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

BioScience 67: 84–90.
doi:10.1093/biosci/biw156 Advance Access publication 21 December 2016

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

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 (*Beta 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
Carassius auratus	Palearctic	Palearctic (other regions)	Welcomme (1988)
Gambusia affinis	Nearctic and Neotropical	Afrotropical, Australian, Neotropical (other regions), Palearctic	Welcomme (1988); Lucinda (2003); WHO (2003); Baker et al. (2004)
Gambusia holbrooki	Nearctic	Australian, Palearctic	Coy (1979); Landeka et al. (2015); Tabibzadeh (1970)
Oryzias latipes	Palearctic	Neotropical	Welcomme (1988)
Phalloceros cf. *caudomaculatus*	Neotropical	Afrotropical	Welcomme (1988); Lucinda (2003)
Poecilia latipinna	Nearctic and Neotropical	Australian, Oriental	Welcomme (1988); Lucinda (2003)
Poecilia mexicana	Nearctic and Neotropical	Australian	Welcomme (1988); Lucinda (2003)
Poecilia reticulata	Neotropical	Afrotropical, Australian, Neotropical (other regions), Oriental	Welcomme (1988); Lucinda (2003); WHO (2003); Deacon et al. (2011)
Poecilia vivipara	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

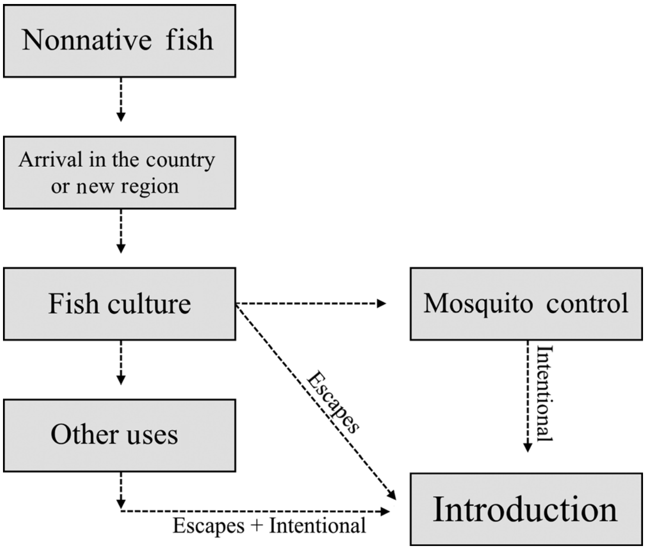

Figure 2. Fish introduction pathways associated with mosquito control. Arrows indicate the sequence between arrival and introduction.

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.

References cited

Angelon KA, Petranka JW. 2002. Chemicals of predatory mosquitofish (*Gambusia affinis*) influence selection of oviposition site by *Culex* mosquitoes. Journal of Chemical Ecology 28: 797–806.

Angulo E, Gilna BG. 2008. International law should govern release of GM mosquitoes. Nature 454: 158.

Araki M, Nojima K, Ishii T. 2014. Caution required for handling genome editing technology. Trends in Biotechnology 32: 234–237.

Arthington AH. 1989. Diet of *Gambusia affinis holbrooki*, *Xiphophorus helleri*, *X. maculatus* and *Poecilia reticulata* (Pisces: Poeciliidae) in streams of southeastern Queensland, Australia. Asian Fisheries Science 2: 193–212.

Azevedo-Santos VM, Pelicice FM, Lima-Junior DP, Magalhães ALB, Orsi ML, Vitule JRS, Agostinho AA. 2015. How to avoid fish introductions in Brazil: Education and information as alternatives. Natureza y Conservação 13: 123–132.

Azevedo-Santos VM, Vitule JRS, García-Berthou E, Pelicice FM, Simberloff D. 2016. Misguided strategy for mosquito control. Science 351: 675.

Baker C, Rowe D, Smith J. 2004. *Gambusia*: A biodiversity threat? Water and Atmosphere 12: 24–25.

Blaustein L, Karban R. 1990. Indirect effects of the mosquitofish *Gambusia affinis* on the mosquito *Culex tarsalis*. Limnology and Oceanography 35: 767–771.

Britton JR, Orsi ML. 2012. Non-native fish in aquaculture and sport fishing in Brazil: Economic benefits versus risks to fish diversity in the upper River Paraná Basin. Reviews in Fish Biology and Fisheries 22: 555–565.

Caraballo H, King K. 2014. Emergency department management of mosquito-borne illness: Malaria, dengue, and West Nile virus. Emergency Medicine Practice 16: 1–23.

Casal CMV. 2006. Global documentation of fish introductions: The growing crisis and recommendations for action. Biological Invasions 8: 3–11.

Cavalcanti LPG, Pontes RJS, Regazzi ACF, Júnior FJP, Frutuoso RL, Sousa EP, Filho FFD, Lima JWO. 2007. Efficacy of fish as predators of *Aedes aegypti* larvae, under laboratory conditions. Revista de Saúde Pública 41: 1–6.

Chandra G, Bhattacharjee I, Chatterjee SN, Ghosh A. 2008. Mosquito control by larvivorous fish. Indian Journal of Medical Research 127: 13–27.

Cohen J. 2016. The race for a Zika vaccine is on. Science 351: 543–544.

Coy NJ. 1979. Freshwater Fishing in South-West Australia. Jabiru.

Cucherousset J, Olden, J. D. 2011. Ecological impacts of non-native freshwater fishes. Fisheries 36: 215–230.

Cunico AM, Allan JD, Agostinho AA. 2011. Functional convergence of fish assemblages in urban streams of Brazil and the United States. Ecological Indicators 11: 1354–1359.

Deacon AE, Ramnarine IW, Magurran AE. 2011. How reproductive ecology contributes to the spread of a globally invasive fish. PLOS ONE 6 (art. e24416).

Diagne CT, et al. 2015. Potential of selected Senegalese *Aedes* spp. mosquitoes (Diptera: Culicidae) to transmit Zika virus. BMC Infectious Diseases 15 (art. 492). doi:10.1186/s12879-015-1231-2

Dobson SL, Bordenstein SR, Rose SI. 2016. *Wolbachia* mosquito control: Regulated. Science 352: 526–527.

Enserink M. 2010. GM mosquito trial alarms opponents, strains ties in Gates-funded project. Science 330: 1030–1031.

———. 2014. Crippling virus set to conquer Western Hemisphere. Science 344: 678–679.

———. 2015. An obscure mosquito-borne disease goes global. Science 350: 1012–1013.

Espinoza-Gómez F, Hernández-Suárez CM, Coll-Cárdenas R. 2002. Educational campaign versus malathion spraying for the control of *Aedes aegypti* in Colima, Mexico. Journal of Epidemiology and Community Health 56: 148–52.

Esvelt KM, Smidler AL, Catteruccia F, Church GM. 2014. Concerning RNA-guided gene drives for the alteration of wild populations. eLife 2014 (art. 3e03401). doi:10.7554/elife.03401

Focks DA, Sackett SR, Bailey DL, Dame DA.1981. Observations on container-breeding mosquitoes in New Orleans, Louisiana, with an estimate of the population density of *Aedes aegypti* (L.). American Journal of Tropical Medicine and Hygiene 30: 1329–1335.

Francis RA, Pyšek P. 2012. Management of freshwater invasive alien species. Pages 435–446 in Francis RA, ed. A Handbook of Global Freshwater Invasive Species. Earthscan.

García-Berthou E. 1999. Food of introduced mosquitofish: Ontogenetic diet shift and prey selection. Journal of Fish Biology 55: 135–147.

García-Berthou E, Alcaraz C, Pou-Rovira Q, Zamora L, Coenders G, Feo C. 2005. Introduction pathways and establishment rates of invasive aquatic species in Europe. Canadian Journal of Fisheries and Aquatic Sciences 62: 453–463.

Gkenas C, Oikonomou A, Economou A, Kiosse F, Leonardos I. 2012. Life history pattern and feeding habits of the invasive mosquitofish, *Gambusia holbrooki*, in Lake Pamvotis (NW Greece). Journal of Biological Research–Thessaloniki 17: 121–136.

Goodsell JA, Kats LB. 1999. Effect of introduced mosquitofish on Pacific tree frogs and the role of alternative prey. Conservation Biology 13: 921–924. doi:10.1046/j.1523-1739.1999.98237.x

Han WW, Lazaro A, McCall PJ, George L, Runge-Ranzinger S, Toledo J, Velayudhan R, Horstick O. 2015. Efficacy and community effectiveness of larvivorous fish for dengue vector control. Tropical Medicine and International Health 20: 1239–1256.

Harris AF, et al. 2012. Successful suppression of a field mosquito population by sustained release of engineered male mosquitoes. Nature Biotechnology 30: 828–830.

Hemingway J, Ranson H. 2000. Insecticide resistance in insect vectors of human disease. Annual Review of Entomology 45: 371–391.

Landeka N, Podnar M, Jelić D. 2015. New data on the taxonomic status and distribution of *Gambusia* sp. in Croatia and Bosnia and Herzegovina. Periodicum Biologorum 117: 415–424.

Langeani F, Castro RMC, Oyakawa OT, Shibatta OA, Pavanelli CS, Casatti L. 2007. Diversidade da ictiofauna do alto rio Paraná: Composição atual e perspectivas futuras. Biota Neotropica 7: 181–197.

Leprieur F, Beauchard O, Blanchet S, Oberdorff T, Brosse S. 2008. Fish invasions in the World's river systems: When natural processes are blurred by human activities. PLOS Biology 6 (art. e28).

Lindholm AK, Breden F, Alexander HJ, Chan W-K, Thakurta SG, Brooks R. 2005. Invasion success and genetic diversity of introduced populations of guppies *Poecilia reticulata* in Australia. Molecular Ecology 14: 3671–3682.

Lockwood JL, Cassey P, Blackburn T. 2005. The role of propagule pressure in explaining species invasions. Trends in Ecology and Evolution 20: 223–228.

Loreto ELS, Wallau GL. 2016. Risks of *Wolbachia* mosquito control. Science 351: 1273.

Lucinda PHF. 2003. Family Poeciliidae. Pages 555–581 in Reis RE, Kullander SO, Ferraris C Jr., eds. Check List of the Freshwater Fishes of South and Centarl America. EDIPUCRS.

Luna JED, Martins MF, Anjos AF, Kuwabara EF, Navarro-Silva MA. 2004. Susceptibility of *Aedes aegypti* to temephos and cypermethrin insecticides, Brazil. Revista de Saúde Pública 38: 1–2.

Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M, Bazzaz FA. 2000. Biotic invasions: Causes, epidemiology, global consequences, and control. Ecological Applications 10: 689–710.

Margaritora FG, Ferrara O, Vagaggini D. 2001. Predatory impact of the mosquitofish (*Gambusia holbrooki* Girard) on zooplanktonic populations in a pond at Tenuta di Castelporziano (Rome, Central Italy). Journal of Limnology 60: 189–193.

Martínez-Ibarra JA, Guillén YG, Arredondo-Jiménez JI, Rodríguez-López MH. 2002. Indigenous fish species for the control of *Aedes aegypti* in water storage tanks in Southern México. BioControl 47: 481–486.

Morrison AC, Zielinski-Gutierrez E, Scott TW, Rosenberg R (2008) Defining challenges and proposing solutions for control of the virus vector *Aedes aegypti*. PLOS Med 5 (art. e68). doi:10.1371/journal.pmed.0050068

O'Neill, S. 2015. The dengue stopper. Scientific American 312: 72–77.

———. 2016. *Wolbachia* mosquito control: Tested. Science 352: 526.

Ortega JCG, Júlio Jr HF, Gomes LC, Agostinho AA. 2015. Fish farming as the main driver of fish introductions in Neotropical reservoirs. Hydrobiologia 746: 147–158.

Pamplona LGC, Alencar CH, Lima JWO, Heukelbach J. 2009. Reduced oviposition of *Aedes aegypti* gravid females in domestic containers with predatory fish. Tropical Medicine and International Health 14: 1347–1350.

Pimentel D, Lach L, Zuniga R, Morrison D. 2000. Environmental and economic costs associated with nonindigenous species in the United States. BioScience 50: 53–65.

Pinheiro VCS, Tadei PW. 2002. Frequency, diversity, and productivity study on the *Aedes aegypti* most preferred containers in the city of Manaus, Amazonas, Brazil. Revista do Instituto de Medicina Tropical de São Paulo 44: 245–250.

Pyke GH. 2008. Plague minnow or mosquito fish? A review of the biology and impacts of introduced *Gambusia* species. Annual Review of Ecology, Evolution, and Systematics 39: 171–191.

Rahel FJ. 2007. Biogeographic barriers, connectivity and homogenization of freshwater faunas: It's a small world after all. Freshwater Biology 52: 696–710.

Rehage JS, Barnett BK, Sih A. 2005. Foraging behaviour and invasiveness: Do invasive *Gambusia* exhibit higher feeding rates and broader diets than their noninvasive relatives? Ecology of Freshwater Fish 14: 352–360.

Relyea RA. 2005. The impact of insecticides and herbicides on the biodiversity and productivity of aquatic communities. Ecological Applications 15: 618–627.

Rupp HR. 1996. Adverse assessments of *Gambusia affinis*: An alternative view for mosquito control practitioners. Journal of the American Mosquito Control Association 12: 155–166.

Saleeza SNR, Norma-Rashid Y, Sofian-Azirun M. 2014. Guppies as predators of common mosquito larvae in Malaysia. Southeast Asian Journal of Tropical Medicine and Public Health 45: 299–308.

Sarwar M. 2015. Control of dengue carrier *Aedes* mosquitoes (Diptera: Culicidae) larvae by larvivorous fishes and putting it into practice within water bodies. International Journal of Preventive Medicine Research 1: 232–237.

Simberloff D. 2006. Invasional meltdown 6 years later: Important phenomenon, unfortunate metaphor, or both? Ecology Letters 9: 912–919.

Simberloff D, Von Holle B. 1999. Positive interactions of nonindigenous species: Invasional meltdown? Biological Invasions 1: 21–32.

Simberloff D, et al. 2013. Impacts of biological invasions: What's what and the way forward. Trends in Ecology and Evolution 28: 58–66.

Tabibzadeh I, Behbehani G, Nakhai R. 1970. Use of gambusia fish in the malaria eradication programme of Iran. Bulletin World Health Organization 43: 623–626.

US National Research Council. 2016. Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values. National Academies Press.

Vasconcelos PFC. 2015. Doença pelo *vírus Zika*: Um novo problema emergente nas Américas? Revista Pan-Amazônica de Saúde 6: 9–10.

Vitule JRS, Freire CA, Simberloff D. 2009. Introduction of non-native freshwater fish can certainly be bad. Fish and Fisheries 10: 98–108.

Walshe DP, Garner P, Abdel-Hameed Adeel AA, Pyke GH, Burkot T. 2013. Larvivorous fish for preventing malaria transmission. Cochrane Database of Systematic Reviews 12 (art. CD008090).

Welcomme RL. 1988. International Introductions of Inland Aquatic Species. FAO Fisheries. Technical Paper no. 294.

[WHO] World Health Organization. 2003. Use of Fish for Mosquito Control. WHO Regional Office for the Eastern Mediterranean.

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.