still living who can remember
that Salisbury [now Harare] was once no more free from malaria than any
other place in the country.” It is most likely that people with malaria in
Harare actually acquired the infection when they traveled outside the city
and that some of the supposed cases of malaria were other fevers of un-
known origin; nevertheless, Leeson’s statement reflects a reduction in
malaria observed in Harare. Leeson attributed the absence of malaria in
Harare to the development of improved housing, drainage, sanitation, and
roads that prevented the breeding of mosquito vectors An. funestus and An.
gambiae.

Human activities can modify the effect of environmental change in
other ways. In the South Eastern Lowveld, Zimbabwe has major facilities
for irrigating the agricultural production of sugar, wheat, and citrus. In
theory, the risk of malaria could have increased because water provided for
irrigation can create new habitat for breeding mosquitoes and allow mos-
quito populations to become less dependent on rainfall. However, for
years, Zimbabwe has had an effective malaria control program for the ir-
rigation projects. Human migration has also been important for the spread
of malaria in Zimbabwe. Neighboring Mozambique, where the warmer and
more humid conditions are more suitable for the transmission of
malaria, was the source of refugees fleeing into Zimbabwe during Mozam-
bique’s civil war. The mixture of local and refugee populations near the
border facilitated the spread of malaria. Movement of populations com-
plifies any analysis linking reports of malaria to local environmental con-
ditions.

Malaria in Gambia and Niger
Malaria is one of the most important causes of death among Gambian chil-
dren; about 4 percent of children in rural areas die of malaria before reach-
ing the age of five years (Greenwood and Pickering 1993). Given such a
high death toll, it is remarkable that the consequences of malaria were considerably worse in the 1950s. What happened even earlier is unknown because the 1950s are the earliest period in which systematic health surveys of the local (i.e., non-European) population were conducted. Reductions in rainfall have contributed to the reduction in malaria transmission since the 1950s. However, since drought is so harmful to natural resources, plans for economic development seek to combat the effects of drought. Unfortunately, these efforts often have the side effect of increasing the spread of malaria. Trends in malaria infection in West Africa reflect a tension between climatic forces tending to reduce transmission and human activity tending to increase transmission, underscoring the need for an integrated assessment of global change to consider multiple factors (see Chapter 5).

Rainfall is the major environmental determinant of the transmission of malaria in Gambia. A single, short rainy season starts in May or June and ends in October or November, followed by a long, dry season (Koram et al. 1995). Malaria is highly seasonal, roughly coinciding with the rainy season. Entomologists studying the mosquito vectors of West Africa are trying to identify exactly how and where transmission occurs in a limited fashion during the dry season; small foci of transmission are the source of expansion of transmission during the rainy season (ColuzzI 1993). Additionally, there is considerable variation in the amount of rainfall during the rainy season in West Africa (Toure et al. 1999). Over the past 30 years or so, Gambia and surrounding areas have experienced a decline in precipitation (Greenwood and Pickering 1993). Thus, drought conditions, which have deleterious effects on agricultural and forest resources, have the beneficial effect of reducing the transmission of malaria. Some models of climate change predict even more drying in the region (Dixon et al. 1996).

Vegetation cover, which exhibits spatial and temporal variability, is an important predictor of the risk of malaria in West Africa and may be determined on the basis of data collected by remote-sensing satellites (see Chapter 3 and Thomson et al. 1997). However, bednets treated with the insecticide permethrin also affect the epidemiology of malaria in Gambia (Thomson et al. 1999). The use of bednets reduces exposure to infective mosquito bites; the effect of insecticide may be particularly important for preventing severe infections with high densities of parasites. The Gambian National Impregnated Bednet Programme has been working to treat all bednets found in all villages. A spatial model for predicting the risk of malaria in Gambia incorporates data on the use of bednets and estimates of vegetation cover (Thomson et al. 1999). The use of satellites for mapping environmental determinants of disease in Africa is an active area of investigation (Liverpool School of Tropical Medicine 2000).

Activities for economic development can promote the transmission of malaria even in dry areas. Poor practices of water management can create
opportunities for year-round transmission of malaria where rainfall is virtually nonexistent. In Niger, in the oasis of Bilma in the Sahara Desert, only 0.8 mm of rain fell during a 12-month period that saw an increase in transmission of *P. falciparum*, the deadliest malaria parasite (Develoux et al. 1994). The prime breeding site for mosquito larvae was considered to be a large freshwater pond created during the prior decade by water leeking continuously from a broken borehole pipe. All of the other watering points were brackish and did not support the breeding of *An. gambiae*, the vector of greatest concern in the area.

Salinization of water is another environmental determinant of the transmission of malaria that also reflects a tension between climatic forces tending to reduce transmission and human activities tending to increase transmission. The entire country of Gambia is a narrow strip north and south of the River Gambia, which runs from east to west for about 300 miles and empties into the Atlantic Ocean. The mangrove swamps in the estuarine lower reaches of the River Gambia provide saltwater habitat for *Anopheles melas*. *Anopheles melas* is a malaria vector but is much less effective at transmitting malaria than *An. gambiae*, the freshwater breeder that dominates the transmission of malaria in the country. Some salinization of the ground water in Banjul, the capital city, has already occurred because of the years of drought and overexploitation of ground water; further salinization will occur with the accelerated rise in sea level expected under scenarios of climate change (Jallow et al. 1996). However, although a net increase in salinization should have the benefit of reducing the transmission of malaria, an integrated assessment must consider the tremendous cost associated with the loss of a supply of fresh water and agricultural capacity.

Human activities to counter salinization have the unintended consequence of increasing the transmission of malaria (Coluzzi 1994). Interventions to desalinize water have accelerated in recent years as a result of population growth, availability of new technologies, and international funding. As mangrove swamps are transformed into agricultural zones, often for the production of rice, *An. melas* is replaced by freshwater breeders *An. gambiae*, *An. funestus*, and *An. arabiensis*.

Growth in population also has mixed effects on the transmission of malaria. Urbanization can contribute to reduced transmission if proper land and water management prevents the creation of pools of stagnant water, which provide breeding sites for vector mosquitoes. But these ideal conditions are often not met. In Gambia, the periurban areas around the capital, Banjul, are experiencing a rapid pace of new construction with poor access roads and drainage (Koram et al. 1995). The new construction combined with rice farming along swamps provides excellent habitat for the breeding of *An. gambiae* during the rainy season. Travel to rural areas,
where the transmission of malaria is even greater, also contributes to the risk of acquisition of malaria by urban residents. Overall, in the periphery of Banjul, malaria is associated with poor quality housing, crowding, and travel to rural areas. Urbanization may also increase the risk of the transmission of malaria by causing a shift from salt water to fresh water. In a study of Cotonou in Benin, the replacement of pile-dwelling traditional villages in lagoon areas with unplanned urban areas favored the replacement of a less effective vector, *An. melas*, by a more effective vector, *An. gambiae* (Coluzzi 1994).

Even in villages, changes in land use generated by the activities of an expanding population can create new opportunities for the transmission of malaria. In Niger and other countries, the excavation of clay for bricks for housing construction leaves large pits that fill with water, providing a breeding site for vector mosquitoes (Buck and Gratz 1990). Originally, these pits were at a considerable distance from human dwellings. As villages have expanded, people have moved in close proximity to the pits and have placed themselves at much greater risk of being bitten by mosquitoes. Moreover, the water in the pits allows transmission throughout the year, instead of the seasonal transmission associated with rainfall. An integrated assessment should consider changes in seasonal patterns of transmission, but such an approach is hindered in locations where a diagnosis of malaria is not routinely confirmed by an examination of parasites in a blood sample. In Niger, malaria parasites could not be found in the blood of many cases of malaria diagnosed on the basis of clinical symptoms alone; this was especially true in the dry season, when hardly any of the reported malaria cases had parasites (Buck and Gratz 1990).

**Malaria in Sri Lanka**

In 1963, after years of sustained control of malaria, only 17 cases of malaria were documented in the entire country of Sri Lanka. Of the 17, only 6 had acquired the infection in the country; the remaining 11 cases had been the result of infection from transmission outside the country (Wijesundera 1988). It seemed that the program to eradicate malaria would succeed in Sri Lanka. Eradication would be truly an amazing feat considering the long and devastating history of malaria on the island. Almost a thousand years ago, the kingdom of Yala in the southeast part of the island was deserted because of fever sickness, probably malaria (Jayawardene 1993). The worst Sri Lankan epidemic of malaria of the twentieth century occurred in 1934–35, when an estimated 80,000 people died in seven months (Jayawardene 1993).

Unfortunately, the program to eradicate malaria was not maintained (see also Box 12.3). The number of cases of malaria started to rebound in 1967. An important factor was the breakdown in the control of malaria due to logistical difficulties and the development of resistance to the insecti-
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One of the great ironies of climate and geography in Sri Lanka is that water, which is necessary for the breeding of vector mosquitoes, is often too abundant to provide suitable breeding sites. Although too little rain can inhibit breeding by drying out pools of water, too much rain can also inhibit breeding by washing out pools of water. The upper reaches of the
Figure 12.3  a: Annual incidence of malaria in Sri Lanka, 1911–96. Source: Redrawn with permission from Konradsen 1998, Figure 3. b: Concentration of falciparum malaria cases near Kandy, Sri Lanka, in May and June of 1987. Source: Wijesundera 1988, Figure 4. Reprinted with permission from Elsevier Science. c: Climatic zones of Sri Lanka. Source: Wijesundera 1988, Figure 2. Reprinted with permission from Elsevier Science.
Table 12.1 Rainfall and River Discharge in Upper Mahaweli, Sri Lanka, 1986–1987

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<th>Rainfall (mm)</th>
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<td>June</td>
<td>667</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>47</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Aug</td>
<td>640</td>
<td>73</td>
</tr>
</tbody>
</table>

Source: Data from Wijesundera 1988, Table 1.

Mahawelis lie in the designated wet zone of the island, in the southwest, with annual rainfall of 2,000–5,000 millimeters (see Fig. 12.3c). Rainfall is present throughout the year, with one peak from the northeast monsoon between November and February and another peak from the southwest monsoon between May and September (Wijesundera 1988). Malaria is usually absent in the wet zone, since such heavy rainfall inhibits the breeding of vector mosquitoes by washing out pools along river and stream beds. However, in an unusually dry year, conditions in the wet zone may be suitable for an outbreak of malaria. A dry year in the wet zone makes the conditions more like those of the dry zone in Sri Lanka, where there is no southwest monsoon, annual rainfall is only about 1,500 mm, and malaria is perennial. The period from May 1986 to August 1987 was a period of relatively low rainfall in the upper Mahaweli, so the climatic conditions were favorable for an outbreak of malaria (see Table 12.1).

Changes in rainfall alone do not explain the role of water because the Mahaweli River is a managed system. An examination of the amount of water discharged into the river upstream of the outbreak of malaria shows low volumes of discharge in 1986 and 1987 (see Table 12.1), but this problem was not entirely because of low rainfall. In 1976, when the Polgolla
dam was built in the area, transmission of malaria occurred downstream. The response was a program of intermittent flushing of the river, which interrupted transmission by washing out the sites suitable for vector breeding. However, water shortages forced the termination of this strategy to control vectors. The fundamental problem was that the priority for water use was hydropower and irrigation; only the excess was allowed downstream for inundating the breeding sites of vectors (Wijesundera 1988).

The resettlement of people is also part of the explanation for the outbreak. The inundation of land during the creation of reservoirs forced people from the local area with no experience of malaria to move to the dry zone where malaria is perennial. For social and economic reasons, migrants often traveled back and forth between malarious and nonmalarious areas. Nonimmune settlers picked up malaria more easily and were debilitated even as they were forced to continue subsistence activity (Jayawardene 1993). Movement from the malarious areas back to areas previously free of malaria further exacerbated the spread.

One study suggests that the climatic conditions favoring the transmission of malaria in Sri Lanka will become more common (Dhanapala 1998). Atmospheric models of a doubling of the atmospheric concentration of CO₂ predict warming (see Chapter 7) that will lead to more aridity in Sri Lanka because of increased evaporation and transpiration of water. Under model scenarios, the area of the dry zone of the island, where malaria is perennial, will increase by 45–65 percent while the area of the wet zone of the island, where malaria is rare, will decrease by 45–55 percent.

Temporal variation in rainfall will also continue to be important for the transmission of malaria. Historically, Sri Lanka has experienced variation in rainfall influenced by the ENSO pattern of atmospheric and oceanic circulation (see Chapter 8). The likelihood of an epidemic of malaria was increased by the failure of the southwest monsoon in the wet zone during a year in the El Niño phase of ENSO combined with the frequent failure of the northeast monsoon in the preceding year (Bouma and van der Kaay 1996). An unusually dry year in Sri Lanka plays the same role as an unusually wet year in Zimbabwe in terms of increasing the risk of malaria. As previously discussed for Zimbabwe, the swings in precipitation and malaria transmission might become more intense and present greater challenges for the control of malaria. On the other hand, assessments of the consequences of climate change may be greatly reduced if the public health community is able to use seasonal to interannual climate forecasts to prevent morbidity and mortality due to malaria (see Chapter 5 and Kovats et al. 1999; NOAA 2000). Strategies to manage water resources while promoting good health are the subject of active research (International Water Management Institute 1999).
Malaria and Global Ecosystem Change

Malaria in Brazil

The number of malaria cases has increased over 10-fold in Brazil since a low of 52,469 cases was reported in 1970 (Sawyer 1993). The official number of cases of malaria was 577,520 in 1990 (Mota 1992) and was only moderately reduced to 455,216 in 1997 (Ministério da Saúde [Brasil] 1998). The pattern of growth in the number of cases has been associated with a shift in the geographic distribution of cases. Malaria has been virtually eliminated from parts of the country with a long history of settlement by non-Indian populations (i.e., the major centers of population in the southeast and northeast near the Atlantic coast). As a public health problem, malaria is now concentrated in Brazil’s frontier of development in the interior, the “Legal Amazon” region in the north and central-west. Each year, between 5 percent and 25 percent of the population along the Trans-Amazon Highway contracts malaria (Walsh et al. 1993).

The major contributor to the resurgence of malaria in Brazil is the migration of Brazilians from established cities and towns to the Amazonian frontier. Since the middle of the twentieth century, Brazil has encouraged agricultural settlement in the Amazon region as a means of distributing land to landless families (Sawyer 1993). The pressure for settlement is not simply a matter of a growing population. In Brazil, the ownership of land is concentrated in the hands of relatively few people, and the existing arrangement is politically and financially difficult to change (Sawyer 1993). Settlement in the Amazon region also serves a geopolitical strategy of surveillance of Brazil’s vast borders with Peru, Bolivia, Colombia, Venezuela, and the Guyanas (Ascher 1999, 115–17).

Settlement of the Amazon region increases the opportunity for exposure to malaria because people who live in or near the forest are at greater risk of being bitten by malaria vectors than are those who live in established towns (Walsh et al. 1993). In particular, migrants who have not acquired immunity readily become ill when exposed to malaria. Immigration to the Amazon region has resulted in extensive contact between the migrants and the principal malaria vector, Anopheles darlingi (Zimmerman 1992). Anopheles darlingi breeds along interior forest streams and river backwaters. It can also breed in artificial ponds that have shaded edges. Deforestation has opened up areas, leading to an increase in the abundance of other vector species that previously were not considered important (Rubio-Palis and Zimmerman 1997). Environmental changes may have an indirect effect on the dynamics of malaria transmission by changing the composition of vector species and the predominant species of malaria parasite.

The pattern of settlement has established a social dynamic that fosters the spread of malaria in the Amazon region. Malaria has undermined the
economic rationale for permanent settlement on family farms because of the burden posed by repeated bouts of malaria. Many young families choose to keep mothers and children away from malaria (Sawyer 1993). Temporary male employment in activities such as road construction and placer mining becomes more appealing. Temporary workers, especially migrant gold miners, have contributed to the spread of malaria. For example, the introduction of 40,000 gold miners into the Yanomami Indian area of the State of Roraima from 1987 to 1990 caused an epidemic of malaria that affected both migrants and Indians. Between 1991 and 1995, malaria was responsible for 25 percent of all deaths among the Yanomami (Confalonieri 1998). During that period, the annual incidence of malaria for Yanomami villages that had contact with immigrants was as high as 1,350 per 1,000 population; in contrast, the annual incidence in villages without such contact was around 20 per 1,000 (Confalonieri 1998).

Transient populations make it more difficult to provide appropriate health services. Treatment of malaria cases is often incomplete because of inadequate medical follow-up and possible side effects. Although incomplete treatment may relieve fever, the underlying infection persists. Since there is considerable movement of people within the Amazon region, infective individuals can be the source of transmission in new areas. Incomplete treatment also tends to generate resistance to the antimalarial drug used, so that future cases of malaria may not respond as well to therapy. The low quality of blood banking services provides a secondary mode of transmission through blood or blood products, which amplifies the primary mode of transmission through the mosquito vector. Transient populations also live in poor housing that increases exposure to mosquito bites at night and limits the opportunity to apply insecticides to interior walls. For those in occupations of extracting resources from forested areas, such as gold mining and rubber tapping, a dwelling might be as simple as a piece of canvas strung over four poles.

With adequate resources in the form of trained governmental and nongovernmental personnel at the local level, intersectoral cooperation, transportation, supplies, and equipment, malaria in the Amazon region can be controlled. However, if resources are lacking and cannot be sustained, even urbanization may not be protective. Transmission of malaria occurs regularly on the periphery of Manaus, a city of 1.5 million inhabitants situated along a tributary of the Amazon River. Manaus is experiencing tremendous growth due to immigration; many immigrants settle in outlying areas surrounded by small streams that have malaria vectors.

Climate change in the Amazon could affect the transmission of malaria. One analysis suggests that the region will become hotter and drier as a direct result of the replacement of the forest by degraded pasture (Shukla et al. 1990). Other global models of climate change related to global emis-
sions of greenhouse gases into the atmosphere also show that tropical areas will become hotter and drier (Rind 1995). However, the nature of the consequences for malaria is unclear. On the one hand, greater temperatures could stimulate the development of the parasite in the mosquito vector. On the other hand, less rainfall could inhibit the breeding of mosquitoes, although uncertainty about the pattern of rainfall is critical, since most transmission occurs at the beginning and at the end of the rainy season. The uncertainties in the possible influence of climate change on malaria depend on uncertainties in the projections of climate change, especially the components related to patterns of precipitation.

**Malaria in the United States**

In two days in the summer of 1993, three residents of a single neighborhood of Queens in New York City experienced onset of fever caused by an infection of *P. falciparum*, the malaria parasite that causes the most serious illness and is potentially life threatening (Layton et al. 1995). Histories of travel ruled out the possibility that the infections were acquired in other countries. Histories of sharing needles or receipt of blood or blood products precluded the possibility of blood-induced transmission. Mosquitoes infected with malaria in other countries and transported by aircraft to the United States were also deemed unlikely sources because of the prevailing winds and the distances between the Queens neighborhood and the closest international airports. With other possibilities eliminated, the public health investigators concluded that the three cases of malaria had been caused by bites from infected mosquitoes that were local to the Queens neighborhood. Their analysis of how the cycle of malaria transmission operated that summer in Queens demonstrates the interplay of environmental conditions and movements of populations around the world that is increasing the vulnerability of the United States to a global resurgence of malaria.

Since malaria in the United States was officially eradicated in the 1950s (Zucker 1996), it may come as a surprise to many that mosquitoes capable of transmitting malaria can be found throughout the country. The most important mosquito vectors are *Anopheles quadrimaculatus* east of the Rocky Mountains, *Anopheles freeborni* west of the Rocky Mountains, and *Anopheles hermsi* in California (Zucker 1996). The United States has a history of endemic malaria at least since colonial times (Faust 1945). Although the transmission of malaria was more intense in the South, malaria was found throughout most of the country. The transmission of malaria was reduced even before World War II because of a combination of improvements in socioeconomic conditions, climatic conditions, increased drainage, better housing and nutrition, migration from rural to urban areas, greater access to medical services, and availability of quinine for treatment. The transmission of malaria was interrupted after World War II be-
cause of an additional program of applying the insecticide DDT on house walls to kill adult mosquitoes and in aquatic breeding sites to kill mosquito larvae (see Box 12.3 and Zucker 1996). Surveillance activities associated with the control of malaria allowed public health officials to focus on areas of transmission and treat people harboring malaria parasites. The goal was to break the cycle of malaria transmission, not to eliminate the mosquito vectors, and that goal was achieved. Thus, the investigators of the New York City malaria outbreak in 1993 knew that a mosquito vector was available, most likely An. quadrimaculatus (Layton et al. 1995).

Malaria parasites are constantly being reintroduced into the United States. For example, in 1992, the U.S. Centers for Disease Control and Prevention (CDC) received reports of 903 cases of malaria that were acquired outside the country (Zucker et al. 1995). These cases, which are designated as imported, reflect a mix of U.S. travelers, U.S. military personnel, and immigrants from countries where malaria is endemic. Every year, a small number of imported cases transmit malaria to others. For example, in 1992, seven cases arose from transmission in the United States (Zucker et al. 1995). As in 1992, the mode of transmission is usually congenital or via blood transfusion. Some imported infections may have been asymptomatic for years. In one instance of congenital transmission of Plasmodium malariae, the mother had emigrated from Laos in 1984 and had had no detectable malaria parasites in her blood. In another instance, a man who had donated blood to his brother was found to be the source of P. malariae, despite the fact that he had emigrated from Canton Province, China, in 1948 with no additional history of exposure through travel.

Imported cases who are harboring gametocytes, the infective stage of the parasite in humans, can provide a source of infection for anopheline mosquitoes, which in turn can transmit malaria to people. From 1957 to 1994, 74 cases of malaria acquired from mosquito-borne transmission were reported in 21 states (Zucker 1996). In one outbreak of Plasmodium vivax in San Diego County, California, transmission was sustained through a second generation of cases; that is, an imported case was the source of infection for more cases, who also became the source of infection for yet more cases (Maldonado et al. 1990). Before 1991, most of the outbreaks occurred in rural areas; from 1991 to 1994, three outbreaks occurred in densely populated urban and suburban areas, including New York City (Zucker 1996). The trend toward urbanization is worrisome because more people are at risk of acquiring infection. The trend toward urbanization is also puzzling, since urbanization is usually associated with the removal of breeding sites of malaria vectors and has contributed to the eradication of malaria in the United States. An explanation of the increased urbanization of malaria requires further research.

In the New York City outbreak of 1993, investigators could identify
likely sources of gametocytes. The Queens neighborhood where the epidemic occurred had experienced a 31 percent increase in the number of foreign-born persons, as reflected in the 1990 census (Zucker 1996). Many of the immigrants were from countries where malaria is endemic, including parts of South America, Central America, Dominican Republic, and Haiti. In addition, more than 100 cases of imported malaria were reported in New York City in 1993 (Zucker 1996). It is clear that international population mobility plays an important role in the spread of malaria. The spread is likely to increase, as the global demographic changes causing population movements are likely to continue (see Chapter 6). However, proper planning can reduce the risk of importation of malaria. For example, a program for resettling East African refugees treated them for malaria before they left Africa (Slutsker et al. 1995).

Climate is also an important factor. Outbreaks of malaria in the United States, including the one in New York City in 1993, are associated with weather that is hotter and more humid than usual (Zucker 1996). Such an association should not be surprising, since a minimum ambient temperature is required to maintain the cycle of transmission in the mosquito vector, with the most virulent species of malaria requiring the warmest temperatures. In addition, the cycle of transmission is accelerated under warmer temperatures, that is, the parasite develops in a shorter period of time. Under scenarios of climate change in which the United States becomes warmer, the potential for the transmission of malaria is likely to increase (Patz et al. 1996). However, the resources of a wealthy country for surveillance and control of disease will probably prevent malaria from becoming an endemic problem again.

Conclusion

A better understanding of the global forces affecting the transmission of malaria should lead to improved models for the understanding of transmission and for the development of regional strategies of disease control. Also, it is well known that the transmission of malaria depends on local conditions, local perturbations, and local catastrophes. This means that local scenarios of the transmission of malaria must be analyzed in order to develop control strategies that are environmentally sound and socially desirable and that will function at the local level. The public health community will have to work with other sectors to control malaria as part of a larger effort to protect public health in a changing ecosystem.

Suggested Study Projects

Suggested study projects provide a set of options for individual or team projects that will enhance interactivity and communication among course participants (see Appendix A). The Resource Center (see Appendix B) and
references in all of the chapters provide starting points for inquiries. The process of finding and evaluating sources of information should be based on the principles of information literacy applied to the Internet environment (see Appendix A).

The objective of this chapter’s study projects is to develop an understanding of the dynamics and control of malaria in relation to global ecosystem change.

**PROJECT 1: Global Ecosystem Change and the Transmission of Malaria**
The objective of this study project is to develop an understanding of the effects of global ecosystem change on the transmission of malaria.

**Task 1.** Identify and describe periods of increased transmission of malaria in different locations (1950 to the present).

**Task 2.** Compare how population growth, population movement, economic development, and climate have contributed to the increases in transmission of malaria described in task 1.

**Task 3.** Describe how possible changes of the factors mentioned in task 2 could affect the transmission of malaria in the future.

**PROJECT 2: Framework for Ecological Change and Emerging Disease in Chapter 10**
The objective of this study project is to develop an understanding of the framework for analyzing ecological change and emerging disease.

**Task 1.** Write a comprehensive paper on the relationship between this case study on malaria and the framework for ecological change and emerging disease discussed in Chapter 10.

**PROJECT 3: Control Measures**
The objective of this study project is to develop an understanding of ways to control malaria.

**Task 1.** Describe current public health policies and practices to control malaria in a particular location.

**Task 2.** Describe current public health policies and practices to deal with potential changes in malaria control strategies.

**Task 3.** Describe options for malaria control that address one or more of the global forces affecting the transmission of malaria.

**Acknowledgments**
We thank Robert Zimmerman and Ulises Confalonieri for comments and suggestions on the manuscript. We also appreciate Wim van der Hoek, who supplied a graphic on the incidence of malaria in Sri Lanka; Kim Lindblade, Ned Walker, and Steve Connor, who provided information on malaria in Africa; Simon Mason and Yves Tourre, who identified use-
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ful climate information for Africa; and the assistance of Jonathan Patz and Nirmalya Kumar in finding references.

References


Jallow BP, Barrow MKA, Leatherman SP. 1996. Vulnerability of the coastal zone of The
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Electronic References


