Non-indigenous freshwater fishes on tropical Pacific islands: a review of eradication efforts

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Abstract Many fishes introduced by humans to islands in the Pacific region have established reproducing populations. As a result, there have been changes to insular aquatic faunas, some obvious and some subtle. Introduced fishes are threats to ecosystems and native species, but little is published about efforts to eradicate them. We compiled information on eradication efforts for freshwater fishes introduced to tropical Pacific islands. Over 60 non-native species of freshwater fishes, representing 18 families, are established on Pacific islands. They represent a diversity of morphologies, environmental tolerances, behaviours, dietary specialisations, and other life-history attributes. We found information on past or present invasive fish eradication efforts for the Hawaiian Islands, Nauru, Kiribati, Palau, Guam, Fiji, and the Galapagos. The main fishes targeted have been tilapias (family Cichlidae) and live-bearers (Poeciliidae). A few eradication efforts succeeded when using chemical ichthyocides, typically rotenone. Future needs include review and modification of existing methodologies to improve efficacy, and development and testing of new chemical and non-chemical methods that may be more selective and less harmful to non-target species.

Keywords: Invasive fishes, Cichlidae, Poeciliidae, Hawaii, Nauru, Kiribati, Palau, Guam, Fiji, Galapagos, tilapia, *Oreochromis mossambicus*, removal methods, physical, chemical, biological

INTRODUCTION

Many species of fishes introduced to islands in the Pacific region have established reproducing populations (Maciolek 1984; Eldredge 2000). Most introductions were associated with aquaculture, commercial and sport fishing, the ornamental fish trade, biological control, and research; some were intentional and others accidental (Maciolek 1984). Introductions of non-native fish in the Pacific began in the 1800s, but newly established species are still being discovered. The introductions have led to marked and often repeated changes to insular aquatic faunas (Jenkins *et al*. 2009), with effects that have often been variable and unanticipated. For instance, the introduction of Mozambique tilapia (*Oreochromis mossambicus*) on many Pacific islands during the mid 1900s was later recognised as disastrous. Among other impacts, it led to the near disappearance of traditional milkfish (*Chanos chanos*) culture (Nelson and Eldredge 1991; Spennemann 2002; Jenkins *et al*. 2009). Moreover, because Mozambique tilapia tolerate high salinity, they also invaded estuaries and other coastal marine environments (Lobel 1980; Maciolek 1984).

Other negative ecological consequences of non-native fishes were illustrated by armoured suckermouth catfishes (family Loricariidae), which are abundant in streams and lakes in Hawaii. The burrows excavated by these species for spawning and nesting destabilise banks and increase erosion (Yamamoto and Tagawa 2000; Nico *et al*. 2009). Other groups such as poeciliids pose multiple threats. These small fishes were initially introduced to the Pacific region for biological control of mosquitoes and later as aquarium releases. Two widely introduced species, the guppy (*Poecilia reticulata*) and western mosquitofish (*Gambusia affinis*), threaten Hawaii's anchialine pool environments (Brock and Kam 1997; Yamamoto and Tagawa 2000). Introduced poeciliids that prey heavily on native aquatic insects likely contributed to the decline or extinction of native stream-breeding damselfly species on Oahu, and the extinction or near-extinction of two other species in Hawaii (Englund 1999). Poeciliids are also the likely source of non-native parasites now present in Hawaiian freshwater ecosystems (Font 2003). Apart from these examples, the ecological and economic impacts of non-native fishes are poorly understood or inadequately documented (Maciolek 1984; Englund 1999). In part, this is because of a lack of field studies (Fuller *et al*. 1999), but even where environmental changes have been observed, cause and effect relationships are difficult to establish.

Because introduced fishes can pose ecological or economic harm (Courtenay and Stauffer 1984; Nelson and Eldredge 1991; Simon and Townsend 2003; Vitule *et al*. 2009), there have been periodic attempts to eradicate some populations (Kolar *et al*. 2010). However, there is little published information about eradication attempts in the Pacific. In part, this reflects the few attempts at removal but there is also evidence that many failed eradication attempts are never published or are otherwise unreported. This is unfortunate because any removal attempts, regardless of the outcome, may provide important insights for future eradication endeavours. Planned eradications that were never attempted may also be useful if they allow other researchers and managers to assess their own current plans, and perhaps reduce the risk of repeating past mistakes. Consequently, more complete knowledge of fish eradication projects in the Pacific region should help improve decision-making processes about how best to use limited resources when dealing with invasive fishes.

In this paper we compile information on past and ongoing plans and projects to eradicate non-native fish populations within the Pacific, largely focusing on smaller islands and island groups near the equator. Much of the information is unpublished. We also briefly describe the diversity of the non-native ichthyofauna as well as the types of inland aquatic habitats invaded along with their native faunas. Such information helps to identify the issues faced when an eradication of invasive fishes is attempted. Lastly, because the methods used in the Pacific to eradicate non-indigenous fishes are only a subset of the methods used elsewhere, we review the global techniques and strategies used to eradicate or control invasive or undesirable fishes.

METHODS

We focused our review on small Pacific islands within the boundaries of the Tropic of Capricorn and the Tropic of Cancer and included obscure literature, agency reports, personal communications, and internet sources. Other information on the diversity of invasive fishes and habitats, details of eradication projects, and methods from other parts of the world were based on an extensive literature review. We supplemented some information from personal experiences over more than 25 years of research on non-native fishes, including some research on fishes in their native ranges. We excluded Pacific islands outside the tropical zone, largely because substantial information

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about fish eradication and control in places such as New Zealand is readily available in the technical and scientific literature (e.g., New Zealand Department of Conservation 2003; McDowall 2004a; Neilson *et al*. 2004; Nishizawa *et al*. 2006; Yonekura *et al*. 2007).

Positive identification of introduced fishes is often difficult, partly because of unresolved taxonomy and unstable nomenclature of many fish groups. Some taxa, such as the tilapias, are particularly problematic because of frequent hybridisation in captivity and in the wild, as well as the creation of new strains by aquaculture researchers (Costa-Pierce 2003; D'Amato *et al*. 2007). Ichthyologists also periodically re-examine non-native fish specimens and, in some cases, have corrected previous misidentifications (e.g., Courtenay *et al*. 2004). Consequently, some names appearing in past publications are no longer valid.

AQUATIC HABITATS AND NATIVE FAUNAS

Inland aquatic habitats of Pacific islands are diverse, varying dramatically in type, distribution, elevation and coverage (Ellison 2009). Small or low-lying islands typically have few, if any, surface freshwater habitats and therefore are rarely able to support freshwater fish. Larger and more diverse islands rival large continental regions for the diversity of aquatic habitats, many of which are suitable for a wide variety of fish species.

Pacific island drainages are typically small and streams are relatively short compared to continental rivers. Nevertheless, the more topographically diverse islands may contain a wide array of lentic and lotic habitats, ranging from moderately large streams, channels, and ditches to natural and artificial lakes and ponds. Elevated islands often have streams that originate in uplands; cascade down steep slopes and cliffs; contain habitats such as falls, high-velocity runs, rapids, and deep pools; and become estuarine where they empty into the ocean. Waterfalls near the coast can act as barriers, which determine the distribution of some aquatic invertebrates and most fishes (Keith 2003). Temporal differences can also exist. During rainy seasons high-gradient streams become torrential, but during droughts smaller streams are often reduced to a series of isolated pools.

The diversity and abundance of native fishes and aquatic invertebrates varies greatly among the different Pacific island groups (Donaldson and Myers 2002; Keith 2003; McDowall 2004b). Many species are unique (endemic) to particular islands or island groups, with some only in specific habitats (Brock and Bailey-Brock 1998; Keith *et al*. 2002; Keith 2003). Aquatic invertebrate groups native to the Pacific islands can be quite diverse. By comparison, native freshwater fish faunas are generally depauperate. Indeed, some island lakes and streams that are naturally devoid of native fishes support a diverse fauna of invertebrates. Much still remains unknown about the inland aquatic faunas of Pacific islands; field studies continue to yield new information on the natural history and biology of native species as well as the discovery of new species (Keith 2003; Englund 2008).

Many of the native fishes present in streams on Pacific islands belong to families that are predominantly marine. The life-history strategy among most such groups (e.g., sicydiine gobies and eleotrids) is amphidromy, where juveniles feed and adults spawn in freshwater habitats and larvae are carried to estuaries or the sea (Keith 2003; McDowall 2007). In contrast, adults of catadromous species (e.g., anguillid eels) spawn at sea and sub-adults migrate to freshwater habitats. Many native inland fishes and invertebrates of Pacific islands have restricted ranges, small population sizes, and no natural defences against invaders so they are vulnerable to extirpation or extinction where non-native fishes become established.

DIVERSITY OF NONINDIGENOUS FISHES ON PACIFIC ISLANDS

Most non-native freshwater fishes established in the Pacific are found on the larger islands because these sites offer a diversity of aquatic habitats, including many places suitable for invasion. In the Pacific, non-native fishes commonly occur in heavily disturbed sites (e.g., roadside ditches and artificial reservoirs), but some are also found in relatively pristine habitats (e.g., caldron lakes and mountain streams). On large, diverse islands such as Oahu (Hawaii) and Guam, non-native fish abundance in certain habitats, such as some natural streams and artificial reservoirs, are often at densities far exceeding those of native fishes present (Yamamoto and Tagawa 2000; L. G. Nico pers. obs.). Much less vulnerable to invasion are the many small, low-lying Pacific islands, because these areas have few freshwater habitats.

Four publications review information on non-indigenous fishes of the Pacific region. In a comprehensive analysis of introduced freshwater fishes in the Hawaiian Islands and other tropical islands of Oceania (excluding New Guinea and the region south of the Tropic of Capricorn), Maciolek (1984) documented 41 non-marine fish species representing 14 families. A review by Nelson and Eldredge (1991) focused on the widely introduced tilapiine cichlids, and detailed their distribution and status on islands throughout the South Pacific and Micronesia. The information on the status of introduced fishes established in Hawaii (Maciolek 1984) was updated by Devick (1991) and Eldredge (2000) added new data, provided information for New Guinea and identified 86 freshwater fish species introduced into fresh and brackish waters in the region. However, it remained unclear how many species were considered to be established. Our review of the Eldredge checklist (which inadvertently excluded loricariid catfishes) revealed that at least 62 species of freshwater fish representing 18 families have become established in the Pacific islands.

This remarkable range of taxa includes those that originated from Asia, Africa, Europe, and South, Central and North America. The most widely introduced fish families are Cichlidae (e.g., tilapias) and Poeciliidae, each with up to 9 species established. Other families include Centrarchidae (black basses and sunfishes), Cyprinidae (carps and minnows), and Loricariidae (suckermouth armoured catfishes). The most widely introduced species include Mozambique tilapia, one or more species of mosquitofish (*Gambusia*), guppy, and common carp (*Cyprinus carpio*).

Some introduced species are tropical and others from temperate climates. Most primarily inhabit fresh water, but others are euryhaline and able to survive and/or reproduce in fresh, brackish and marine environments. A few are air-breathing fish (e.g., synbranchid eels, loricariid and clariid catfishes) and able to persist in habitats nearly devoid of dissolved oxygen. Body size ranges from the guppy, with adult males typically < 2.5 cm total length, to the Asian carps (e.g., grass carp, *Ctenopharyngodon idella*), which commonly grow to well over one meter. Nearly all major trophic levels are represented, including small and large herbivores, omnivores, and predators. The herbivores include some that specialise on phytoplankton (e.g., silver carp; *Hypophthalmichthys molitrix*), attached algae (e.g., loricariid catfishes), and macrophytes (e.g., grass carp). Among carnivores, some species prey mostly on fishes and other vertebrates (e.g., members of the genera *Cichla* and *Channa*), whereas others, typically smaller predators, normally consume invertebrates, including insects and small crustaceans (e.g., oriental weatherfish, *Misgurnus anguillicaudatus*).

NON-NATIVE FISH ERADICATION PROJECTS IN THE TROPICAL PACIFIC

There are few documented accounts of invasive fish eradication or control projects for the tropical Pacific. A few published articles mention fish control operations for selected Pacific islands, but usually lack details. Here we review information on attempted or planned invasive fish eradications for seven islands or island groups in the tropical Pacific (Table 1): the Hawaiian Islands, Nauru, Kiribati, Palau, Guam, the Galapagos, and Fiji (Fig. 1).

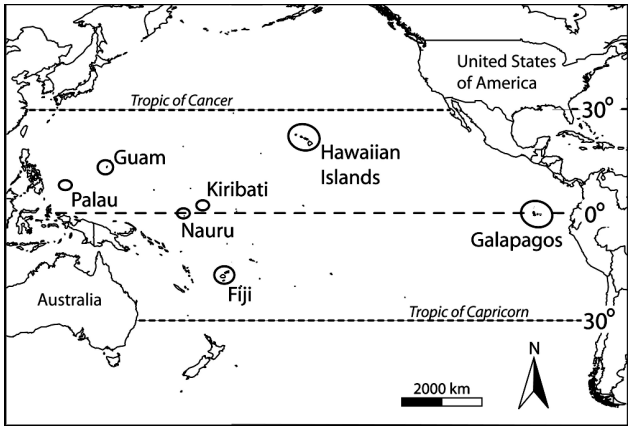

Fig. 1 The Pacific Ocean showing locations of the seven island groups where documented non-native fish eradication or control projects have occurred.

Hawaiian Islands

There has been emphasis on research and assessment of the spread and impacts of invasive aquatic organisms in the Hawaiian Islands (Eldredge 1994; Yamamoto and Tagawa 2000; Englund 1999, 2008). However, not until the past one or two decades has removal been considered regularly as a management option. The literature indicates toxicants had never been used for fisheries management in Hawaii prior to about 1970 (Lennon et al 1971) and, although eradication was discussed (Doty 1974), there were no known fish eradication projects from 1965 to 1979 (J. Maciolek pers. comm.).

The more serious attempts to eradicate invasive fish in Hawaii have focused on anchialine pools, which are small, landlocked water bodies near the coast and only with subterranean connections to the sea (Brock and Kam 1997; Yamamoto and Tagawa 2000; Santos 2006). Such pools are largely associated with geologically young lava fields and therefore they are most abundant on the highly volcanic Big Island of Hawaii (Yamamoto and Tagawa 2000). Anchialine pools are influenced by tides and commonly contain brackish water, although salinities may vary within and among pools depending on their distance from the ocean and amount of freshwater inflow (J. Maciolek pers. comm.). These pools represent unusual ecosystems, in part because they are inhabited by endemic native invertebrates, including some that are imperilled species (Brock and Kam 1997; Yamamoto and Tagawa 2000; Santos 2006). The Hawaiian Islands probably have the greatest number of anchialine pools in the world, but many have been modified or destroyed in the last 60 years due to a combination of coastal development and introduction of non-native species (Brock and Bailey-Brock 1998, Santos 2006).

Over 95% of existing anchialine pools of Hawaii are invaded by non-native fishes, primarily poeciliids and tilapia (Yamamoto and Tagawa 2000). In these pools the poeciliids (mainly western mosquitofish and guppy) negatively impact native shrimps or "opae'ula" (*Halocaridina rubra*), apparently through direct predation, habitat displacement (by driving the shrimp into underground fissures and crevices), or both (Brock and Kam 1997; Yamamoto and Tagawa 2000). Opae'ula shrimp are minute (< 15 mm long) herbivores and in anchialine pools may be a keystone species because of their heavy grazing on attached algae. Declines of opae'ula shrimp in the presence of poeciliids are followed by overgrowth of algae, changes in the dominance of algal species, and declines in native invertebrates (Brock and Kam 1997; Capps *et al*. 2009).

Brock and Yam (1997), without providing precise locality or date information, reported that they successfully used rotenone to remove non-native fishes (presumably poeciliids) from some relatively isolated anchialine pools. More recently, at Kailua-Kona (Fig. 2a) on the island of Hawaii, rotenone was used with similar success, with evidence that the full complement of native species rapidly recovered (Chai and Mokiao-Lee 2008). However attempts elsewhere succeeded against tilapia but failed for mosquitofish possibly due to reinvasion via an underground link to a nearby artificial pond. Rotenone is considered toxic to organisms that respire through gills, but native invertebrates such as opae'ula shrimp often re-colonised treated anchialine pools from their underground refuge even before rotenone fully degraded (Brock and Yam 1997; Yamamoto and Tagawa 2000).

Rotenone was suggested as the most efficient way to remove tilapia and guppies in two anchialine pools on private property near Kiholo Bay (Hawaii Department of Land and Natural Resources 2000), but it is unknown if the removal effort was ever attempted. The use of rotenone is often controversial in Hawaii. Those wanting to use the toxicant in open waters for invasive fish removal typically encounter problems obtaining official permission. For example, the Malama Kai Foundation received funding from the National Oceanic and Atmospheric Administration in 1999 to restore certain anchialine pools on the island of Hawaii. Restoration was to include removal and control of non-native species, but, because the pools had subterranean connections, removal of non-natives by manual methods was not feasible. According to available information, the Foundation was unable to secure state permission to use rotenone, thereby stalling restoration efforts (http://www.malama-kai.org/management/ponds.htm).

Upland streams in Kokee State Park, Kauai Island, have been invaded by rainbow trout (*Oncorhynchus mykiss*), but restoring these streams to their natural fishless condition would necessitate use of a chemical ichthyocide (Englund and Polhemus 2001). However, public acceptance for such a project seems unlikely because the use of poison, particularly rotenone, would likely harm non-target indigenous and endemic aquatic arthropods (Englund and Polhemus 2001). Furthermore, Englund (2008) concluded that the use of ichthyocides would likely be unsuccessful where invasive fishes present (i.e., poeciliids and tilapia) can survive in high-salinity coastal waters and ultimately re-invade streams following chemical treatment. The use of toxicants at sites such as Kane'ohe Bay would also encounter technical problems because of the large size of the bay, and public resistance. However, eradication might be possible in high-gradient streams that terminate into the ocean via high waterfalls, because the falls would function as barriers preventing re-invasion by any non-native fishes escaping to coastal waters (Englund 2008).

As an alternative to chemicals, a state biologist in Hawaii investigated the possibility of importing male pike killifish (*Belonesox belizanus*), a small piscivorous poeciliid fish native to Central America, with the intent of releasing a few into anchialine pools as a biological control against other, but smaller, non-native poeciliids (M. Yamamoto pers. comm.). It was believed that pike killifish, a surface dweller, would preferentially prey on other poeciliid fishes and generally avoid bottom or cave

Table 1 Non-native fish eradication and control attempts in the tropical Pacific.

Group	Targeted taxa	Habitat and site	Method (Year)	Outcome	References
Hawaii	Poeciliid fishes	Anchialine pools	Rotenone (1990s?)	Success	Brock and Kam (1997)
	Western mosquitofish	Anchialine pools; Kailua-Kona (Hawaii)	Hand nets, seines, traps	Failed	Chai and Mokiao-Lee 2008; Carey *et al*. 2011; D. Chai (pers. comm.)
			Rotenone (2007)	Success	
	Western mosquitofish plus tilapia	Anchialine pool; Wai'olu (Hawaii)	Rotenone 5 ppm (2008) and later at higher concentration	Success on tilapia; failed on mosquitofish	Carey *et al*. 2011; D. Chai (pers. comm.)
	Loricariid catfish *Pterygoplichthys*	Waihawa Reservoir (Oahu)	Back pack and boat mounted electroshockers	Failed	M. Yamamoto (pers. comm.)
Nauru	Mozambique tilapia	Inland ponds and brackish lagoons	Rotenone	Mixed success	Ranoemihardjo 1981; B. Ponia (pers comm.)
Kiribati	Mozambique tilapia	Temaiku fish farm	Rotenone, seine nets; increased fertility using fertiliser and decaying tilapia (1982)	Failed	Teroroko 1982, 1990
Palau	Mozambique tilapia	Four ponds on Malakal, three fresh, one brackish	Non chemical methods including explosives (2003)	Failed	EQPB 2004, GISD 2006; E. Edesomel (pers. comm.)
			Levels reduced by pumping, then rotenone and perhaps some chlorine (2004)	Succeeded at three sites	
Guam	Hybrid tilapia presumably *Oreochromis mossambicus* x *O. urolepis hornorum*	Small reservoir	Illegal poisoning, chemical unknown	Success (?)	Maciolek 1984
	Chevron snakehead	River catchment	Physical methods including baited drop lines, seine nets and dip nets	Incomplete	B. Tibbatts (pers. comm.)
Galapagos	Nile tilapia	Freshwater crater lake	Rotenone (2008)	Success	L.G. Nico (unpublished data)
Fiji	Juvenile Mozambique tilapia	Two ponds filled with seawater	Biological control using a predator, Hawaiian ladyfish (early 1970s or before)	Partial success	Popper and Lichatowich 1975

areas where native shrimp normally occur. Moreover, it was reasoned that an all-male pike killifish population, unable to reproduce, would naturally die off within a short period. Given that mosquitofish and other established poeciliids were already preying on native shrimp and other invertebrates, supporters of the plan argued that the introduction of a few non-reproducing predatory fish was worth the risk. However, proponents of the plan were unable to convince the Hawaii Department of Agriculture to change the legal status of pike killifish from its existing designation as a prohibited species to a less restricted status that would allow its import for research purposes.

There has not been much contemplation of fish eradication in Hawaii outside anchialine pools even though non-native fishes are abundant in many of Hawaii's lakes and streams including suckermouth armoured catfishes (family Loricariidae) in the genera *Pterygoplichthys*, *Hypostomus* and *Ancistrus* (Yamamoto and Tagawa 2000). Electroshockers have proved ineffective against these catfish, presumably because the electrical field does not penetrate into their burrows (Table 1).

According to R. Englund (pers. comm.), dewatering is performed regularly by the U.S. Fish and Wildlife Service in Hawaii at Hanalei National Wildlife Refuge (Kauai Island) and Pearl Harbor National Wildlife Refuge (Oahu Island) to rid taro fields of tilapia. The U.S. National Park Service is planning to explore alternatives on how best to eradicate tilapia from historical fish ponds on the island of Hawaii.

Nauru

Mozambique tilapia were introduced to Nauru circa 1960 for mosquito control and as a food fish (Ranoemihardjo 1981; Fortes 2005). The species rapidly expanded its range throughout the island, competed with native milkfish for food and space, preyed on young milkfish, and caused a decline in Nauru's traditional milkfish culture (Ranoemihardjo 1981; Nelson and Eldredge 1991; Spennemann 2002). At the request of the Republic of Nauru, the Food and Agriculture Organization (FAO) of the United Nations initiated a tilapia eradication program in 1979-1980. Methods considered included complete drying of selected smaller ponds, stocking predatory fish as a biological control, removal of tilapia with nets and traps, and application of fish toxicants (Ranoemihardjo 1981). Following bioassay tests to determine adequate concentration, rotenone was applied to a series of ponds and lagoons, with mixed success. Although Ranoemihardjo (1981) concluded that repeated rotenone application would eventually eliminate remaining tilapia, there were problems resulting from a shortage of manpower and equipment, and the onset of the rainy season. Later authors described the 1979-1980 eradication effort as unsuccessful (Nelson and Eldredge 1991; Thaman and Hassall 1996; Fortes 2005).

Mozambique tilapia remain a problem in Nauru because they commonly re-invade previously treated ponds. A practical strategy for dealing with the species may require a national tilapia plan that includes policies, education and training, polyculture, and other potential

species for use in aquaculture (Fortes 2005). Some ponds cleared of Mozambique tilapia were later stocked with Nile tilapia (*Oreochromis niloticus*), which are considered more desirable as a culture fish by many aquaculture proponents. The Secretariat of the South Pacific Community (SPC) believes that complete eradication of Mozambique tilapia in Nauru and other small Pacific islands would be difficult or impossible, and probably not worth the resources required. The alternative is population control aimed at: 1) preventing spread of Mozambique tilapia and other non-native fishes; 2) removing Mozambique tilapia from ponds or aquaculture areas where it is considered a nuisance and competitor; and 3) identifying and protecting areas known to contain endemic or otherwise threatened local populations of indigenous species (B. Ponia pers. comm.). The SPC is also considering introducing Nile tilapia into areas occupied by Mozambique tilapia, hoping that the two species will hybridise into a more desirable aquaculture food fish.

Kiribati

As for other Pacific islands, the introduction of Mozambique tilapia to Kiribati has negatively affected the culture of milkfish (Gillett 1989). However, attempts to eradicate tilapia have been unsuccessful (Teroroko 1982; Eldredge 1994). According to Maciolek (1984), the Republic of Kiribati considered that tilapia required major eradication effort by its Department of Natural Resources. We found no recent updates of this situation, whether the eradication efforts (Table 1) described by Teroroko (1982) continue or whether the tilapia population on the island has declined. In a 2002 fishery country profile for Kiribati, the FAO reported that an 80-ha milkfish farm established on South Tarawa in the late 1970s was unproductive, partly because ponds contained introduced tilapia (FAO 2002).

Palau

In 2003, tilapia were found in water bodies on Palau's island of Malakal and identified by one of us (LGN) as Mozambique tilapia, although introgressive hybridisation could not be ruled out (specimens catalogued as UF 163824, ichthyological collection, Florida Museum of Natural History). In December 2003, the President of Palau declared a "Quarantine Emergency" in response to which Palau's Bureau of Agriculture coordinated the use of ichthyocides. These were applied in early 2004 by a multi-agency team led by staff of the Palau Environmental Quality Protection Board (EQPB) at the four sites containing tilapia.

Three of the sites were fresh water, each covered 0.1 to 0.2 ha and included two in close proximity known as the "Japanese fuel tank" or "barrack" ponds (Fig. 2b) and the third in a rock quarry site on Palau Transportation Company property (Fig. 2c). The rock quarry site was characterised as a complex of small water bodies, including a quarry pond, two smaller retention ponds, a puddle and an overflow stream. The last of the four sites was a large rectangular (150-m x 25-m; 0.4 ha), brackish-water pond along the northeast coast of Malakal Island constructed as a dry dock by the Japanese during World War II (Fig. 2d). In 2004, the four sites were treated with rotenone (supposedly in conjunction with chlorine at one site) resulting in recovery of at least 38,800 dead tilapia (EQPB 2004), although many more dead were not recovered (E. Edesomel pers. comm.).

In January 2006, the Quarantine Emergency was lifted and the government declared that "no known infestations" of tilapia existed in the country (EQPB 2004; GISD 2006). However, new reports of tilapia in the rock quarry pond in 2006 were verified by EQPB. It was uncertain whether

Fig. 2 Inland water bodies on Pacific islands treated with chemicals for purpose of eradicating invasive fish: anchialine pool (A) on Big Island of Hawaii where rotenone was used to remove non-native poeciliids; three artificial ponds (B-D) in Palau where rotenone or chlorine was used to remove Mozambique Tilapia. All attempts were successful, except for site C, the quarry pond (see text for additional information). Photographs by David Chai (A); William Barichivich (B and D), and L. G. Nico (C).

that discovery represented a new, separate introduction or was of fish that survived the 2004 rotenone treatment (GISD 2006; PNISC 2006). Rotenone reapplied to the quarry pond during 2006-2007, killed at least 300 additional tilapia, mostly small juveniles (PNISC 2006; PIICT 2009). During our visit to the quarry pond in early 2010, we captured and preserved a few juvenile specimens, an indication of continued tilapia reproduction.

Guam

Maciolek (1984:147) reported that hybrid tilapia (presumably *Oreochromis mossambicus* x *O. urolepis hornorum*) were stocked into a small reservoir on Guam, but noted the fish were later eliminated as a result of "illegal poisoning." Details are lacking, so it remains unclear the type of chemical involved. Guam Division of Aquatic and Wildlife Resources (DAWR) personnel are currently attempting to remove introduced chevron snakeheads (*Channa striata*) from the Ajayan River drainage in southern Guam; a population present since the 1970s as a result of escapes from a local aquaculture facility (B. Tibbatts pers. comm.). DAWR biologists do not use fish toxicants and are reluctant to use electrofishing gear because of concerns of harming native eleotrids and gobiid fishes.

Galapagos

In 2006, a reproducing population of Nile tilapia was discovered in a natural freshwater crater lake in the Galapagos Archipelago of Ecuador (L. G. Nico unpubl. data). Galapagos National Park authorities decided on use of rotenone and U.S. Geological Survey biologists were asked to assist in the eradication. In early 2008 rotenone was applied and approximately 40,000 dead and dying tilapia were removed from the lake. Prior to application of rotenone, aquatic invertebrates were collected and held in nearby refuge tanks. After removal of the tilapia, and once all residual rotenone in the lake had degraded sufficiently, captive invertebrates were released back into the lake to speed recovery of invertebrate communities that might have been affected by the chemical. The eradication was considered a success and a paper describing the project in detail is in preparation.

Fiji

During the early 1970s, perhaps before, experiments were conducted in two seawater ponds on Fiji using the predatory Hawaiian ladyfish (*Elops hawaiensis*) to control small juvenile Mozambique tilapia (Popper and Lichatowich 1975). After about 70 days, it was concluded that no tilapia fry were present in the small (0.2 ha) pond and that juvenile tilapia numbers were reduced in the larger (2 ha) pond, but we found no information to indicate the methods were ever applied on a broader scale or for eradication. Although details are scant, the study was apparently conducted with the aim of reducing interspecific competition of tilapia so as to improve their culture, rather than for the purpose of eradicating the non-native fish.

FISH ERADICATION METHODS: STATE OF KNOWLEDGE

Throughout the world, attempts to eradicate non-native fish populations have had widely mixed results (Cailteux *et al*. 2001; Kolar *et al.* 2010). No single known eradication method succeeds in all environments or for all fish species, although much new knowledge has been gained over the past few decades. Most successful eradications relied on fish toxicants, mainly rotenone (Britton *et al*. 2009). However, the use of these ichthyocides has often failed, although some failures were likely the result of poor planning or inadequate implementation. Rinne and Turner (1991) evaluated 26 projects that used toxicants to remove unwanted fishes from streams in the western United States (USA). Nine (35%) projects were judged to be "successful," 15 (58%), were "unsuccessful" or "failures," and two were "short term success" or of "variable success." Meronek *et al*. (1996) assessed 51 projects that used physical and/or chemical methods control one or more target fish species, and judged 32 to be successful. However, their definition of success did not necessarily mean eradication.

Globally, few entire populations of invasive species of fish have been targeted for eradication and, among those, few were successful. The few successes have been in small, shallow, easily accessible, sparsely vegetated, closed aquatic systems such as ponds or small lakes. Eradication in more open or complex systems such as large streams and wetland habitats is generally impossible or, at best, difficult and expensive. Whether eradication of non-native fishes is a viable option, the degree of difficulty depends on factors such as the type, abundance, and geographic distribution of the targeted species plus the physical and biological composition, size, complexity, and sensitivity of the invaded environment (Kolar *et al*. 2010). Also to be considered are: the existence of, or potential for, development of reliable methods, and availability of funding, human power, expert leaders and trained crews (Donlan and Wilcox 2007). Appropriate planning requires clear identification of goals or criteria to be met before eradication proceeds (Chadderton 2003). This may involve implementation of an adaptive management strategy (Gehrke 2003; Kolar *et al*. 2010).

Successful eradication requires some basic knowledge of the targeted species and the invaded environment. A critical first step is positive species identification in part to confirm that it is truly non-native (Fuller *et al*. 1999). Following confirmation of an invasion, rapid but comprehensive field surveys using appropriate gear are needed to ascertain its geographic extent. If eradication is deemed viable, it is essential to rapidly gather basic information on abundance, reproductive status and strategies, life history, environmental tolerances, and population dynamics. Such information may provide clues about a non-native species' characteristics that may be targeted or otherwise useful for developing the eradication effort.

In general, methods for eradication of invasive fishes can be divided into three categories: chemical, physical, or biological. An integrated approach is often chosen, using multiple methods in combination (Lee 2001; Diggle *et al*. 2004; Kolar *et al.* 2010). Many invasive fishes have high reproductive potential and the survival of even one adult pair can potentially lead to thousands of offspring. For this reason, spawning grounds are often a primary target of both eradication and control efforts (Diggle *et al*. 2004).

Chemical methods

Fish toxicants (i.e., ichthyocides, piscicides, or fish poisons) are the primary method for eradicating invasive fishes, with more than 40 different chemicals used worldwide (Kolar *et al.* 2010). Most such products have not been fully developed or tested, many are not approved for fish management and only a few are widely and consistently used (Dawson 2003; Clearwater *et al*. 2008; Cailteux *et al*. 2001; Kolar et al. 2010). The most commonly used ichthyocides are rotenone and Antimycin-A (Fintrol®). We have not compiled information on the legal status of rotenone and other fish toxicants for the many Pacific island governments. However, guidelines for the effective and safe planning and execution of projects using rotenone are widely available (Finlayson *et al*. 2000; Moore *et al*. 2008). The American Fisheries Society also has a Rotenone Stewardship Program and periodically offers

training courses on how to plan and execute rotenone and antimycin projects (see http://www.fisheries.org/units/rotenone/).

Rotenone is naturally found in plants of the family Leguminosae and is the active ingredient in some plants used by early Pacific islanders as a poison in the harvest of food fish (Morrison *et al*. 1994). In North America, rotenone has been used by fish biologists as a piscicide since the 1930s against numerous fish species and in habitats ranging from still to flowing waters (Rinne and Turner 1991; McClay 2005). There is now a substantial literature on the use of this toxicant (Wydoski and Wiley 1999; Cailteux *et al*. 2001; McClay 2005).

Antimycin is a fungal antibiotic recognised for its potential use in fish management since the early 1960s (Finlayson *et al*. 2002; Moore *et al*. 2008). Rotenone and antimycin are both general piscicides, but depending on the habitat and fish species to be controlled, they have sometimes been used selectively (Willis and Ling 2000; Moore *et al*. 2008). For example, scaled fish and some rotenone-resistant species are often susceptible to antimycin (Finlayson *et al*. 2002). Because efficacy depends on water and habitat characteristics (e.g., pH, water flow, and amount of leaf litter), antimycin is sometimes used in small streams whereas rotenone is used in large, deep lakes (Finlayson *et al*. 2002). Application of each chemical typically involves release of diluted liquid solutions directly into the water, although rotenone powder is commonly used. There has also been research on ingestible, feed pellets (poison bait) containing rotenone or antimycin, (Mallison *et al*. 1995; Kroon *et al*. 2005).

The main advantages for antimycin are its effectiveness at lower concentrations and non-detectability by fish, whereas rotenone has the advantages of broad range of toxicity to all species of fish and effectiveness under a wide range of pH conditions (Finlayson *et al*. 2002). Rotenone is generally much less expensive than antimycin. Both chemicals degrade relatively quickly into harmless compounds and are neutralised by potassium permanganate (Moore *et al*. 2008). Depending on water temperature and sunlight exposure, degradation may be within days or weeks for rotenone or within hours or days for antimycin (Dinger and Marks 2007). Depending on concentration, both chemicals can be harmful to aquatic invertebrates, especially those that have gills. However, much less is known about the non-target effects of antimycin (Finlayson *et al*. 2002; Dinger and Marks 2007).

Less studied, potentially useful toxicants include a diverse group of plant-derived saponins or triterpene glycosides, including certain products listed in the literature as teaseed cake and Mahua oilcake (Clearwater *et al*. 2008). Additional promising ichthyocides include squoxin, selective against northern pikeminnow (*Ptychocheilus oregonensis*) and several others because of their apparent selectivity, low toxicity to non-target organisms, ease of application, safety to humans, persistence in the environment, low tendency to bioaccumulate, and low cost (Dawson 2003). However, although there is a need and continued interest in developing these and other new piscicides, costs and time associated with research and registration may preclude their availability in the near future.

Most fish toxicants have the disadvantage of non-specificity, causing death or harm not only to targeted non-native fish but also non-targeted native fishes and aquatic invertebrates. Many non-native species are less sensitive to ichthyocides than the non-target species (Schofield and Nico 2007; Schreier *et al*. 2008). Fish toxicants that kill native species, commonly require restocking to offset their effects, although in some tropical insular Pacific habitats this is often unnecessary because native fishes and macroinvertebrates reinvade naturally from coastal areas or nearby inland drainages. However, caution is necessary especially since simultaneous chemical treatment of more than a few streams could eliminate non-migratory stream invertebrates from the entire island. Furthermore, the unwise use of fish toxicants in drainages containing imperilled native species may have disastrous results (see Holden 1991).

Physical methods

Nets, traps, gigs, spears, electrofishing gear, explosives, and management of water levels and flows are all physical methods used to control invasive fish populations. Most of these have limited potential for eradication (Roberts and Tilzey 1996; Wydoski and Wiley 1999; Mueller 2005; CDFG 2007; Kolar *et al.* 2010).

Eradications using nets and traps are limited to small, isolated water bodies or portions of drainages. For instance, intensive seining during 1976-1978 reportedly removed all non-native sheepshead minnow (*Cyprinodon variegatus*) and its hybrids from a small stream system in Texas, USA (Minckley and Deacon 1991). Gill netting helped to eradicate non-native trout from high mountain lakes in California, USA (Knapp and Matthews 1998; Vredenburg 2004) and Banff National Park in Canada (Parker *et al*. 2001). Small traps were used to eradicate non-native fish from an isolated pool in Mexico (Lozano-Vilano *et al*. 2006). In contrast, tests of gill nets in New Zealand ponds (Neilson *et al*. 2004) failed to eradicate or control rudd (*Scardinius erythrophthalmus*).

Backpack electrofishing gear has been tested for removal of non-native salmonid populations in small upland streams in North America with mixed results (Moore *et al*. 1986; Thompson and Rahel 1996; Kulp and Moore 2000). Electrofishing (by boat or backpack) may be useful for control but not eradication in larger or more complex water bodies. For example, boat-mounted electrofishing gear has been deployed regularly since 2001 to remove Asian swamp eels (Synbranchidae) from canals in south Florida, USA. Approximately 1,400 swamp eels were removed the first year but results appeared to have little initial effect on overall population size or size-length structure (L. G. Nico, unpubl. data).

Underwater explosives such as detonation cord can kill or injure fishes (Teleki and Chamberlain 1978; Keevin 1998), but is expensive and largely ineffective for eradication of invasive species (CDFG 2007). Considerable variation exists in blast effects depending on charge type (e.g., low-velocity versus high-velocity detonation; linear versus point source), charge weight, blast design (e.g., detonation depth), and habitat characteristics (e.g., depth and bottom configuration) (Keevin 1998). Vulnerability to explosives (i.e., mortality rate and severity of injury) also varies between fish species. Fish with gas bladders (buoyancy organs) suffer great harm whereas those that lack gas bladders (e.g., swamp eels) often survive underwater explosions (Goertner *et al*. 1994).

Fishes can exhibit differences in thermal tolerance, but manipulation of water temperature to eradicate or control non-native fish is seldom feasible. In a rare example, Stauffer *et al*. (1988) determined that the lower lethal temperature of non-native blue tilapia (*Oreochromis aureus*) in the Susquehanna River of Pennsylvania (USA) was about 5°C. The local tilapia population overwintered in the thermal effluent of an electric power plant, so the plant temporarily lowered the water temperature during winter. This apparently eliminated the local population, but the tilapia persisted because of other thermal discharges along the river.

Complete dewatering to eradicate non-native fish populations has been proposed for some large reservoirs (CDFG 2007), but has largely been limited to small water bodies, usually aquaculture ponds (Alvarez *et al*. 2003; Mueller 2005). The water level of lakes or reservoirs is sometimes lowered in conjunction with the use of fish toxicants (CDFG 2007), thereby reducing the amount of toxicant needed and containing targeted fish within smaller and more exposed areas.

Increased harvest pressure as a method of controlling invasive or unwanted fishes can involve modification of regulations to promote angling, commercial harvesting or incorporating derbies and offering bounties (Lee 2001). However, because fishes vary in their susceptibility to capture, the methods used by anglers and commercial fishers are typically size and species selective. Consequently, the likelihood of removing an entire population through increased harvest is generally low (Thresher 1996, Yonekura *et al*. 2007).

Biological methods

The release of predators to prey on undesirable or invasive species as a form of biological control has a long history although it is not commonly used against invasive fishes. As in terrestrial environments, this approach to non-native fishes could have unintended consequences (Fuller *et al*. 1999). Contagious diseases such as koi herpes virus or KHV has potential use against non-native species, but is controversial because of potential harm to related desirable species (Gilligan and Rayner 2007) and likely difficulties with correcting unintended consequences. Moreover, surviving fish might have immunity to the disease, rendering the method useless after one application. Still, introduction of a highly-specific contagious disease could be helpful if combined with other methods.

Genetic manipulations which have been proposed include: 1) chromosome set manipulations involving production and release of triploid sterile non-native fish with the intent of reducing the population size of targeted naturalised individuals; and 2) recombinant DNA methods involving transgenic techniques designed to produce sterile fish or spread deleterious transgenes (i.e., "Trojan horse" genes) to a target non-native species (Gilligan and Rayner 2007; Thresher 2008). In Australia, there have been investigations into the use of "daughterless genetic technology" to combat introduced fish, especially common carp. This involves creating a heritable gene that suppresses the production of female offspring, causing a reduction in the nuisance population over successive generations (Gilligan and Rayner 2007). Few genetic manipulations have been tested in the field. One exception is release of sterile males to help control sea lamprey (*Petromyzon marinus*) in the Laurentian Great Lakes (Bergstedt and Twohey 2007).

A promising and potentially benign biological control method under development is to use pheromones, which are natural chemicals secreted by many fish and important in influencing their behaviour. To date, development of this method has been directed at the control of sea lamprey in North America (Sorensen and Hoye 2007). Field tests demonstrated that pheromone signals attract sea lampreys into traps. However, the campaign to control sea lamprey in the Laurentian Great Lakes—although providing ground-breaking methods of potential benefit for eradication of other species—has been intensive, long (over five decades), and expensive (approximately US$20 million annually) (Kolar *et al*. 2010).

CONCLUSIONS

Because invasive species cause ecological and economic harm, eradication remains an important management option. However, like other invasive animals and plants, invasive fishes can be difficult and expensive to eradicate. On islands, eradications of invasive fish may be simpler than in mainland areas, partly because an invading population is more spatially restricted. To date, the methods used against invasive fishes on Pacific islands are similar to those used elsewhere in the world. On the other hand, the state of knowledge on fish eradication is dynamic and, because each eradication project has its own unique set of problems, solutions may be site or species specific.

Eradication projects targeting invasive fishes are often controversial, partly because of the likelihood of collateral damage to native species (Britton *et al*. 2008) and especially when non-specific fish toxicants, such as rotenone, remain one of the few effective tools. The risk that an eradication attempt will harm native species is of particular concern on Pacific islands where native faunas include many endemic species. Consequently, early planning requires risk assessments to determine the relative benefits of eradicating non-native species against the potential harm native organisms. Such decisions need to be judged on a case-by-case basis, requiring awareness of the different eradication methods and strategies, and associated positive and negative consequences, as well as substantial knowledge of the targeted species, the invaded habitat, and substantial information on the native fauna present.

The time and effort expended on basic information about invasive fish depends on characteristics of the species, size and complexity of the invaded environment, risks that the population will rapidly or easily spread, and its potential undesirable effects. The possibility of eradication decreases and the potential costs increase as the invading populations disperse. Consequently, eradication is best attempted almost immediately upon discovery of new invasive populations (Simberloff 2009). Unfortunately, since monitoring is often inadequate, non-native populations are often large and widely distributed when biologists become aware of their existence.

Recognising the risks of delay, McDowall (2004a) concluded "…where potentially invasive species are known to be present, the first action must be to attempt control or eradication, and once that has been done, to then take the time to carefully evaluate the risk posed by a species." Similarly, Simberloff (2009) argued that successful eradication calls for quick action—in some situations a "scorched-earth" approach—with minimal time spent conducting research, although he recognised that some cases require sophisticated scientific research prior to action. For non-native fishes, a basic understanding of their biology is necessary to ensure that eradication methods chosen are appropriate and offer the greatest chances of success.

Successful eradications have key elements in common (Simberloff 2009): 1) detecting an invasion early and acting quickly to eradicate it; 2) sufficient resources allocated to the project from start to finish including post-eradication surveys and follow-up, if necessary; 3) a person or agency with the authority to enforce cooperation; 4) the targeted species studied well enough to suggest vulnerabilities (often basic natural history suffices); and 5) optimistic, persistent, and resilient project leaders.

Globally, improved methods and strategies are needed to eradicate invasive fishes, especially where these species are causing the decline of endemic or imperilled native fauna. Future research will likely focus on the control or eradication of a few of the more notorious invaders, although methods developed against one species may be applied to other taxa. Future needs include: 1) re-examination and adjustment of methodologies; 2) development and testing of additional ichthyocides especially those that are more selective and less harmful to non-target species; 3) newer biological techniques, including "Trojan genes" and pheromones, which should enable selective targeting of fish for removal. Unfortunately, it is likely that many of these advances will be costly to develop and field applications possibly decades away.

Because budgets are usually limited, setting priorities is essential. Focus is often directed at species perceived to be especially harmful. In considering Pacific islands, a complementary approach to species targeting is ecosystem prioritisation (Jenkins *et al*. 2009). This strategy recognises that a common goal of non-native eradication is protection of native biodiversity. Most native freshwater fishes inhabiting Pacific islands have complex life cycles and their survival is dependent on high connectivity between terrestrial, freshwater, and marine systems. To maintain biodiversity and reduce the impact of invasives, ecosystem prioritisation demands conservation and management of entire catchments, particularly those that are intact and unique (Jenkins *et al*. 2009).

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