Controlling Vectors and Hosts of Parasitic Diseases Using Fishes

A case history of schistosomiasis in Lake Malaŵi

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Current estimates of the global prevalence of parasitic diseases range from 600 million cases caused by protozoan and metazoan parasites (Kolberg 1994) to more than 1 billion total cases (Goodman 1994). Strategies for reducing the transmission of these diseases include: immunization programs; reduction of parasite loads in human populations via chemotherapy; modification of cultural practices through public health education, clean water, and sanitation projects; habitat modification (e.g., drainage of stagnant water bodies); and biological and chemical vector and host control (Warren and Mahmoud 1990, WHO 1990). Due largely to financial constraints (Kolberg 1994), however, many of these approaches are inapplicable or unfeasible in underdeveloped countries, where the vast majority of the infections occur.

> **Much of the published research on the use of predatory fishes to regulate the population densities of disease vectors has not yielded the predictive capabilities that wise management strategies require**

Immunization is often not even an option as a check against the spread of parasitic infections because vaccines have not been developed for many tropical diseases, especially those caused by metazoan parasites (Warren and Mahmoud 1990). In addition, cost precludes chemotherapy as a disease control strategy in endemic regions where rapid reinfection requires repeated treatment over long periods of time (Slootweg et al. 1994). Moreover, pharmaceuticals have become obsolete where parasites have developed resistances to these compounds (Kolberg 1994).

Access to clean water and adequate systems for the disposal of human wastes are important in the prevention of waterborne parasitic diseases because they act to prevent the completion of parasite life cycles. Development in this area, however, has been poor. In 1990, only 10%, 13%, and 16% of rural populations in eastern Mediterranean countries, southeastern Asian countries, and Africa, respectively, had access to suitable sewage disposal systems (WHO 1990); establishment of new facilities is just keeping pace with population growth. Additionally, draining ponds that harbor parasites and their vectors may work against the development needs (e.g., aquaculture) in many countries (Chiotha et al. 1991a).

Finally, there are serious limitations to the use of pesticides for vector control. Individual applications of a biocidal agent produce sustained results only when the vector species are locally extirpated (Conway 1976). Thus, multiple applications are necessary for vector control, often at substantial cost. Environmental contamination resulting from pesticide use is itself a risk to public health and nontarget species (e.g., natural predators of vectors), and resistance to pesticides often develops in the vector populations (Ejiofor 1989, Kolberg 1994, WHO 1992). Often the most cost-effective strategies for controlling and preventing parasitic diseases in developing countries may be health and hygiene education and biological vector control.

The latter of these two alternatives is the focus of this article—

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Table 1. Aquatic vectors and intermediate hosts of parasitic diseases that are potentially susceptible to some degree of fish predation and recent estimates of the global occurrence of infection with the parasites (taken from Kolberg 1994, Warren and Mahmoud 1990, and WHO 1990).

Disease	Vector or reservoir host	Estimated occurrence of infection
Microparasitic diseases		
Viruses		
Dengue fever	*Aedes* spp. (Culicidae)	Not available; widespread in the tropics
Arboviral encephalitis	*Aedes, Culex, Culiseta, Mansonia,* and *Psorophora* spp. (Culicidae)	Not available; found throughout the world
Yellow fever	*Aedes, Haemagogus,* and *Mansonia* spp. (Culicidae)	Not available; found in Africa and Latin America
Protozoans		
Malaria	*Anopheles* spp. (Culicidae)	270 million
Macroparasitic diseases		
Nematodes		
Dracunculiasis (Guinea worm disease)	*Cyclops* spp. (Copepoda)	250,000
Filariasis	Biting arthropods (including Chironomidae, Culicidae, and Simuliidae)	90 million
Onchocerciasis (river blindness)	*Simulium* spp.	20 million
Trematodes		
Schistosomiasis	*Biomphalaria, Bulinus, Oncomelania,* and *Tricula* spp.	200 million

specifically, the use of fishes to check the population densities of aquatic vectors and intermediate hosts of parasitic diseases. Following a brief discussion of parasite life cycles and the theory of predatory vector and host control, we review the current literature on the use of fishes in biological control and discuss the present state of knowledge of the role of fishes in regulating vector populations. We then describe an example from Lake Malaŵi in which a decrease in snail-eating fishes has been associated with the invasion of intermediate host snails into the open waters, which in turn is associated with a drastic increase in schistosomiasis (bilharzia) among both native and expatriate populations in Malaŵi. Lastly, we propose recommendations for future research on fish-mediated host control.

Disease control via vector and host suppression

Three groups of parasites are recognized by Hassell and May (1989): metazoan parasitoids, microparasites, and macroparasites. Parasitoids are metazoans that deposit their eggs or larvae in or on "living" hosts (largely arthropods), the tissues of which serve as a food source for the developing larvae. Microparasites are characterized by high rates of reproduction directly within their hosts, usually inside host cells (Begon et al. 1986, Hassell and May 1989). They include viruses, bacterial pathogens, and parasitic protozoans. Macroparasites, on the other hand, do not complete reproduction directly within their hosts, and they are generally larger and have longer generation times than microparasites (Begon et al. 1986, Hassell and May 1989). Several macroparasitic organisms that attack animals are found among flatworms (Platyhelminthes), roundworms (Nematoda), and arthropods. Whereas microparasitic life cycles can often be completed within their hosts, macroparasites produce infective stages that are released from the host. Both micro- and macroparasites include organisms that are transmitted directly from host to host as well as organisms that require an intermediate host or a vector to complete their life cycle.

Many mathematical models have been developed that describe the population dynamics of vector-transmitted parasites and their hosts (e.g., Cohen 1976, Hassell and May 1989, Macdonald 1957, Nicholson and Bailey 1935). The generalized, algebraic statements given by Begon et al. (1986) most simply illustrate the life cycles of parasites. The most important parameter for understanding the dynamics of a given parasitic infection is the parasite's basic reproductive rate (R_p), defined as the average number of new cases of the disease that arise from each infected host (Begon et al. 1986). An infection will spread in a population when $R_p > 1$, and it will die out when $R_p < 1$. $R_p = 1$ defines the transmission threshold of a parasitic disease.

The primary determinants of the basic reproductive rate for vector-transmitted parasites (e.g., the four *Plasmodium* species that cause malaria) are the population densities of vectors (e.g., mosquitoes) and vertebrate hosts (e.g., humans), the effective disease transmission rate (e.g., the rate of mosquito biting that leads to infection), the fraction of infected vectors and hosts that survive to become infectious, and the average period of time that infected vectors and hosts remain infectious.

The simple relationships given by Begon et al. (1986), as well as more complex, dynamic models, which have been validated with empirical data to a limited extent (Hassell and May 1989), indicate that there are, indeed, threshold densities of hosts (both definitive and intermediate) below which parasite populations cannot persist. Thus, measures that reduce the population densities of vectors may be effective in preventing or controlling these diseases.

Several of the world's most destructive parasitic diseases are transmitted by invertebrate vectors inhabiting aquatic ecosystems during at least one of their life stages, and many of these vectors may be preyed on by fish (Table 1). Indeed, much work has been done to investigate the role of fish in reducing vector or intermediate host abundances.

The use of fish to control mosquito vectors

Of all microparasitic human disease vectors, mosquitoes (Diptera: Culicidae) are potentially the most susceptible to fish predation. Mosquitoes are also required for the transmission of filarial macroparasites (Table 1). At least 216 fish species from 30 families have been used in biological control efforts waged in 41 countries against the larvae of 35 mosquito species (Ejiofor 1989). Although the majority of mosquito control efforts have focused on malaria, larvivorous fish have been used or proposed for the control of other mosquito-transmitted diseases, such as yellow fever (Ejiofor 1989), arboviral encephalitis (Yu and Kim 1993), Brugian filariasis (Panicker et al. 1992), and dengue fever (Swaddiwudhipong et al. 1992).

Past investigations of the use of larvivorous fishes to regulate mosquito vector populations have been based on laboratory feeding studies or field trials that were not properly controlled (Fletcher et al. 1992). Mortality of mosquito larvae measured in laboratory aquaria may not be applicable in situ.

Even well-controlled studies are limited in what they reveal about the potential success of vector control in the field. Laboratory studies of the feeding behavior of single fish species are important in determining its food preferences and the handling time it requires for different prey items. A fish species may, however, select prey items in natural environments that are completely different from those readily consumed in the laboratory. Interspecific competition may modify the resource value of different prey items, thereby modifying prey selection. In addition, the habitat heterogeneity of aquatic ecosystems cannot be completely simulated in an aquarium. Refugia from predation that are not present in the laboratory may be available to prey species in nature. Consequently, biological control strategies should not be implemented solely on the basis of promising laboratory results.

In the past, lack of statistical controls and low numbers of trials have characterized most field investigations of fish-mediated mosquito control (Fletcher et al. 1992), limiting confidence in their results and restricting their applicability. Two recent exceptions are worthy of note. Panicker et al. (1992) conducted a cost–benefit analysis of the revenues gained from fish production and the degree of fish-mediated control of the filariasis vectors (*Mansonia* spp.) in 1561 domestic ponds in the state of Kerala, India. Three different methods of aquaculture were examined: monoculture with *Ctenopharyngodon idella* Valenciennes (763 ponds); monoculture with *Osphronemus goramy* Lacépdè, a widely distributed, prized food-fish native to the Greater Sunda Islands (128 ponds; Sterba 1966); and polyculture with six minnow species (Cyprinidae: 670 ponds). Thirty reference ponds in the area were not stocked. After ten months, 80%, 81%, and 70% of the ponds stocked with *C. idella, O. goramy*, and the carp mixture, respectively, were free of weeds, eliminating breeding of the filariasis vectors that use vegetated habitats. Only 20% of the reference ponds were free of aquatic vegetation at the end of the study. At the same time, all three methods of aquaculture produced substantial increases in fish production. This success has prompted the National Bank for Agriculture and Rural Development of India, in collaboration with India's Vector-Control Research Centre, to implement these fish culture methods as part of its development program in the Shertallai region.

Another successful vector control strategy has recently been developed and implemented in the port city of Assab, Ethiopia. In a 12-month investigation conducted by Fletcher et al. (1992), the native cyprinodontid fish *Aphanius dispar* (Rüppel) was added to several randomly selected cisterns, water storage barrels, ritual ablution basins in mosques, and wells throughout the city. The fish were restocked every month where necessary to replenish populations. During the study, mosquitoes were found in 34% of the unstocked sites, and anopheline mosquitoes (which are malaria vectors) in 4% of the unstocked sites. *A. dispar*, by contrast, kept overall mosquito presence to 4.5% of the stocked sites and anopheline mosquito presence to just 0.4% of the stocked sites. The addition of fish to these water storage containers was well accepted by the residents, who became aware of the role of larvivorous fish in mosquito control and found the fish to be useful for keeping their water free of other aquatic organisms. As a result, Ethiopia's National Organization for the Control of Malaria and other Vector-Borne Diseases, in collaboration with municipality and health authorities of Assab, have stocked all 367 major wells in the city with *A. dispar* and are distributing the fish to homeowners who wish to add them to their water storage containers.

The use of fishes to control hosts of schistosomiasis

Aside from filariasis, schistosomiasis (bilharzia or snail fever) is the only macroparasitic disease with aquatic intermediate hosts against which fish have been employed as biological control agents (Table 1). A review of the recent literature has not revealed any records of the use of fishes to control dracunculiasis hosts (copepods) or onchocerciasis vectors (blackflies).

Schistosomiasis is a debilitating parasitic disease caused by trematodes of the genus *Schistosoma*. One of the most important public health problems in the tropics and subtropics (WHO 1965), it probably originated around the Great Lakes of Central Africa and eventually spread to other parts of Africa, the West Indies, and South America (Jordan and Webbe 1969). The disease now occurs in 74 countries and is ranked second to malaria as a cause of human morbidity by a parasitic agent (Noble and Noble 1982, Ukoli 1984). Current estimates put the number of people infected at 200 million (Mott 1984). Another 600 million are under constant threat of infection as the disease continues to spread to new areas (Jordan et al. 1980).

Five species of schistosome are recognized as important parasites of humans. *Schistosoma mansoni* Sambon, *Schistosoma haematobium* (Bilharz), and *Schistosoma japonicum* Katsurada are the most widespread, and *Schistosoma intercalatum* Fisher and *Schistosoma mekongi* Voge, Bruckner, and Bruce are more restricted in their distributions (Rollinson and Simpson 1987). The effects of a single schistosome species can vary, such that infected individuals might show no symptoms

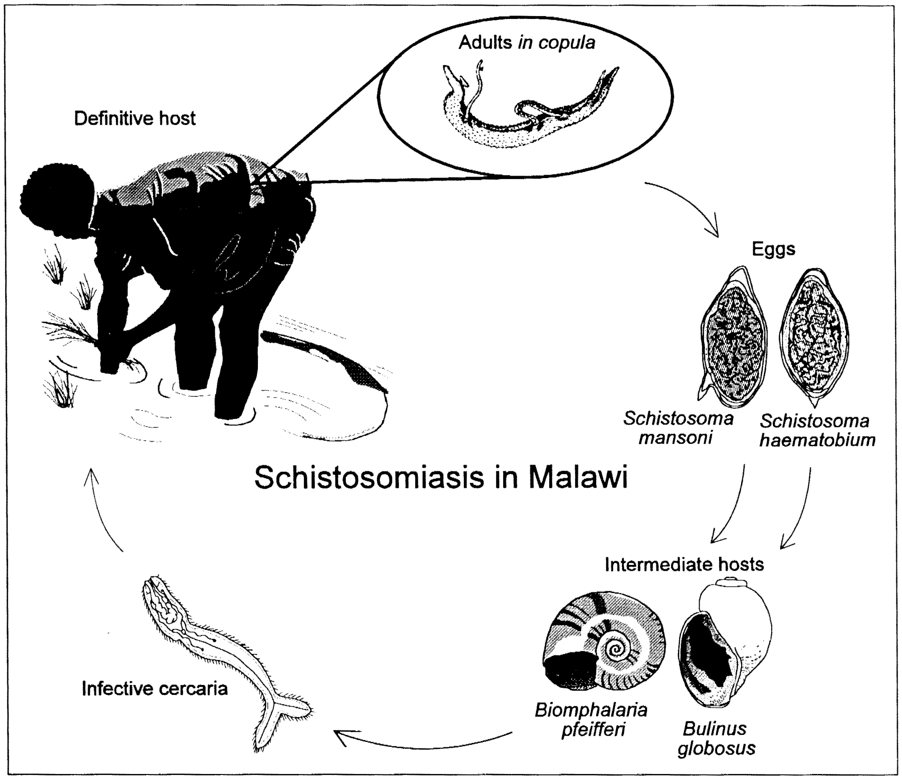

Figure 1. Life cycle of a schistosome.

(Chitsulo 1984, Rosenfield 1979) or might undergo considerable pathological changes, such as gynecological lesions (Wright et al. 1982). Nevertheless, relatively few infected individuals die as a result of the disease (Foster 1967, Jordan and Webbe 1969). The most immediately apparent cost of schistosomiasis is the money spent on treatment and intermediate host control, but the indirect effects on a country's economy can be even more expensive. A study conducted in Sudan, for example, indicated that schistosomiasis depletes the blood hemoglobin levels to the extent that oxygen flow to the muscles and the brain is limited, thereby impairing physical activity (Rosenfield 1979). A 16%–18% reduction in productivity was found among Sudanese infected with schistosomiasis (El Karim et al. 1980).

Schistosomes require specific snail species (e.g., *Biomphalaria, Bulinus, Oncomelania,* and *Tricula* spp.) to complete their life cycles (Figure 1; Warren and Mahmoud 1990). Most of the past work on schistosomiasis control via fishes has been conducted with opportunistic snail feeders in the laboratory or in limited field studies and has been characterized by many of the faults discussed above for research on mosquito-feeding fishes (Slootweg et al. 1994). Several cichlid species are promising candidates for the biological control of schistosome intermediate hosts because of both their widespread distribution in both the Old World and New World tropics and the specializations for molluscivory common in this group (Eccles and Trewavas 1989, Greenwood 1981).

One candidate cichlid is *Geophagus brasiliensis* Quoy and Gaimard, which is widely distributed throughout Brazil (Weinzettl and Jurberg 1990). In the laboratory, *G. brasiliensis* preyed rapidly on snails up to 8 mm in diameter but was unable to consume snails in the 12–14 mm size class, which suggests that although this cichlid may control recruitment of small snails to the population, it may not be able to eliminate older and larger gastropods. In the outdoor pond experiments, aquatic plants and natural substrates were added to each pond, which contained a ramp that rose out of the water. Despite these potential refugia, snails were quickly eliminated from the ponds, after which time *G. brasiliensis* bred successfully. Other fish species were not used concomitantly, so the potential influence of interspecific competition on snail predation by this species remains unknown. *G. brasiliensis* tolerates a wide range of environmental conditions, so it may be a suitable biological control agent in many habitats throughout its natural range.

The ability to regulate snail densities has also been indicated for *Lepomis microlophus* (Günther; Centrarchidae), the shellcracker sunfish, in laboratory trials (Carothers and Allison 1968) and in introductions into Puerto Rican aquaculture ponds (Ferguson 1978). *L. microlophus* is native to the southeastern portion of the United States (Lee et al. 1980). Again, laboratory studies did not elucidate the potential influence of refugia or intraspecific competition on snail predation.

Slootweg et al. (1994) summarize the results of several snail control efforts throughout Africa using the cichlid *Astatoreochromis alluaudi* Pellegrin, which is naturally distributed in Lakes Victoria, Kioga, Nabugabo, Edward, George, Kachira, and Nakavali (Greenwood 1981). The results of field investigations with *A. alluaudi* have ranged from highly successful snail control to no control. This inconsistency may be attributable to the foraging behavior of the fish and the plasticity of its pharyngeal jaw apparatus (Slootweg et al. 1994), a structure that most molluscivorous cichlids use to crack snail shells. Adult *A. alluaudi* may switch from snails to more easily processed prey (e.g., soft-bodied insects) when competition with other predators is low. Many of the field trials that showed no snail control were conducted in the absence of other fish predators. Furthermore, only populations of *A. alluaudi* that feed on hard-bodied prey as juveniles develop the hypertrophied pharyngeal bone structure necessary for feeding on snails (e.g., schistosomiasis intermediate hosts) as adults. This finding may explain why wild-caught adults with hypertrophied pharyngeal jaws initially reduced snail densities, whereas subsequent generations, which failed to develop pharyngeal hypertrophy, could not regulate snail populations (Slootweg et al. 1994).

Schistosomiasis in Lake Malaŵi—a case history

The widespread occurrence of schistosomiasis in Malaŵi has been recognized for more than 70 years (Cullinan 1945, Dye 1924, Ransford 1948). Transmission of schistosomiasis has historically occurred in the swampy areas and protected backwaters adjacent to the shoreline of Lake Malaŵi, where snail hosts such as *Bulinus globosus* (Morelet), which harbors *S. haematobium*, are relatively abundant (Teesdale and Chitsulo 1983). At the time of Evans' (1975) study, the open waters of Lake Malaŵi were considered schistosomiasis free.

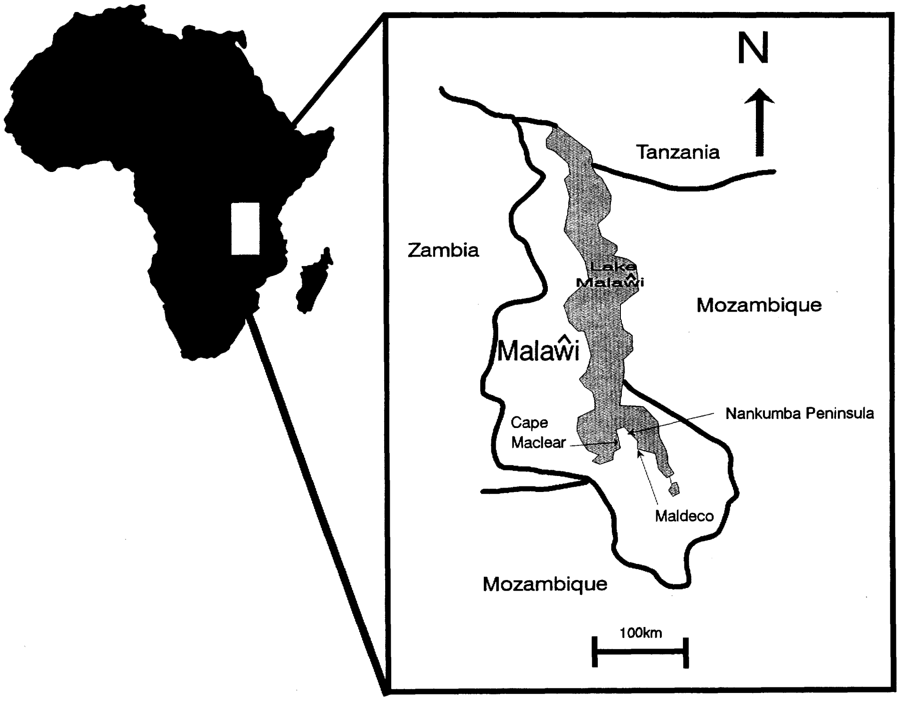

Figure 2. Map of Lake Malaŵi, showing the Nankumba Peninsula.

A team of scientists (including the authors) from the University of Maryland and Pennsylvania State University has been studying the biology of the cichlid fishes around the Nankumba Peninsula (Figure 3) in southern Lake Malaŵi since 1977 and has provided anecdotal evidence of increased incidence of shistosomiasis. From 1977 through 1987 none of the team contracted schistosomiasis from diving and swimming around the Nankumba Peninsula. In 1991, however, five of six divers were infected with schistosomiasis, and in 1992 one of the authors (Stauffer) was also infected. Two Peace Corps volunteers also contracted schistosomiasis while visiting Cape Maclear (on the Nankumba Peninsula) in 1992 and developed novel central nervous system manifestations (CDC 1993).

Consequently, a team from the Division of Parasitic Diseases (of the Centers for Disease Control and Prevention) led by one of the authors (Cetron), in concert with the Malaŵi Ministry of Health, conducted a serologic survey of more than 1000 expatriates for schistosomiasis. Of these, 33% showed evidence of prior infection with *S. haematobium*. This unexpectedly high incidence of schistosomiasis suggested a dramatic increase in the densities of intermediate hosts in Lake Malaŵi, which we postulate to be the result of a decrease in the number of molluscivorous fishes (McKaye et al. 1986). Beginning in 1991, there was also an increase in the number of complaints of a cercarial dermatitis-like syndrome known as swimmers' itch, which may be caused by either mammalian or avian schistosomes.

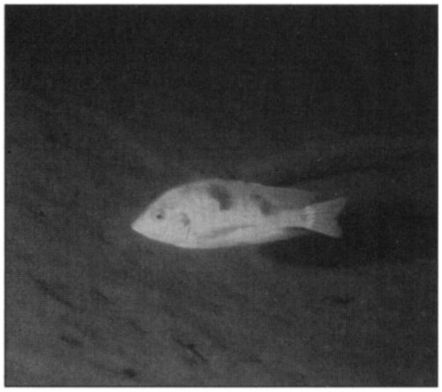

Figure 3. *Trematocranus placodon* off the sand beach at Chembe Village in 1978.

For the most part, the expatriates residing in Malaŵi are not directly exposed to the rivers, swamps, and backwater areas as are many Malaŵians; however, they are exposed to the open waters of Lake Malaŵi. Thus, the screening of the expatriate population provides additional information relative to the abundance of schistosomes in the open waters of Lake Malaŵi. Certainly, the demand for serologic testing by expatriates has increased since April 1993. The morbidity associated with schistosomiasis infection among expatriates is difficult to ascertain, because too few of the seropositive cohort have returned to their health care providers for follow-up evaluation. Nevertheless, acute Katayama syndrome[1] due to schistosomiasis acquired from Lake Malaŵi continues to occur among expatriates. The transmission rates are sufficiently high to pose significant risk to the many tourists and expatriates who visit Lake Malaŵi National Park (approximately 11,000 visitors per year). Further research is needed to understand why Malaŵi's expatriates continue to suffer from rare and unusual manifestations of schistosomiasis including central nervous system dysfunction and acute Katayama syndrome due to *S. haematobium*. The possibility of a hybrid strain of schistosome in the waters of Lake Malaŵi should not be discounted. Novel spine morphologies observed on the eggs of a putative hybrid schistosome, for example, could cause the

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[1] M. Wolfe et al., 1996, manuscript in review. Medical Services, US State Department.

eggs to be concentrated in the tissues of the central nervous system rather than the bladder.

The problem among expatriates, however, is merely the tip of a much larger problem affecting the citizens of Malaŵi; Chembe Village at Cape Maclear is one example. Chembe Village has a population of approximately 4000 people, with slightly less than 50% under 14 years of age. In 1981, 36% of the school children had hematuria (blood in the urine) as determined by reagent dipsticks. The children were not checked for intestinal schistosomiasis; however, in more detailed studies of people from this village, the presence of microscopic hematuria was consistent with *S. haematobium* infection. The 1981 survey was repeated in 1991 and 1994, with 67% and 83% of the children, respectively, having hematuria.

In 1994, 607 school children were evaluated, which represented 70% of the total enrollment. The highest prevalence of hematoria (87%) was observed among 5- to 15-year-olds. Grossly bloody urine or the presence of blood clots in the urine was seen in 72 of 607 children (12%). A 10-ml aliquot of formalin-preserved urine from each child was filtered through standard nytrel filters and the filter membranes examined by microscopy so the number of schistosome ova could be counted. Overall, 75% of the children (455 of 607) had schistosome eggs in their urine. Of these, 60% had between 1 and 24 eggs per 10 ml of urine, 11% had between 25 and 49 eggs per 10 ml, and 29% had more than 50 eggs per 10 ml.

Hypotheses to explain the increased incidence of schistosomiasis in Lake Malaŵi. McKaye et al. (1986) postulated that the combination of lack of suitable habitat and the prevalence of fish predators limit host snail populations along the sandy shorelines of Lake Malaŵi. They further predicted that any reduction of snail-feeding fishes would result in an increase in the incidence of bilharzia in southern Lake Malaŵi.

In formulating this prediction, McKaye et al. (1986) demonstrated that molluscivorous fishes, such as *Trematocranus placodon* (Regan; Figure 2) and *Mylochromis anaphyrmus* (Trewavas), can control snail densities by predation. In addition, snail-eating fishes regulated snail hosts of *S. haematobium* and *S. mansoni* in both laboratory and aquaculture facilities; these fishes preferred host snails of the genus *Bulinus* over the common open-water snails of the genus *Melanoides* (Chiotha et al. 1991a, b). This preference of the snail-eating fishes for *Bulinus* spp. is probably related to the fact that the highly sculptured and thick shells of *Melanoides* spp. thwart attacks of molluscivores, as suggested by Vermeij and Covich (1978).

Distribution of snail hosts in Lake Malaŵi. In the 1980s, data on the densities and distributions of several species of snails around the Nankumba Peninsula were collected and examined (Louda and McKaye 1982, Louda et al. 1983, 1984). Gastropod densities were greatest in the shallow waters (1.5–4.5 m deep) of the lake, which supports the hypothesis that snail populations are regulated by predatory fishes, which are less abundant in the shallowest reaches. This view was bolstered by the observation that no schistosome host snails, the favored food of these molluscivores (Chiotha et al. 1991a, b), were found in the open waters.

Between 1993 and 1995, we again surveyed this region and found a population of *B. globosus* on the lakeshore in the Maldeco area, just south of Nankumba Peninsula on the western shore of the southeast arm of the lake. This observation is the first recorded of this host snail along the open lakeshore itself. Of particular interest was finding that one snail collected behind the Maldeco Fisheries Unit was infected with a mammalian schistosome. In additional, 13 *B. globosus* individuals were collected in eel grass (*Vallisneria* sp.) beds in the lake at Cape Maclear in 1994, which in extensive surveys in the 1980s contained none of these host snails (Louda and McKaye 1982, Louda et al. 1983, 1984, McKaye et al. 1986). Laboratory-raised offspring of these snails were susceptible to *S. haematobium* miracidia that were developed from eggs present in the urine samples from Chembe Village children during a pretreatment screening,[2] demonstrating that this population could serve as the intermediate host of *S. haematobium*. In 1995, *B. globosus* was the most common snail species in the pools created by wave action along the lakeshore near Maldeco.

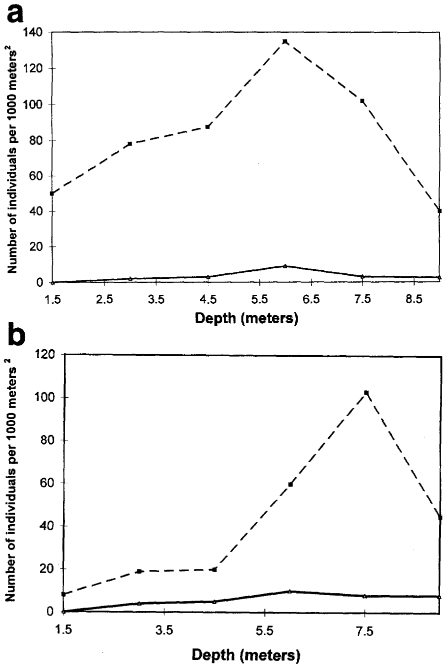

Figure 4. (**a**) Density of three-spot molluscivores (*Trematocranus placodon* and *Trematocranus microsotma*) at Cape Maclear, Lake Malaŵi, Africa, in 1978 (dashed line) and in 1994 (solid line). (**b**) Density of diagonally striped molluscivores (*Mylochromis anaphyrmus* and *Mylochromis sphaerodon*) at Cape Maclear, Lake Malaŵi, in 1978 (dashed line) and in 1994 (solid line).

Decrease in snail-eating fish. To investigate whether the increase in snails is correlated with a decrease in fishes, we compared transect data from the late 1970s with that from 1994. During the late 1970s, SCUBA divers swam 50-m transects at depths of 1.5 m, 3 m, 4.5 m, 6 m, 7.5 m, and 9 m in front of the Fisheries Research Station located at Cape Maclear and recorded the number of snail-eating fishes observed within 4 m of each side of the transect line (McKaye et al. 1986). These transects were repeated in 1994. Between 1978 and 1994, the number of three-spot molluscivores (*T. placodon, Trema-*

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[2] J. J. Sullivan, 1995, personal observation.

tocranus microstoma) declined at all depths. The decrease was most dramatic at a depth of 6 m, where the density declined from 138 per 1000 m^2 to 5 per 1000 m^2 (Figure 4a). Likewise, the number of diagonally striped molluscivores (*M. anaphyrmus* and *Mylochromis sphaerodon* [Regan]) declined drastically at all depths (Figure 4b). No molluscivores were observed at the shallowest depths in 1994. We attribute this reduction to extensive gill netting and illegal beach seining (e.g., lining the seines with mosquito netting), which have been common since 1985.

The decline in abundance of snail-eating fishes is not restricted to the areas immediately surrounding Nankumba Peninsula. The number of molluscivores taken in experimental trawl fisheries has also declined severely. South of Boadzulu Island, which is located near Maldeco, experimental trawl samples between 20–40 m showed a decrease in the total biomass of molluscivores (e.g., *Chilotilapia rhoadesii* [Boulenger], *Lethrinops mylodon* Eccles and Lewis, *M. anaphyrmus,* and *T. placodon*) from 190.2 metric tons/yr in the 1970s to 41.3 metric tons/yr in the 1990s. During the same period, the biomass of these same fishes decreased in the entire southeast arm of the lake from 680 to 373.7 metric tons/yr.

Control of schistosomiasis in Lake Malaŵi. A sustainable approach to schistosomiasis control is urgently needed, especially at lakeshore villages. Potential methods include: improved water supply, sanitation, health education, chemotherapy, molluscicides, and biological control agents. Detailed discussion of these methods can be found in Ansari (1973), Berg (1964, 1973), Bradley and Webbe (1978), Jordan and Webbe (1969), Kuris (1973), Michelson (1958), Rosenfield (1979), and WHO (1965).

The use of fishes to control snail hosts of schistosomes has been confined to relatively few countries, including Cameroon, Kenya, Sudan, Zaire, and Brazil (Brown 1980, Jordan et al. 1980, Slootweg et al. 1994). Chiotha et al. (1991a) proposed that biological controls might be an alternative for controlling snails in aquatic habitats in Malaŵi, and Chiotha et al. (1991b) demonstrated that the facultative molluscivore *T. placodon* is, in fact, effective in controlling schistosome snail hosts in aquaculture ponds in Malaŵi. Based on our recent results, we now hypothesize that the observed increase in transmission of bilharzia from the open waters of Lake Malaŵi is directly related to the increase in the numbers of schistosome hosts, which in turn is associated with the reduction of molluscivorous fishes as a result of overfishing. To fully exploit the potential of snail-eating fishes to control the incidence of schistosomiasis in the open waters of Lake Malaŵi will require the following:

- A program to breed *T. placodon*, a known biological control agent of bilharzia snail hosts, in sufficient numbers for reintroduction into the lake. Preliminary evidence from the aquaculture facilities at Bunda College, University of Malaŵi, indicates that this species will breed in captivity.
- Investigations to determine the breeding and raising conditions of the brood ponds that will ensure that cultured *T. placodon* develop and maintain the molariform pharyngeal teeth that allow them to feed effectively on snails. Preliminary evidence in our laboratory indicates that if artificially bred *T. placodon* are fed soft flake foods, molariform teeth on their pharyngeal bones do not develop, whereas fish fed on hard pellet food develop molariform teeth. Without these molariform teeth, adults are not capable of crushing snails.
- The implementation of regulations to prevent fishing in the breeding arenas of the snail-eating fishes. Based on eight years (1977–1985) of controlled fishing at our study sites by the local fishermen in Chembe Village, we know that it is possible to limit the harvest of these fishes at certain localities and during the peak breeding seasons by hiring local fishermen to enforce the fishing regulations. Once the regulations are in effect, local management plans can be tested for their efficacy in interrupting the life cycle of schistosomes by reducing host snail populations. Ideally, if such plans prove successful they can be expanded to appropriate locales in other areas of Lake Malaŵi.
- Investigations to determine: life-history characteristics of potential intermediate hosts, including the intermediate host status of *Bulinus nyassanus* (Smith), *Bulinus succinoides* (Smith), and other snails not currently known to participate in the life cycle of schistosomes; the in situ effect of predation on mollusc densities using underwater cage studies; the population dynamics of intermediate host snail species; the population densities of Lake Malaŵi gastropods; and the distribution of snail species and their predators throughout the lake.

Despite the need for these data, the increased incidence of bilharzia is so severe that efforts to mitigate its spread must be implemented immediately. We suggest the implementation of a strict management and control policy for snail-eating fishes, given that for the first time a decrease in fish abundance has been directly linked to an outbreak of human disease. In the short term, complete treatment of the residents of Chembe Village is being undertaken. In the long run, an integrated program must be developed that includes incidence surveillance, improved sanitation and water resources, health education targeted at school-age children, and surveillance and control of intermediate hosts.

A look to the future

The interactions that occur between many species of predatory fishes and disease vectors and hosts are fundamental parts of the epidemiology of several devastating parasites. Much of the published research on the use of predatory fishes to regulate the population densities of disease vectors has not yielded the predictive capabilities that wise management strategies require. The limitations of past vector control studies have illuminated several weak spots in the science of fish-mediated biological control.

Studies are still being published with poor replication and improper controls. More rigorous experimental design criteria need to be applied to research on vector and host regulation by fishes. Demonstrating that a single fish species significantly reduces host densities in the laboratory is insufficient evidence to support the use of that species in a vector and host control program. The importance of prey refugia (Thomas and Tait 1984) and interspecific competition (Slootweg et al. 1994) in more complex ecosystems (e.g., lakes and streams) may be underestimated by laboratory and pond studies as well. Investigations in outdoor experimental ponds using mixtures of fish species and simulated refugia and studies in field enclosures in natural environments would help forge a better understanding of the relationships between fish predators and the vectors and intermediate hosts of parasitic diseases.

We strongly support the World Health Organization's (1982) recommendation to avoid the introduction of exotic species for biological vector and host control due to their potential threat to native species. More effort in locating indigenous candidate predators is needed because suitable indigenous fish species have not been identified in many areas where diseases are prevalent. Lake Malaŵi is an exception to this generalization—at least 20 indigenous snail-feeding fish species have been identified from the lake. Dracunculiasis and onchocerciasis are two more macroparasitic diseases transmitted by vectors that are aquatic during at least part of their lives. Biological control strategies employing fishes have not been developed for these diseases. Although education programs have recently been successful in reducing the number of dracunculiasis infections (Kolberg 1994), fish-mediated strategies for controlling both onchocerciasis and economically important vector-borne diseases of farm animals remain open to investigation.

The ultimate goal of biological control is a reduction in the prevalence of disease and not merely a reduction in vector and host densities. Epidemiological data need to be gathered in conjunction with vector and host control studies to better characterize the value of the control measures. In other words, the threshold vector densities required for disease transmission need to be determined when researching a biological control strategy. Finally, a single prevention or control measure will rarely work against any particular disease (Kolberg 1994, Slootweg et al. 1994, Thomas and Tait 1984). Continued effort needs to be made in bringing together several strategies for the control of complex parasitic diseases.

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