Management in Practice

Eradication of two non-native cichlid fishes in Miami, Florida (USA)

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Abstract

The proliferation of non-native fishes in Florida is a serious problem, and new species continue to be introduced to the state. Fishes in the Family Cichlidae have been especially successful colonizers of south Florida freshwater habitats. Herein we report a multi-agency effort to eradicate two non-native cichlid fishes in Miami, Florida (Bay Snook *Petenia splendida* and Blue Mbuna *Labeotropheus fuelleborni*). These fishes were removed before they were observed in the extensive, interconnected canal system through which they may have been able to expand throughout south Florida and access protected areas such as Everglades National Park. The study site, Pinecrest Gardens, is important because it contains remnant coastal cypress-strand habitat in an increasingly urbanized landscape that historically provided refuge to native amphidromous fishes and invertebrates. The project took considerable time (3.5 years), and we detail in this report how it evolved from a focus on isolating the non-native fishes and reducing their population sizes to an eradication. Gardens' staff hydrologically isolated their ponds from nearby waterbodies by plugging a culvert with a solid gate. That provided the interagency team with more time to remove the potential threats. Compromises were made between fish management strategies and the Gardens' priorities. Hurricane impacts helped shift priorities to more aggressive fish-management strategies. Cooperation among several federal and state agencies, as well as the Gardens, was key to the project's success. We hope this effort may serve as a model for removing non-native species before they spread into ecosystems where eradication is not practical.

Key words: Cichlidae, *Labeotropheus,* multi-agency response, *Petenia*, rotenone

Introduction

In Florida's freshwaters, over 150 species of non-native fishes have been collected, and more than 30 species are established (USGS-NAS 2018). About six new species become established each decade, and few examples of successful eradications exist (reviewed in Schofield and Loftus 2015). Almost all efforts that have successfully eradicated non-native fishes have taken place in small, hydrologically closed systems, such as ponds (e.g., Shafland and Foote 1979; Hill and Cichra 2005), although at least one eradication attempt was successful in a natural, flowing system (Hill and Sowards 2015). The vast canal systems of south Florida provide a challenge to non-native fish management, which emphasizes the importance of detection and removal of new species before they can enter the system.

The interconnected network of thousands of kilometers of canals in south Florida provides suitable habitat for dozens of species of non-native fishes (Shafland et al. 2008; Schofield and Loftus 2015). The extent and nature of the system makes it difficult to manage non-native fish populations. Many canals are cut into the limestone bedrock and some penetrate the underlying aquifer, which buffers thermal and physico-chemical extremes and provides a refuge from more extreme conditions sometimes found in natural habitats (Schofield et al. 2010). Furthermore, the canal systems are interconnected, and once a species has colonized one part of the system, it may spread throughout the entire network and potentially gain access to natural areas, such as Everglades National Park. The application of piscicide in the extensive, open canal system would be complex, costly and difficult. At this moment, with the tools currently available, once a non-native species has entered the canal system of south Florida and established a reproducing population, it is extremely difficult to slow or stop its geographic spread. Thus, preventing the introduction of new species into the canal systems of south Florida is of vital importance to combatting the spread of non-native fishes.

This report details the detection, identification, and eradication of two non-native cichlid fishes (Bay Snook *Petenia splendida* Günther, 1862 and Blue Mbuna *Labeotropheus fuelleborni* Ahl, 1926). Cichlids have been especially successful in colonizing south Florida waterways, and at least 24 species are either currently or formerly reproducing (Schofield and Loftus 2015). Of the 17 non-native fish species documented in Everglades National Park, 10 are cichlids (Kline et al. 2014). Some factors thought to facilitate successful colonization by cichlids include: similarity of south Florida's climates to native ones (tropical Asia, Africa, and the Americas), wide tolerance of ecophysiological variables (e.g., low oxygen, salinity), and parental care of young. The ecological impacts of past introductions of non-native fishes are relatively unknown (Schofield and Loftus 2015) and addition of new species could impose an additional burden on the ecosystem with unforseen consequences. By removing these two species before they were able to enter public waterways, we eliminated a potential environmental threat to the State as well as supported a unique ecosystem that is one of the last remnants of its kind in an increasingly urban landscape and that historically served as a refuge for tropical peripheral species (Gilmore and Hastings 1983; Loftus and Kushlan 1987).

The evolution of this fish removal project is detailed herein. It began by isolating the non-native fish populations by sealing off access to adjacent water bodies and reducing population sizes with little hope for eradication. This strategy was implemented due to trade-offs made to accommodate the municipal park (Pinecrest Gardens, Miami, Florida) and avoid negative public relations. Later in the project, due to the after-effects of a hurricane, the focus of the project shifted from control to eradication. Cooperation among several state and federal agencies as well as the park was key to the successful eradication of the two cichlid species.

Methods and results

Focal species

Petenia splendida is the sole species in its genus. Native to the Atlantic slope Grijalva, Hondo, and Usumacinta rivers of Guatemala and Mexico and the Belize River system of Belize, including the type locality Lake Peten Itza, Guatemala, it is popular with angling tourists and artisanal fishers (Quintana 2015). *Petenia splendida* is sometimes called “Bay Snook”, although it occurs mostly in rivers and is not a snook (Family: Centropomidae). It is a piscivore, a feeding guild that can have a disproportionally negative effect on native fishes (e.g., Mitchell and Knouft 2009). With protractile jaws and large body size (up to 50 cm standard length [SL], Kullander 2003), *P. splendida* can engulf prey fish that fit within gape limitations (Cochran-Biederman and Winemiller 2010). It attains sexual maturity at 16.5 cm total length (TL) and is known to occur in the brackish Laguna Bacalar and Laguna del Pom (Miller et al. 2005). In its native waters, *Petenia* reproduced throughout the year, but spawning peaked in June and July with mean fecundity of 2,400 eggs per female (Arredondo-Figueroa et al. 2013). We suspected that, like some other Central American cichlids, *P. splendida* would likely be able to colonize the canal system of south Florida and that it may negatively affect native species due to its predatory nature.

Labeotropheus fuelleborni is one of five *Labeotropheus* species endemic to Lake Malawi, Africa (Eschmeyer et al. 2017; Pauers 2017). It forages on aufwuchs, a combination of plants and animals that attach to rock substrata (Ribbink 1990). *Labeotropheus fuelleborni* is a maternal mouth brooder, like many cichlids, which facilitates both egg and larval survival (Gay 2016). In addition, mother and young are mobile so they can move as a group to improve survival. At the study site, it thrived in the limestone-lined waterfall pool where pelletized food was daily fare. Cichlids from the African Rift Lakes have not previously been documented in south Florida canals; however, their ability to colonize that habitat and their potential ecological role in those novel situations is unknown.

Petenia splendida and *L. fuelleborni* were first detected at our study site (Pinecrest Gardens) in 2014 (Table 1). Neither of these two species had previously been seen or collected in the wild in the USA (USGS-NAS 2018).

Study site

Pinecrest Gardens (25.67N; −80.29W) is a 5.4-hectare parcel that previously housed the privately-owned Parrot Jungle tourist attraction from the 1930s

Table 1. Timeline of events related to eradication of *P. splendida* and *L. fuelleborni* from Pinecrest Gardens, Miami, FL (USA). ENP = Everglades National Park; FWC = Florida Fish and Wildlife Conservation Commission; ECISMA = Everglades Cooperative Invasive Species Management Area; USFWS = US Fish and Wildlife Service; NPS = National Park Service; USGS = US Geological Survey.

Date	Activity	Gear	Location	Agency/Group
April 2014	*Petenia splendida* first reported	visual observation	Pinecrest Gardens; main pond, parking-lot pond	ENP
July 2014	FWC collects first specimens of *P. splendida* for identification	dipnets and castnets	Pinecrest Gardens	FWC
19–20 August 2014	Work day - *P. splendida* removed completely from parking-lot pond, but only partially from main pond; *L. fuelleborni* first reported	seine, fyke net, minnow trap, cast net, dip nets, fish spear	Pinecrest Gardens; parking-lot pond and main pond	ECISMA (mulit-agency group)
19 August 2014	Boat electrofishing in canal (4,440 pedal seconds)	boat electrofisher	Snapper Creek Canal upstream from the water control structure (fresh side)	USFWS
20 November 2014	Boat electrofishing in canal (2,980 pedal seconds)	boat electrofisher	Snapper Creek Canal downstream from water control structure (estuarine side)	NPS
December 2014	Culvert connecting Gardens to Snapper Creek Canal sealed		Pinecrest Gardens	Pinecrest Gardens staff
25 May 2016	*Petenia splendida* removed	backpack electrofisher, seine, hook and line	Pinecrest Gardens; main pond	USGS and FWC
25 May 2016	*Labeotropheus fuelleborni* removed	backpack electrofisher	Pinecrest Gardens; waterfall pond	USGS and FWC
1–2 November 2016	*Petenia splendida* removed	backpack electrofisher, seine, hook and line	Pinecrest Gardens; main pond	USGS and FWC
1–2 November 2016	*Labeotropheus fuelleborni* removed	backpack electrofisher	Pinecrest Gardens; waterfall pond and parking-lot pond	USGS and FWC
1 November 2016	Boat electrofishing in canal (1,394 pedal seconds)	boat electrofisher	Snapper Creek Canal downstream from water control structure (estuarine side)	NPS
9 November 2016	Boat electrofishing in canal (940 pedal seconds)	boat electrofisher	Snapper Creek Canal upstream from water control structure (fresh side)	FWC
21 March 2017	*Petenia splendida* removed	backpack electroshocker, seine, hook and line	Pinecrest Gardens; main pond	USGS and FWC
21 March 2017	*Labeotropheus fuelleborni* removed	backpack electroshocker	Pinecrest Gardens; waterfall pond	USGS and FWC
10 September 2017	Hurricane Irma			
September 2017	Parking-lot pond completely drained, all fish removed		Pinecrest Gardens; parking-lot pond	Pinecrest Gardens staff
19–20 September 2017	Post-hurricane sampling; *P. splendida* removed; decision made to use rotenone	backpack electrofisher	Pinecrest Gardens; main pond and waterfall pond	USGS and FWC
4–7 November 2017	Rotenone applied; dead fish removed from ponds	dip nets	Pinecrest Gardens; main pond and waterfall pond	USGS and FWC
8 November 2017	Pond restocked with native fishes		Pinecrest Gardens; main pond and waterfall pond	USGS
14 December 2017	Resampled renovated pond with electrofisher (541 pedal seconds) and restocked with native fishes	backpack electrofisher	Pinecrest Gardens; main pond and waterfall pond	USGS and FWC
14 March 2018	Resampled renovated pond with electrofisher (892 pedal seconds) and restocked with native fishes	backpack electrofisher	Pinecrest Gardens; main pond and waterfall pond	USGS and FWC
1 October 2018	Culvert re-opened and connection between Pinecrest Gardens and Snapper Creek re-established		Pinecrest Gardens; main pond and waterfall pond	Pinecrest Gardens

until the property was acquired by the Village of Pinecrest in 2002. It is now a public park. The Gardens contain approximately 1.7 hectares of native forested wetland comprised of approximately 1.2 hectares of tropical hardwood hammock and 0.4 hectares of native cypress slough hammock. In addition, the Gardens contain the only remnant of the original streambed of Snapper Creek; the remainder of which has been altered and converted into a canal.

Pinecrest Gardens has historically provided habitat for fishes and invertebrates of special interest. In the 1980s, Loftus et al. (1984) identified two tropical peripheral fishes at Pinecrest Gardens, Bigmouth Sleeper *Gobiomorus dormitor* Lacepède, 1800 and Mountain Mullet *Agonostomus monticola* (Bancroft, 1834), as well as the uncommon Mangrove Gambusia *Gambusia rhizophorae* Rivas, 1969, a first record for Florida freshwaters. The River Shrimp *Macrobrachium acanthurus* (Wiegmann, 1836) has also been collected from the Gardens. The last record of *A. monticola* occurred in the mid-2000s, but *M. acanthurus* has persisted in the Gardens through 2018. Both groups of animals require access to saltwater habitats for larval development, followed by access to warm, clean freshwater habitats as juveniles and adults. The coastal location, protective tree canopy and flowing freshwater of the remnant stream in the Gardens combine to make it one of the few places in south Florida that may allow populations of these shrimps and fishes to persist.

Petenia splendida was first reported from Pinecrest Gardens in April 2014 by J. Kline, Everglades National Park (Table 1). Species identification was confirmed by author KBG in July 2014. At the beginning of the project (2014), *P. splendida* occupied two waterbodies on the property – the large main pond (Figure 1) and the parking-lot pond, which is a small concrete display pond (semi-circle with ca. 3-meter diameter). The parking-lot pond is not hydrologically connected to any other water features in the Gardens. *Labeotropheus fuelleborni*, first noted in the Gardens in August 2014, was found primarily in the waterfall pond, which is a solution hole with no surface water connection to the main pond. Later in the project, it was also found in the parking-lot pond. Water levels in the main pond and its satellite solution holes are driven by pumped wellwater and hydrostatic pressure from the water table (i.e., Biscayne Aquifer), which is in turn affected by rainfall, tides, and water levels of the adjacent Snapper Creek (C-2) Canal. Water levels in the canal are manipulated via a water-control structure (S-22) that essentially divides the upstream freshwater portion of the canal from estuarine conditions downstream. The canal empties into Biscayne Bay approximately two km downstream of the control structure. A culvert connected the main pond system in the Gardens with the canal, opening on the estuarine side of the control structure (Figure 1). Water is not always present in the culvert. Historically, the connection allowed fish to move from the canal into the Gardens' ponds and vice versa during times

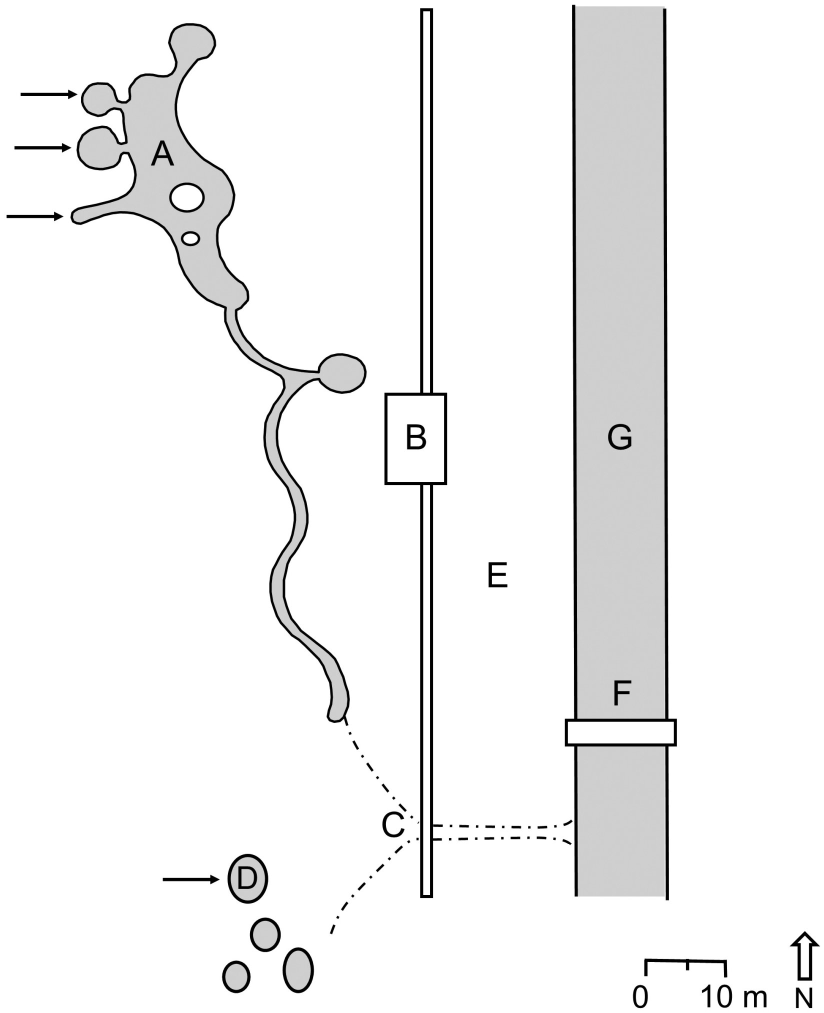

Figure 1. Schematic diagram of ponds at Pinecrest Gardens. A = main pond; B = historic entrance building; C = culvert; D = waterfall pond; E = Red Road, bike path, and landscaped easements; F = water-control structure S-22; G = Snapper Creek Canal (C-2). Arrows indicate water in-flows. Hatched lines indicate historic overland water flows during high-water events that connected the Gardens with Snapper Creek Canal. The waterfall pond (D) normally has no overland water connection to the main pond system. The swan pond and the parking-lot pond are not shown on this map and are not hydrologically connected to any other ponds.

of high water. Due to concern that non-native cichlids (especially *P. splendida*) could potentially escape the Gardens, Pinecrest staff securely sealed the culvert in December 2014, so that no water could exit the Gardens via the culvert. Water from the ponds then seeped into the limestone ground with no apparent surface outflow.

There is one additional pond at Pinecrest Gardens – the swan pond, a borrow pond which, like the parking-lot pond, is not hydrologically connected to the main pond or its satellite solution holes. Neither *P. splendida* nor *L. fuelleborni* was ever observed in the swan pond.

2014

In July 2014, KBG met with Gardens personnel to discuss the situation and collected specimens for positive identification (Table 1). It was noted that a significant population of *P. splendida* was present, including many juveniles, indicating the fish were reproducing. The Everglades Cooperative Invasive Species Management Area (ECISMA) held a work day at the Gardens in August 2014, where *P. splendida* was targeted in the main pond and the parking-lot pond (Table 1). Twenty-three *P. splendida* were collected from the main pond, and 173 were collected from the parking-lot pond. This effort completely removed all *P. splendida* from the parking-lot pond. During the work day, hundreds of *L. fuelleborni* were noted occupying the waterfall pond. Like *P. splendida*, the population was reproducing, and individuals of multiple size classes were present. Interestingly, additional non-native fishes thought to have been illegal aquarium releases were found and removed from the parking-lot pond during the work day, including Jack Dempsey cichlid *Rocio octofasciata* (Regan, 1903), and a squeaker catfish *Synodontis* sp. No *Labeotropheus fuelleborni* were found in the parking-lot pond during the ECISMA work day.

May 2016 to March 2017 (pre-Hurricane Irma)

USGS personnel joined the effort in May 2016. From May 2016 to March 2017, FWC and USGS staff worked together to remove *P. splendida* and *L. fuelleborni* from the Gardens (Table 1). Gear used included small seines, a backpack electrofisher, and hook-and-line to selectively removed individuals of the two cichlid species without negatively impacting large prized fishes in the Gardens' ponds. Of the prized fishes, some were native species (Tarpon *Megalops atlanticus* Valenciennes, 1847, Common Snook *Centropomus undecimalis* [Bloch, 1792]) and others were non-native, including several Koi hybrids *Cyprinus carpio* Linnaeus, 1758 × *Cyprinus rubrofuscus* Lacepède, 1803 (hereafter called "Koi"), a single Redtail Catfish *Phractocephalus hemioliopterus* (Bloch and Schneider, 1801), one Ripsaw Catfish *Oxydoras niger* (Valenciennes, 1821), a large barb (possibly *Hampala macrolepidota* Kuhl and van Hasselt, 1823) and about 20 Pacu (either Tambaqui *Colossoma macropomum* [Cuvier, 1816] or Pirapitinga *Piaractus brachypomus* [Cuvier, 1818]; hereafter called "Pacu"). The Gardens wanted to retain these prized fishes due to their display value. The non-native ones were determined to be a low risk for escape into south Florida canals because they were not expected to breed in Florida, thus escape of small fry and/or juveniles was unlikely. Those fish species, especially Pacu and Koi, had been present in Pinecrest Gardens for many years and had never reproduced. In south Florida, Koi and Pacu are commonly displayed in water gardens and there has never been evidence of reproduction (USGS-NAS 2018). Additionally, the adult fish were large-bodied, and were unlikely to escape through a grated culvert once it was eventually unsealed and the connection to the Snapper Creek canal restored.

During the pre-Hurricane Irma time period, *P. splendida* was only present in the main pond, and the following numbers were removed from

Figure 2. Photographs of *Petenia splendida* (top; taken by HJ) and *Labeotropheus fuelleborni* (bottom; taken by PJS) collected from Pinecrest Gardens, Miami, FL.

that location: 25 May 2016 (n = 14), 1–2 November 2016 (n = 31) and 21 March 2017 (n = 31; Table 1; Figure 2). *Labeotropheus fuelleborni* was present in two locations: the waterfall pond and the parking-lot pond. Although no *L. fuelleborni* had been present in the parking-lot pond during the ECISMA work day in 2014, it was subsequently detected there in November 2016. Hundreds of *L. fuelleborni* (Figure 2) were collected from the waterfall pond on each date *P. splendida* were collected and from the parking-lot pond in November 2016; however, numbers and size of *L. fuelleborni* were not recorded.

At this point in the project, we had little hope of completely eradicating the cichlids and were focused on reducing population sizes. Large (reproducing-age) *P. splendida* were specifically targeted, but we removed as many individuals of all sizes as possible (including juveniles). Vouchers were sent to the Florida Museum (Gainesville, Florida) for verified identification and curation into the fish collection (UF 236748, 238397, 190139, 239268, 239271).

Hurricane Irma aftermath

Hurricane Irma struck Florida on 10 September 2017 and heavily affected Pinecrest Gardens by downing many trees and flooding the lower gardens and ponds. Electric power was lost for several days, and consequently pumps that moved water through the Gardens did not function, likely leading to low-oxygen conditions (but no dissolved-oxygen measurements were taken). After the storm passed and the Gardens assessed damages, it was found that many fishes had died in the ponds or were stranded in vegetation, while others had spread to new locations within the Gardens. The fish likely died either from the low-oxygen conditions or because they were displaced out of the ponds and onto land by flooding.

All fishes in the parking-lot pond died, and the pond was subsequently drained. Thus, all *L. fuelleborni* were eliminated from that pond. In the main pond, all Pacu, Koi, *C. undecimalis* and the large catfishes were killed, but the single *M. atlanticus* survived along with many *P. splendida*. We attempted to collect *P. splendida* in the main pond on 19 September 2017, a week after the hurricane, but had difficulty moving about in the pond due to downed trees and branches. Only two *P. splendida* were captured in the main pond; however, many smaller individuals (5–8 cm TL) were seen swimming there. In the waterfall pond, some Koi survived the storm, as well as many *L. fuelleborni*. *Petenia splendida* were also collected from the waterfall pond (n = 6). This was the first and only time *P. splendida* was found outside the main pond. It was likely that extensive flooding from the hurricane temporarily connected the main pond and the waterfall pond, allowing it to disperse.

In the aftermath of the storm, the Gardens closed to the public for several weeks to clean up the downed trees and other property damage. Following a discussion of fish-management options on 20 September 2017 with Pinecrest Gardens' managers, the decision was made to renovate the main pond and waterfall pond with rotenone after moving the remaining prized fishes (including one *M. atlanticus* and several Koi) to the swan pond. CFT Legumine™ was the roteneone product selected due to its effectiveness on cichlid fishes and low mortality to non-target invertebrates (Nico et al. 2015).

Rotenone treatment and follow-up

The ponds in the Gardens comprised 490 cubic meters (0.4 acre/feet or approximately 130,000 gallons). That volume includes the main pond and the sinkholes that had no surface connection (including the waterfall pond). On 4 November 2017, 1.9 liters (0.5 gallons) of CFT Legumine™ (5% rotenone solution) was applied, achieving a rate of 4.0 parts per million of product. Rotenone was not used in the parking-lot pond or the swan pond. For the next three days, all fishes were removed from the treated ponds and their identity recorded. We visually surveyed the treated areas in the Gardens several times each day to check for remaining fishes. The main pond is shallow (less than 1 meter deep) and the water is clear, thus it was relatively easy to observe fishes from walkways in the Gardens. A subsample of each species (except Eastern Mosquitofish *Gambusia holbrooki* Girard, 1859) was measured (TL).

Eight non-native fish species were collected during the rotenone treatment, including 158 *P. splendida* and 145 *L. fuelleborni* (Table 2). One large (> 30 cm TL) Walking Catfish *Clarias batrachus* (Linnaeus, 1758) was seen alive in the main pond, but eluded capture. Of the native amphidromous fauna, one *M. acanthurus* (46 mm carapace length) was collected during the pond renovation; no other tropical peripherals were found.

Table 2. Results of rotenone treatment at Pinecrest Gardens, November 2017. Number of each species collected is given for 4, 5 and 6 November. Size is given as mean cm total length (TL) ± standard deviation (SD). N/A = Not available.

Family	Species	Common name	4-Nov	5-Nov	6-Nov	Total	Mean size (cm TL ± SD)	Size range	N measured
non-native fishes									
Clariidae	*Clarias batrachus*	Walking Catfish	18	2	3	23	29.9 ± 12.4	9.5–52.0	18
Loricariidae	*Pterygoplichthys* spp.	Sailfin Catfish	5	0	0	5	26.7 ± 2.5	24.5–30.5	5
Cichlidae	*Cichlasoma bimaculatum*	Black Acara	127	101	35	263	13.7 ± 3.7	5.5–22.0	55
Cichlidae	*Hemichromis letourneuxi*	African Jewelfish	1	4	0	5	3.0	N/A	1
Cichlidae	*Labeotropheus fuelleborni*	Blue Mbuna	81	64	0	145	9.4 ± 2.9	4.5–16.5	67
Cichlidae	*Parachromis managuensis*	Jaguar Guapote	0	1	0	1	10.0	N/A	1
Cichlidae	*Petenia splendida*	Bay Snook	95	55	8	158	10.9 ± 2.4	6.0–19.5	94
Cichlidae	*Pelmatotilapia mariae*	Spotted Tilapia	470	87	20	577	14.3 ± 4.4	5.0–24.0	164
native fishes									
Lepisosteidae	*Lepisosteus platyrhincus*	Florida Gar	2	0	0	2	550	N/A	1
Anguillidae	*Anguilla rostrata*	American Eel	8	1	0	9	33.9 ± 6.9	25.5–44.5	8
Poeciliidae	*Gambusia holbrooki*	Eastern Mosquitofish	43	28	0	71	N/A	N/A	N/A
Poeciliidae	*Poecilia latipinna*	Sailfin Molly	7	4	1	12	7.4 ± 1.6	4.0–8.5	7
Centrarchidae	*Lepomis macrochirus*	Bluegill	2	0	0	2	8.3 ± 0.4	8.0–8.5	2
Eleotridae	*Dormitator maculatus*	Fat Sleeper	8	6	1	15	11.6 ± 4.5	7.0–18.5	8
Eleotridae	*Eleotris amblyopsis*	Largescaled Spinycheek Sleeper	3	6	3	12	15.5 ± 4.0	11.0–18.5	3
Grand total	1300								

We returned to the site twice more (December 2017 and March 2018; Table 1) to perform additional visual inspections and qualitatively survey the fish community using a backpack electrofisher. No *P. splendida* nor *L. fuelleborni* was seen during these follow-up visits. Grass Shrimp *Palaemonetes paludosus* (Gibbes, 1850) and *M. acanthurus* were observed without restocking, indicating they survived the rotenone treatment.

Snapper Creek (C-2) Canal sampling

Petenia splendida could have escaped from the Gardens and made its way into the Snapper Creek Canal before the culvert was sealed in 2014. With our colleagues at the US Fish and Wildlife Service and National Park Service, we sampled the canal multiple times on both sides of the salinity structure with electrofishing boats (Table 1). No specimens of either *P. splendida* or *L. fuelleborni* were seen or collected in the canal. Furthermore, no reports of those species have been received in any other localities beyond the populations at Pinecrest Gardens.

Pond restocking

To test whether the rotenone had sufficiently degraded and the ponds were ready for restocking, sentinel fishes (Fat Sleeper *Dormitator maculatus* [Bloch, 1792]), sunfishes *Lepomis* spp.) were placed in perforated containers (wire minnow traps with the entrance holes sealed or buckets with many holes) and left in the waterfall and main ponds overnight on

7 November 2017 (three days after the rotenone application). All sentinel fishes survived this test, and thus restocking began in the main pond and waterfall pond on 8 November. Ponds were stocked with native fishes collected locally, including sunfishes (Bluegill *Lepomis macrochirus* Rafinesque, 1819; Dollar Sunfish *L. marginatus* [Holbrook, 1855]; Spotted Sunfish *L. punctatus* [Valenciennes 1831]; Bluespotted Sunfish *Enneacanthus gloriosus* [Holbrook, 1855]), poeciliids (*G. holbrooki*; Least Killifish *Heterandria formosa* Girard, 1859; Sailfin Molly *Poecilia latipinna* [Lesueur, 1821]) and other local native species. We returned in December 2017 and March 2018 to continue stocking the pond with native fishes.

In October 2018, Pinecrest Gardens staff re-opened the culvert and re-established the seasonal hydrological connection with Snapper Creek Canal.

Discussion

There are few reports of successful eradications in Florida that proceeded by removing individual fishes (Hill and Sowards 2015; Schofield et al. 2018). At the beginning of this project, we were focused on population reduction by removing individual fishes, although it is unlikely that either cichlid species would have been eradicated in this manner (i.e., without rotenone). Thus, while Hurricane Irma had many negative consequences on Florida in general and Pinecrest Gardens in particular, it also changed conditions in the ponds and provided the opportunity to completely eliminate two potential threats to the south Florida ecosystem. After their elimination, the connection between the Gardens to Snapper Creek Canal was restored. This may allow tropical peripherals such as *A. monticola* and *G. dormitor* to once again use the Gardens as a refuge.

Several successful eradications of non-native fishes have taken place in Florida freshwaters using piscicides such as rotenone (e.g., Hogg 1976; Courtenay and Robins 1973; Shafland and Foote 1979; Courtenay et al. 1984, 1986; Hill and Cichra 2005; Shafland et al. 2008). At this time, piscicides are probably the most useful tool for eliminating localized populations of non-native species in Florida's freshwaters. Alternate management options may be useful for controlling non-native fish populations. For example, Hill (2016) reported that low water levels in a Florida lake led to severe population reductions of a non-native cichlid fish, probably via reduction in habitat complexity (i.e., refugia) that in turn increased predation pressure on the cichlid. Because many non-native fish species in south Florida are sensitive to cold temperatures (Schofield and Kline 2018), lowering water-levels could have broad effects on the non-native fish community (Schofield et al. 2010). However, the act of lowering canal water levels may be too complicated and difficult to allow its use as a practical management technique. We are hopeful that in the future new technologies may be developed that cause less collateral damage to native species and can be more widely applied.

The decision to remove *P. splendida* and *L. fuelleborni* was relatively simple based on the historical success of cichlids' abilities to become established in south Florida, the fact that both cichlid species were reproducing and thriving in the Gardens, and the potential for their escape into the Snapper Creek Canal. Of the two, *P. splendida* was the more urgent threat, due to its predacious nature and presence in the main pond that was historically connected to the adjacent canal. There is debate regarding the amount of research that must be accomplished before an eradication attempt is made (Simberloff 2003). Each case is different and must take multiple factors into account. Several factors went into our decision to switch from control to eradication (with rotenone) following the hurricane, including our high degree of certainty that we would be able to remove the species completely given the physical layout of the ponds (isolated from any connecting waterbodies, shallow, relatively small). Also, the temporary closing of the Gardens to the public allowed us to move forward with the pond renovation without disrupting normal Gardens operations.

Preventing release of non-native species is ideal, but despite informative websites, signs and brochures, illegal releases continue to occur. Early detection and rapid response to new non-native species is widely viewed as the most economical and efficient method to reduce or avoid harm (Simberloff 2009). However, when faced with a new introduced species, natural resource managers must balance the time it takes to collect data on the species with the desire to move quickly to remove the threat. The more time available to the non-native species to build up its population and expand its geographic range, the lower the probability of successful eradication. The introduction of non-native species initiates a race against time, and early detection of introductions is therefore of vital importance. In this case, the project took 3.5 years from detection to eradication – hardly "rapid". However, we succeeded because we were able to seal off the Gardens from nearby waterbodies, extending the time to deal with the invasion. In south Florida, the opportunity for eradication narrows considerably once a non-native species penetrates the large interconnected canal system and establishes a reproducing population.

The response of different fishes to Hurricane Irma flooding varied. Fishes originating from South America tended to spread throughout the Gardens as is typical of flooded forests in those areas during the wet season (e.g., Pacu, Black Acara *Cichlasoma bimaculatus* [Linnaeus, 1758]; Goulding 1980). Spotted Tilapia *Pelmatotilapia mariae* (Boulenger, 1899) from West Africa also ventured out of the ponds at high water levels. Conversely, *L. fuelleborni* from the African rift lakes remained in the waterfall pond during the flooding. Due to its ability to disperse in floodwaters, *P. splendida* could have likely escaped the Gardens during the hurricane had the culvert not been sealed.

Cooperation among state and federal agencies and the land-owner were fundamental to the success of this project. Besides the authors on this manuscript, many colleagues were generous with their time and provided support, labor, insight and advice. While our agency missions differ in many aspects, we were able to find a common purpose in removing these potential threats to Florida. We especially benefitted from our contacts within the Everglades Cooperative Invasive Species Management Area (ECISMA 2017) and Florida Non-Native Fish Action Alliance (FNNFAA 2017), two groups that bring together scientists and natural resource managers working on non-native species in Florida. Additionally, managers and staff at Pinecrest Gardens were accommodating and supportive of our efforts.

We hope that this effort serves as an example for future removals of non-native species before they spread into ecosystems where they could cause damaging impacts. Response efforts are often undervalued, as non-native species do not typically capture attention until they are widespread and have caused negative impacts. One problem leading to the undervaluing of response efforts is the lack of ability to predict consequences of the introduction had the response not occurred. In the USA, resources may be prioritized toward controlling existing problems versus preventing new ones (Finnoff et al. 2007), and managers may wait until after new species have arrived and then scramble to limit the damages (Leung et al. 2002; Carlton and Ruiz 2005). If funders, agencies and scientists could develop a broader understanding of the potential effects of non-native species and support early detection followed with response efforts, it might be possible to limit damages from future non-native species, especially those deemed high-risk.

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References

Arredondo-Figueroa JL, Nunez-Garcia LG, Perez-Vega MH, Ponce-Palafox JT, Bariga-Sosa IDLA (2013) Culture of founders and breeding of the bay snook *Petenia spledida* (Pisces: Cichlidae) in a recirculation aquaculture system. *European International Journal of Science and Technology* 2: 123–132

Carlton JT, Ruiz GM (2005) Vector science and integrated vector management in bioinvasion ecology: conceptual frameworks. In: Mooney HA, Mack RN, McNeely JA, Neville LE, Schei PJ, Waage JK (eds), Invasive Alien Species: A New Synthesis. Island Press, Covelo, California, pp 36–58

Cochran-Biederman JL, Winemiller KO (2010) Relationships among habitat, ecomorphology and diets of cichlids in the Bladen River, Belize. *Environmental Biology of Fishes* 88: 143–152, https://doi.org/10.1007/s10641-010-9624-y

Courtenay WR Jr, Robins CR (1973) Exotic aquatic organisms in Florida with emphasis on fishes: a review and recommendations. *Transactions of the American Fisheries Society* 102: 1–12, https://doi.org/10.1577/1548-8659(1973)102<1:eaoifw>2.0.co;2

Courtenay WR Jr, Hensley DA, Taylor JN, McCann JA (1984) Distribution of exotic fishes in the continental United States. In: Courtenay WR Jr, Stauffer JR Jr (eds), Distribution, Biology and Management of Exotic Fishes. Johns Hopkins University Press, Baltimore, pp 41–77, https://doi.org/10.1017/s0376892900015460

Courtenay WR Jr, Hensley DA, Taylor JN, McCann JA (1986) Distribution of exotic fishes in North America. In: Hocutt CH, Wiley EO (eds), The Zoogeography of North American Freshwater Fishes. Wiley & Sons, New York, pp 675–698, https://doi.org/10.2307/1445804

ECISMA (2017) Everglades Cooperative Invasive Species Management Area. http://www.evergladescisma.org (accessed 23 August 2017)

Eschmeyer WN, Fricke R, van der Laan R (2017) Catalog of fishes: genera, species, references. http://researcharchive.calacademy.org/research/ichthyology/catalog/fishcatmain.asp (accessed 23 September 2017)

Finnoff D, Shogren JF, Leung B, Lodge D (2007) Take a risk: preferring prevention over control of biological invaders. *Ecological Economics* 62: 216–222, https://doi.org/10.1016/j.ecolecon.2006.03.025

FNNFAA (2017) Florida Non-Native Fish Action Alliance. https://www.usgs.gov/centers/wetland-and-aquatic-research-center-warc/science/florida-non-native-fish-action-alliance?qt-science_center_objects=0#qt-science_center_objects (accessed 30 December 2017)

Gay J (2016) The mbuna keeper's survival guide. Practical Fishkeeping. https://www.practicalfishkeeping.co.uk/features/articles/2016/7/24/the-mbuna-keepers-survival-guide (accessed 15 August 2018)

Gilmore RG, Hastings PA (1983) Observations on the ecology and distribution of certain tropical peripheral fishes in Florida. *Florida Scientist* 46: 31–51

Goulding M (1980) The Fishes and the Forest. Explorations in Amazonian Natural History. University of California Press, Berkeley, California, 280 pp

Hill JE (2016) Collapse of a reproducing population of non-native African jewelfish (*Hemichromis letourneuxi*) in a Florida lake. *Neobiota* 29: 35–52, https://doi.org/10.3897/neobiota.29.7213

Hill JE, Cichra CE (2005) Eradication of a reproducing population of convict cichlids, *Cichlasoma nigrofasciatum* (Cichlidae), in north-central Florida. *Florida Scientist* 68: 65–74

Hill JE, Sowards J (2015) Successful eradication of the non-native loricariid catfish *Pterygoplichthys disjunctivus* from the Rainbow River, Florida. *Management of Biological Invasions* 6: 311–317, https://doi.org/10.3391/mbi.2015.6.3.11

Hogg RG (1976) Established exotic cichlid fishes in Dade County, Florida. *Florida Scientist* 39: 97–103

Kline JL, Loftus WF, Kotun K, Trexler JC, Rehage JS, Lorenz JJ, Robinson M (2014) Recent fish introductions into Everglades National park: An unforseen consequence of water management? *Wetlands* 34: 175–187, https://doi.org/10.1007/s13157-012-0362-0

Kullander SO (2003) Family Cichlidae. In: Reis RE, Kullander SO, Ferraris CJ Jr (eds), Check List of the Freshwater Fishes of South and Central America. Edipucrs, Porto Alegre, Brazil, pp 605–654

Leung B, Lodge DM, Finnoff D, Shogren JF, Lewis MA, Lamberti G (2002) An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society of London. Series B: Biological Sciences* 269: 2407–2413, https://doi.org/10.1098/rspb.2002.2179

Loftus WF, Kushlan JA (1987) Freshwater fishes of southern Florida. *Bulletin of the Florida State Museum: Biological Sciences* 31: 147–344

Loftus WF, Kushlan JA, Voorhees SA (1984) Status of the mountain mullet in southern Florida. *Florida Scientist* 47: 256–263

Miller RR, Minckley WL, Norris SR (2005) Freshwater Fishes of Mexico. University of Chicago Press, Chicago, 490 pp

Mitchell AL, Knouft JH (2009) Non-native fishes and native species diversity in freshwater fish assemblages across the United States. *Biological Invasions* 11: 1441–1450, https://doi.org/10.1007/s10530-008-9352-9

Nico LG, Englund RA, Jelks HL (2015) Evaluating the piscicide rotenone as an option for eradication of invasive Mozambique tilapia in a Hawaiian brackish-water wetland complex. *Management of Biological Invasions* 6: 83–104, https://doi.org/10.3391/mbi.2015.6.1.07

Pauers MJ (2017) A new species of *Labeotropheus* (Perciformes: Cichlidae) from Southern Lake Malaŵi, Africa. *Copeia* 105: 399–414, https://doi.org/10.1643/ci-16-463

Quintana Y (2015) Assessment of the artisanal giant cichlid (*Petenia splendida*) fishery in Lake Peten Itza, Guatemala. Masters Thesis. University of Florida, 49 pp

Ribbink AJ (1990) Alternative life-history styles of some African cichlid fishes. *Enviromental Biology of Fishes* 28: 87–100, https://doi.org/10.1007/978-94-009-2065-1_5

Schofield PJ, Kline JL (2018) Lower lethal temperatures for nonnative freshwater fishes in Everglades National Park. *North American Journal of Fisheries Management* 38: 706–717, https://doi.org/10.1002/nafm.10068

Schofield PJ, Loftus WF (2015) Non-native fishes in Florida freshwaters: a literature review and synthesis. *Reviews in Fish Biology and Fisheries* 25: 117–145, https://doi.org/10.1007/s11160-014-9373-7

Schofield PJ, Loftus WF, Kobza RM, Cook MI Slone DH (2010) Tolerance of nonindigenous cichlid fishes (*Cichlasoma urophthalmus*; *Hemichromis letourneuxi*) to low temperature: laboratory and field experiments in south Florida. *Biological Invasions* 12: 2441–2457, https://doi.org/10.1007/s10530-009-9654-6

Schofield PJ, Loftus WF, Reaver K (2018) Non-native fishes of the central Indian River Lagoon. *Florida Scientist* 81: 12–24

Shafland PL, Foote KJ (1979) A reproducing population of *Serrasalmus humeralis* Valenciennes in southern Florida. *Florida Scientist* 42: 206–214

Shafland PL, Gestring KB, Stanford MS (2008) Florida's exotic freshwater fishes – 2007. *Florida Scientist* 71: 220–245

Simberloff D (2003) How much information on population biology is needed to manage introduced species? *Conservation Biology* 17: 83–92, https://doi.org/10.1046/j.1523-1739.2003.02028.x

Simberloff D (2009) We can eliminate invasions or live with them: successful management projects. *Biological Invasions* 11: 149–157, https://doi.org/10.1007/s10530-008-9317-z

USGS-NAS (2018) U.S. Geological Survey. Nonindigenous Aquatic Species database [online database]. U.S. Geological Survey, Gainesville, Florida. https://nas.er.usgs.gov/ (accessed 23 September 2018)