

Nonnative Fish to Control *Aedes* Mosquitoes: A Controversial, Harmful Tool

VALTER M. AZEVEDO-SANTOS, JEAN R. S. VITULE, FERNANDO M. PELICICE, EMILI GARCÍA-BERTHOU, AND DANIEL SIMBERLOFF

Zika, chikungunya, yellow fever, and dengue are mainly transmitted to humans through Aedes mosquitoes. In attempts to control these diseases, governments and the public have encouraged the use of fish predators to control mosquito populations. However, the efficacy of using these predators for mosquito-population control is largely unproven and dubious, particularly for container-breeding mosquitoes that reproduce in minute aquatic habitats, which are unsuitable for fish. Moreover, the use of nonnative fish for biological control entails a high potential risk of promoting escapes and invasions, which can impair ecosystem functioning and biodiversity. Although this risk is recognized, the practice may intensify in countries affected by recent epidemics transmitted by Aedes spp. Therefore, we argue that the use of nonnative fishes to control Aedes mosquitoes is ungrounded and ecologically damaging and point out that other approaches (e.g., habitat management, biotechnological tools, and more evidence-based integrated management) should be used to combat mosquito-borne human diseases.

Keywords: *Zika, public health, invasive species, mosquito control, Aedes aegypti*

The recent cluster of neurological disorders linked to Zika virus impelled the World Health Organization (WHO) to declare Zika a “public health emergency of international concern” (Cohen 2016, p. 543). Zika, like chikungunya, dengue, yellow fever, and malaria, is a mosquito-borne disease (Caraballo and King 2014, Vasconcelos 2015). Collectively, these diseases infect 700 million people and kill over 1 million people every year (Caraballo and King 2014). Mosquito vectors vary with disease and geographical area. For Zika, chikungunya, yellow fever, and dengue, the main vector is *Aedes aegypti* (Diagne et al. 2015, Vasconcelos 2015), native to Africa, which has invaded Europe, the Americas, the Caribbean, regions of Africa in which it is not native, and the Middle East (Enserink 2014, 2015); however, other mosquitoes of the same genus also transmit diseases, such as the Asian tiger mosquito, *A. albopictus*. For instance, some outbreaks of chikungunya (in 2004 in East Africa, 2005 in Réunion, and 2007 in India) were due to a mutation that allowed the virus to use *A. albopictus* as a vector, in addition to the more tropical and subtropical *A. aegypti* (Enserink 2014, 2015). With a long history of threatening human well-being, plus the recent publicity surrounding the emerging Zika virus (Enserink 2015), proposals to eradicate *Aedes* mosquitoes will intensify in many countries, particularly in the tropics.

Authorities in various nations have used several methods to control *Aedes* populations, some of which are claimed to be environmentally friendly. One such method is the use of nonnative predatory fish, in the belief that they could effectively control mosquito larvae (e.g., Azevedo-Santos et al. 2016). This method has strong appeal among authorities and the lay public (e.g., Sarwar 2015), but its effectiveness has not been demonstrated (e.g., Rupp 1996, Pyke 2008, Walshe et al. 2013). In addition, it is prone to disrupt aquatic ecosystems, because nonnative fishes are often used. In this short article, we briefly summarize the basis for this strategy and argue that it should not be considered a viable means to combat mosquitoes and the diseases they carry. We also review more sustainable and effective potential alternatives.

Fish against mosquitoes?

Many fish species feed in part on mosquito larvae, but members of the live-bearing Poeciliidae (e.g., *Gambusia* spp. and *Poecilia* spp.) are best known for this habit (Cavalcanti et al. 2007, Chandra et al. 2008, Sarwar 2015). This behavior is the basis of the biological control of harmful mosquitoes via fish predation, considered an easy and low-cost alternative to other methods, such as sanitary measures, habitat management, lethal ovitraps, and insecticides (e.g., Morrison et al. 2008, Azevedo-Santos et al. 2016). However, mosquito



Figure 1. Nonnative poeciliids often used in biological control programmes.

control using nonnative larvivorous fish has a long, controversial history worldwide.

In developing countries such as Brazil, for example, several municipalities have used nonnative fish to fight *A. aegypti*, and the most commonly used species is the guppy, *Poecilia reticulata* (figure 1; Azevedo-Santos et al. 2016). Several other nonnative species have been used for this purpose, including tilapias (e.g., *Oreochromis niloticus*), goldfish (*Carassius auratus*), and Siamese fighting fish (*Betta splendens*). In El Salvador, for example, the Pacific fat sleeper (*Dormitator latifrons*), an Eleotridae from the American Pacific coast, is the most widely used predator (see the supplemental material).

Local and international media have frequently reported the use of fish to fight mosquito vectors, including *Aedes* (see the supplemental material), as well as other genera. Such publicity often spreads the notion that this practice is safe and effective. Although experimental studies usually show that fish can consume large quantities of mosquito larvae (e.g., Cavalcanti et al. 2007, Saleeza et al. 2014),

there is substantial doubt regarding the effectiveness of this technique as a population-control measure (e.g., Rupp 1996, Pyke 2008, Han et al. 2015). A recent comprehensive systematic review regarding malaria concluded that “reliable research is insufficient to show whether introducing larvivorous fish reduces malaria transmission or the density of adult anopheline mosquito populations” (Walshe et al. 2013, p. 2) and that “countries should not invest in fish stocking as a larval control measure in any malaria transmission areas outside the context of carefully controlled field studies or quasi-experimental designs” (Walshe et al. 2013, p. 2). A main cause of failures in biological control lies in the mosquito’s life cycle. In contrast to other culicid genera, including *Anopheles*, *Aedes* are container-breeding mosquitoes, with larvae generally developing in tree holes or artificial containers, such as flowerpot bases, tires, bottles, disposable cups, and other anthropogenic objects (see Focks et al. 1981, Pinheiro and Tadei 2002). It is difficult or impractical to release fish into these small environments. Therefore, fish stocking plays a very limited role, because mosquitoes

Table 1. Examples of fish species introduced for biological control of mosquitoes.

Species	Origin (realm)	Locale of introduction (realm)	References
<i>Carassius auratus</i>	Palaearctic	Palaearctic (other regions)	Welcomme (1988)
<i>Gambusia affinis</i>	Nearctic and Neotropical	Afrotropical, Australian, Neotropical (other regions), Palaearctic	Welcomme (1988); Lucinda (2003); WHO (2003); Baker et al. (2004)
<i>Gambusia holbrooki</i>	Nearctic	Australian, Palaearctic	Coy (1979); Landeka et al. (2015); Tabibzadeh (1970)
<i>Oryzias latipes</i>	Palaearctic	Neotropical	Welcomme (1988)
<i>Phalloceros cf. caudomaculatus</i>	Neotropical	Afrotropical	Welcomme (1988); Lucinda (2003)
<i>Poecilia latipinna</i>	Nearctic and Neotropical	Australian, Oriental	Welcomme (1988); Lucinda (2003)
<i>Poecilia mexicana</i>	Nearctic and Neotropical	Australian	Welcomme (1988); Lucinda (2003)
<i>Poecilia reticulata</i>	Neotropical	Afrotropical, Australian, Neotropical (other regions), Oriental	Welcomme (1988); Lucinda (2003); WHO (2003); Deacon et al. (2011)
<i>Poecilia vivipara</i>	Neotropical	Neotropical (other regions)	Lucinda (2003); Langeani et al. (2007)

will tend to reproduce to some extent in microhabitats that are unavailable or inhospitable to predatory fish. Moreover, adult female mosquitoes are quite discriminating in selecting oviposition sites, and experiments have shown that females use chemical cues to avoid waters containing fish or other predators (e.g., Angelon and Petranka 2002, Pamplona et al. 2009). Therefore, releasing fish in selected sites cannot adequately cover the reproductive spatial range used by mosquitoes and may even stimulate females to select other habitats for oviposition, including cryptic ones, with no real effects on their abundance.

Another important factor is that positive results from laboratory predation trials (e.g., Cavalcanti et al. 2007, Saleeza et al. 2014), as well as evidence that fish are eating mosquito larvae in the field (e.g., Martinez-Ibarra et al. 2002), cannot be taken as strong evidence that larvivorous fish can control wild populations of mosquitoes and, even less, control or eradicate diseases (Han et al. 2015). Mosquitofishes (*Gambusia* spp.) are generalist predators that will switch diets depending on resource availability, often preferring cladocerans or other prey (García-Berthou 1999), and can therefore sometimes even benefit mosquitoes by reducing competition or predation from other invertebrates (Blaustein and Karban 1990). Even if introduced fish reduce mosquito abundance, this does not necessarily translate into changes in the incidence of human diseases (Han et al. 2015).

A pathway for nonnative species

Owing to mosquito-control programs, several fish species from North and Central America (table 1) are currently found in natural and seminatural environments in locations beyond their geographical origin (Welcomme 1988, WHO 2003). Two closely related species, *Gambusia affinis* and *G. holbrooki*, widely known as mosquitofish, have collectively been introduced into more than 40 countries (Welcomme 1988, García-Berthou et al. 2005). Similarly, *P. reticulata*, originally from the northern drainages of South America (Lucinda 2003), was introduced into about 30 countries

in the Americas, Africa, Asia, and Australia (Deacon et al. 2011); some introductions of *P. reticulata* occurred over a century ago (Lindholm et al. 2005).

The introduction pathways are diverse. They can be intentional and direct, such as when official programs release the fish directly into natural environments such as ponds and streams (figure 2). Introductions can also occur when private citizens, misguided by publicity about control programs, receive nonnative species and release them into natural environments. In addition, people often release fish into the environment when they are no longer wanted (e.g., as aquarium ornamentals) or necessary (Azevedo-Santos et al. 2015). Accidental introductions can also occur, especially when fish escape from confined environments (e.g., during transportation or cleaning; Britton and Orsi 2012, Ortega et al. 2015). In tropical countries, the rainy season can also contribute to these accidental escapes, even if fish are initially introduced to isolated containers, wells, or ponds. The point is that the manipulation of nonnative organisms, even in confined circumstances, significantly increases the chances of new introductions.

In this manner, many fish used for the biological control of mosquito vectors have become established introduced species, which makes biomanipulation an important and recognized pathway of nonnative species introduction (Welcomme 1988, Langeani et al. 2007). It is worth noting that introductions will likely intensify in some countries affected by recent epidemics caused by *Aedes* species.

Environmental impacts

Fish introductions cause concern because nonnative species have produced important environmental, economic, and social disturbances in different ecosystems worldwide (Mack et al. 2000, Pimentel et al. 2000, Rahel 2007, Vitule et al. 2009). Many studies have reported that nonnative species have multiple effects on native biota and ecosystem functioning (e.g., Cucherousset and Olden 2011, Simberloff et al. 2013), including predation, competition, bioturbation, and spread of pathogens. In addition, risk and uncertainty are

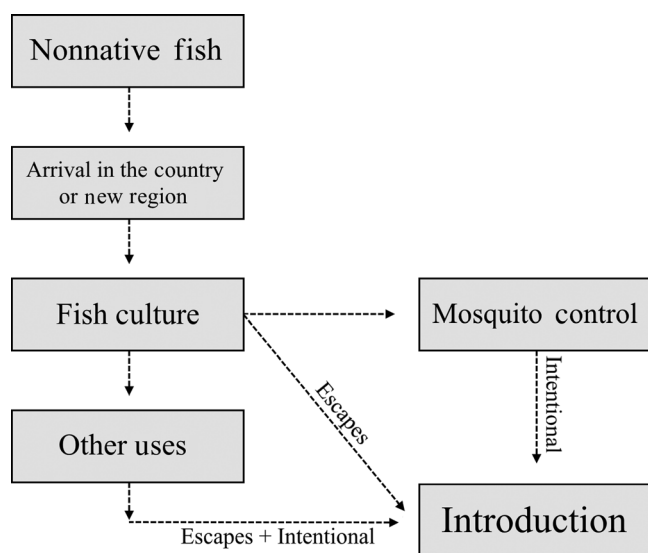


Figure 2. Fish introduction pathways associated with mosquito control. Arrows indicate the sequence between arrival and introduction.

always associated with new introductions, so it is difficult to provide safe predictions about negative impacts and invasion. *Invasional meltdown*, which occurs when newly arrived nonnative species facilitate the spread and impact of other nonnative species (Simberloff and Holle 1999, Simberloff 2006), is also a real possibility, mainly because most river systems in the world are already invaded by multiple nonnative organisms (e.g., Casal 2006, Leprieur et al. 2008).

Introduced Poeciliidae, for example, have caused ecological impacts in several locations. Fish of the genus *Gambusia* affect plankton communities (e.g., Margaritora et al. 2001), other fishes (e.g., Arthington 1989), and amphibians (e.g., Goodsell and Kats 1999). In this context, a review compiled the numerous negative effects of *Gambusia affinis* and *G. holbrooki* (Pyke 2008), species with strong potential to become harmful invaders. They are aggressive fishes that attack other species or compete directly for resources. Moreover, they also cause disturbances to ecosystems, decreasing transparency and water quality through trophic cascades or other mechanisms (Pyke 2008). Fish from other genera, such as *Poecilia* spp., have also disrupted the environments they invade (Arthington 1989, Lucinda 2003). In addition, Poeciliidae often dominate fish assemblages in altered environments (Cunico et al. 2011), which in some cases can cause an additional disturbance to the resident biota.

In addition, species usually used in biological-control programs (table 1) are not selective feeders: *Gambusia*, for example, consume many different prey species, at high rates, when released into natural ecosystems (Rehage et al. 2005). This means that nonnative fishes might consume other resources (e.g., native invertebrates or algae) in addition to targeting *Aedes* larvae, decreasing management effectiveness and inducing changes to food webs and the structure

of natural communities (Gkenas et al. 2012). Finally, aquatic invaders are particularly difficult to eradicate or manage (Francis and Pyšek 2012), so a biological-control introduction of a fish species for mosquito control will be unlikely to be redressed if it should turn out to be problematic.

Alternatives exist

Several alternatives exist for controlling mosquito vectors. Educational campaigns to eliminate favorable environments for reproduction (i.e., stagnant water) are extremely important in reducing populations of *Aedes* mosquitoes. For instance, a randomized trial in Mexico showed that an educational campaign was more effective than chemical spraying in reducing breeding places of *A. aegypti* (Espinoza-Gómez et al. 2002). In fact, education should be considered the primary paradigm for controlling established vector-mosquito populations and preventing or limiting the spread of new introductions (Azevedo-Santos et al. 2015). Local, state, and federal authorities should also consider strict sanitary protocols and penalize people who create conditions for mosquito reproduction. Moreover, health officials should be authorized to inspect sites and fine offenders. The use of insecticides is another alternative that has been employed in many cities (Luna et al. 2004), but its nontarget effects can be substantial (Relyea 2005) and are not fully known, and insecticide use can lead to the evolution of resistant mosquito lineages (Hemingway and Ranson 2000) or reduce the effectiveness of education campaigns (Espinoza-Gómez et al. 2002).

Some novel approaches to mosquito control have received greatly increased attention in the wake of the spread of Zika virus in South America. O'Neill and colleagues (O'Neill 2015) have infected *A. aegypti* with a bacterium in the genus *Wolbachia* originally isolated in fruit flies. The microbe is inherited through both male and female mosquitoes. All eggs of an infected mosquito carry the bacterium, and when an uninfected female mates with an infected male, the resultant eggs do not hatch. Furthermore, infected females block the transmission of dengue, Zika, chikungunya, and yellow fever. Infected mosquitoes have now been released in Australia, Colombia, Vietnam, Brazil, and Indonesia. Oxitec, a commercial firm, has taken a different tack (Harris et al. 2012), inserting a gene that normally causes *A. aegypti* to die before maturity but whose action is suppressed by tetracycline. Mosquitoes are reared on a diet containing tetracycline, and when released into the environment, males mate with wild-type females, all of whose offspring then carry the gene. In the absence of tetracycline in the environment, they die. This is a version of the traditional sterile-insect technique but with the sterile insects produced by genetic engineering combined with tetracycline rather than by radiation. The method was field-tested on Grand Cayman Island and is now being used in Brazil in response to the Zika epidemic. Finally, several authors have suggested that genome-editing using RNA-guided gene drives, particularly those based on CRISPR-Cas9 nucleases, could be used to

suppress mosquito populations or to hinder their ability to transmit a pathogen (Esvelt et al. 2014). For instance, a transgene that inhibits the reproduction or transmission of the pathogen could be attached to the gene drive as “cargo.” For all of these approaches, the key to effectiveness will be how quickly the modified version of the mosquito spreads through the population relative to the speed at which natural selection produces genotypes that prevent the spread (for instance, female *A. aegypti* able to distinguish *Wolbachia*-bearing males or males of the Oxitec mosquito).

These proposals to use new techniques for mosquito control have elicited great concern about possible unintended consequences, exacerbated by the fact that mosquitoes do not respect national borders (Angulo and Gilna 2008). The release of the Oxitec mosquito on Grand Cayman Island in particular elicited major objections (Enserink 2010) because it was not subjected to review by the public or any international body. The release of *Wolbachia*-infected *A. aegypti* has raised concerns with the fact that *Wolbachia* may be transmitted horizontally between species, as well as the fact that released mosquitoes are not bound by borders (Loreto and Wallau 2016). Although it is not zero, the risk of horizontal transmission seems low (Dobson et al. 2016, O’Neill 2016). Similarly, Araki and colleagues (2014) and the US National Research Council (2016) called for caution and thorough risk assessment of plans to use gene drives to edit the genomes of organisms to be released to the environment. However, the rapid spread of Zika virus and the confirmation of its impact on birth defects (Cohen 2016) have overtaken efforts to effect an international agreement on protocols for any of these technologies, as witnessed by the recent releases of modified mosquitoes in Australia and Brazil.

Conclusions

The use of fish to control mosquito–disease vectors raises relevant questions concerning management success and unintended consequences that must be emphasized as concern about mosquito-borne diseases rapidly increases. Scientific evidence does not support the efficacy of the method, which has been a significant source of nonnative fish invasions, posing a substantial threat to aquatic ecosystems. For these reasons, we recommend that decisionmakers avoid this technique and consider alternatives. In regions where this practice has already been carried out, further use should be discouraged because increased propagule pressure can increase impacts and lead to new establishments and invasions (Lockwood et al. 2005, Vitule et al. 2009). It is crucial that newspapers and social media avoid touting the use of fish as a means to control mosquitoes, at least without discussing the possible harmful consequences and alternative strategies.

In an age in which human populations face new epidemics involving mosquito-borne viruses, misguided human actions can increase introductions of new species and increase impacts—all while the health issue remains

unresolved. The risks and uncertainty behind this strategy are too high, and they must be considered when decisions are made, especially in warm tropical regions.

Acknowledgments

VMAS was supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES); FMP and JRSV were supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); and EGB was supported by the Spanish Ministry of Economy and Competitiveness (project nos. CGL2013-43822-R and CGL2015-69311-REDT), the Government of Catalonia (reference no. 2014 SGR 484), and the European Union (COST Action no. TD1209).

Supplemental material

Supplementary data are available at *BIOSCI* online.

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Valter M. Azevedo-Santos (valter.ecologia@gmail.com) is affiliated with the Laboratório de Ictiologia in the Departamento de Zoologia at the Universidade Estadual Paulista “Júlio de Mesquita Filho,” in Botucatu, Brazil. Jean R. S. Vitule is with the Laboratório de Ecologia e Conservação (LEC) in the Departamento de Engenharia Ambiental, Setor de Tecnologia, at the Universidade Federal do Paraná, in Curitiba, Brazil. Fernando M. Pelicice is affiliated with the Núcleo de Estudos Ambientais at the Universidade Federal de Tocantins, in Porto Nacional, Brazil. Emili García-Berthou is with GRECO of the Institute of Aquatic Ecology at the University of Girona, in Catalonia, Spain. Daniel Simberloff is affiliated with the Department of Ecology and Evolutionary Biology at the University of Tennessee, in Knoxville.