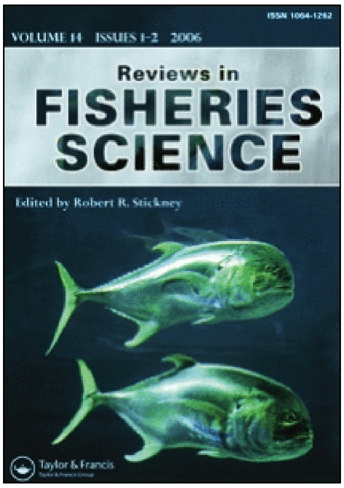

Reviews in Fisheries Science
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713610918

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First published on: 19 November 2009

To cite this Article Shafland, Paul L. , Gestring, Kelly B. and Stanford, Murray S.(2010) 'An Assessment of the Asian Swamp Eel (*Monopterus albus*) in Florida', Reviews in Fisheries Science, 18: 1, 25 — 39, First published on: 19 November 2009 (iFirst)

To link to this Article: DOI: 10.1080/10641260903225542

URL: http://dx.doi.org/10.1080/10641260903225542

Reviews in Fisheries Science, 18(1):25–39, 2010

ISSN: 1064-1262 print
DOI: 10.1080/10641260903225542

An Assessment of the Asian Swamp Eel (*Monopterus albus*) in Florida

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The Asian swamp eel (Monopterus albus) is an air-breathing, sex-reversing, eel-like exotic fish that was first reported from Florida waters in 1997. This illegally introduced fish is now abundant in four major southeastern Florida canal systems, and it continues to slowly spread into nearby areas, including the Everglades. Swamp eel feed on a wide variety of organisms, the most common of which are small fishes, crustaceans (mostly crayfish), and insects. In a laboratory study, swamp eel died at temperatures ≤8°C. No deleterious ecological effects associated with the swamp eel's presence were detected during the 11 years we studied this species, nor was there any evidence that it makes overland movements. Based on these data and observations, the swamp eel in Florida is best described as an illegally introduced, opportunistic and successful predator that feeds on a variety of small prey; fortunately, however, it is unlikely to perpetrate major ecological or economic disturbances.

Keywords exotic fishes, fecundity, fish populations, food habits, lower lethal temperature

INTRODUCTION

The Asian swamp eel (*Monopterus albus*) was first collected from Florida waters in 1997 at two widely separated areas: one in southeast and the other in west-central Florida (United States Geological Service (USGS), 1998; Fuller et al., 1999; Collins et al., 2002). The swamp eel is native to the tropical and subtropical areas of northern India and Burma to China, Asiatic Russia, Japan, and the Indo-Malayan Archipelago (Sterba, 1973; Rosen and Greenwood, 1976; Bailey and Gans, 1998; Collins et al., 2002). Originally treated as a single species, the Asian swamp eel may represent a species complex belonging to the freshwater fish family Synbranchidae (Rosen and Greenwood, 1976; Collins et al., 2002).

The Asian swamp eel is the first established exotic fish in Florida that looks more like an eel or snake than a fish (Shafland et al., 2008). Most are olive-drab brown in color with yellow-orange bellies, but some are brightly colored (e.g., variations of orange, pink, and a calico pattern), and larger ones have an overhanging upper jaw that forms a jowl-like facial appearance (Nichols, 1943; Rosen and Greenwood, 1976). Swamp eel breathe atmospheric air and most (possibly all) mature as females, after which some change to males. In their native range, swamp eel are rarely observed incidentally because most are cryptically colored, primarily active at night, often bury themselves in soft sediments, occupy burrows, and/or hide in crevices (Wu and Kung, 1940; Liem, 1963; Sterba, 1973, 1983; Graham, 1997; Collins et al., 2002). They possess two rows of small mandibular teeth and have reduced eyes covered with a thin layer of skin (Rosen and Greenwood, 1976; Sterba, 1983). Swamp eel lack scales and are almost finless (except in larval stages). The skin exudes a thick protective mucous covering, which, together with its elongated shape, make it well suited for burrowing, and its air-breathing ability makes it well suited for living in shallow, deoxygenated waters (Wu and Kung, 1940; Liem, 1967).

Asian swamp eel typically breathe atmospheric oxygen by rising to the water's surface, protruding their snouts to inhale mouthfuls of air, and then sink to a bottom resting position (Wu and Kung, 1940). Sometimes they use their air-filled buccal cavities to float their snouts just above the water's surface (Wu and Liu, 1940). Atmospheric oxygen is absorbed via a highly vascularized breathing apparatus in the back of their mouths. Although capable of quick movements, undisturbed swamp eel tend to be lethargic in aquaria and rarely active except possibly at night, presumably relying more on stealth than active swimming movements to capture their prey (Wu and Kung, 1940; Wu and Liu, 1940; Liem, 1963, 1987; Sterba,

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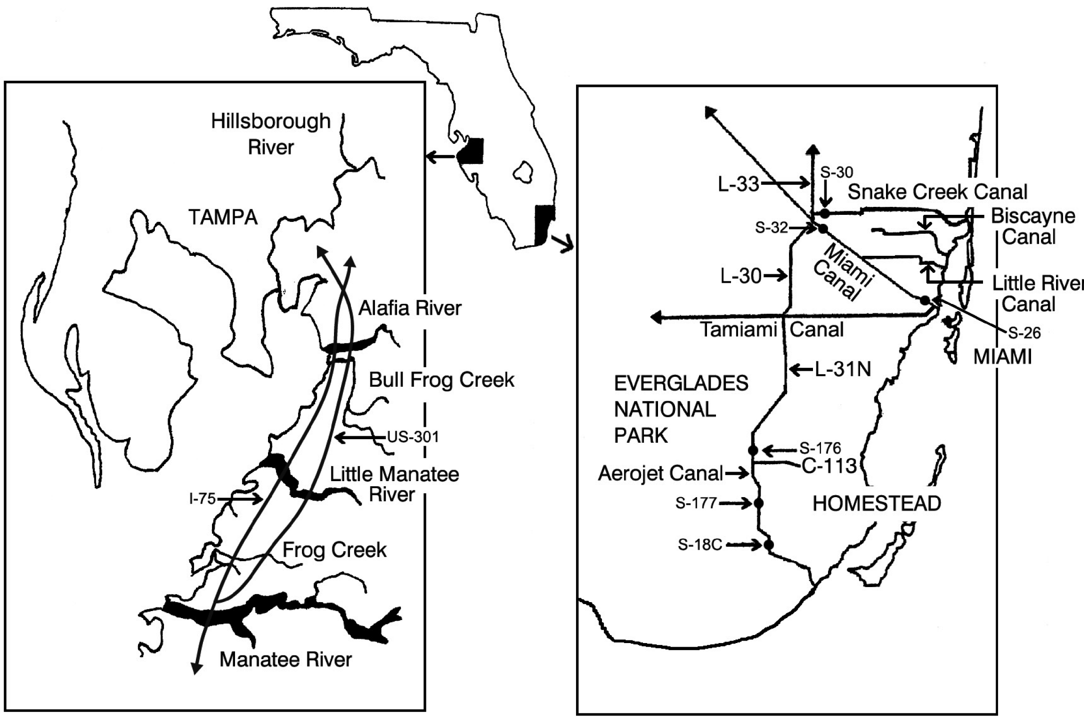

Figure 1 Map illustrating the Florida range of the Asian swamp eel (*Monopterus albus*) and primary sampling areas mentioned in text.

1973, 1983; Graham, 1997; Hill and Watson, 2007; authors' observations).

Discovery of the Asian swamp eel in Florida quickly generated considerable concern largely because of their unusual appearance and life history together with an often cited early report that it had reduced or even eliminated native sunfishes (*Lepomis* spp.) in some Georgia ponds (Anonymous, 1998; Starnes et al., 1998; USGS, 1998; Fuller et al., 1999), though this assertion was subsequently proven premature (Freeman et al., 2005; Straight et al., 2005; T. Reinert, Florida Fish and Wildlife Conservation Commission, personal communication). Almost overnight, the swamp eel became one of several national "poster" species used to support largely unsubstantiated assertions that they cause major ecological and economic damage (e.g., Klinkenberg, 2001; Bricking, 2002; Kluger, 2002). The purpose of this article is to summarize 11 years of data and observations dealing with the swamp eel's associations with other fishes, life history, population dynamics, and the potential limiting effect of low temperatures in order to assess its potential effect on native fishes.

STUDY AREA

In southeast Florida, Asian swamp eel were collected from Snake Creek (C-9), where they were first discovered in 1997 (Collins et al., 2002), and from Biscayne (C-8), Little River (C-7), Miami (C-6), Aerojet (C-111), C-113, and Tamiami (C-4) canals (Figure 1). All of the above canals are part of a large, interconnected, man-made water management system created to provide fresh water and flood protection for southeast Florida (Miami-Dade, Broward, and Palm Beach counties; Cooper and Lane, 1987). Swamp eel were also collected from the Little Manatee River in west-central Florida (Hillsborough County).

In southeast Florida, the Asian swamp eel exists in canals that flow in an easterly or southeasterly direction connecting interior waters with the Atlantic Ocean. Large main canals in Miami-Dade County are box-cut into a coral rock substrate, average about 40 m wide, 3–4 m deep, and submerged vegetation is typically limited to a narrow littoral shelf. These main canals interconnect with a maze of increasingly smaller, shallower, and more vegetated lateral canals that drain urban surface waters during heavy rain events. Some canals flow through one or more man-made "lakes" that range from $<$1–100 ha, a few of which are $>$5–10 m in depth. Periodically, heavy rain events or controlled discharges of water from the Everglades and Lake Okeechobee result in sufficient water flow to carry considerable amounts of vegetation, debris, and detritus to the sea (Cooper and Lane, 1987). The 23-km long Biscayne Canal is somewhat atypical in that relatively little water flows through it, and it rarely experiences the high-flow events of other main canals (authors' observations). Hence, the Biscayne Canal might be better characterized as a narrow, box-cut, linear reservoir rather than a typical main southeast Florida drainage canal that is periodically flushed with large volumes of water.

Asian swamp eel have been collected in west-central Florida from Frog Creek in Manatee County, and Bullfrog Creek and the Little Manatee River in Hillsborough County (USGS, 2009; Figure 1). The Little Manatee River flows about 65 km in a west-northwesterly direction before emptying into Tampa Bay. This river consists of numerous tidally influenced and intertwined

Table 1 Swamp eel sampling periodicity from Snake Creek, Biscayne, and Miami canals, 1997–2008 (n = number of 0.185-ha blocknet samples taken)

	Sampling Method		
Canal	All Species Electrofishing	Swamp Eel Only Electrofishing	Blocknets (n)
Snake Creek	October 1997	September 1998	January 1999 (4)
	October 1998	February 1999	May 2000 (4)
	October 1999	February 2000	May 2001 (2)
	October 2000	February 2001	May 2002 (2)
	October 2001	February 2002	April 2005 (2)
	October 2002	February 2008	
	October 2003		
	October 2004		
	October 2005		
	October 2006		
	October 2007		
	October 2008		
Biscayne	September 1999	December 1999	None taken
	November 2000	March 2000	
	November 2001	June 2000	
	November 2004	March 2001	
	November 2006	June 2001	
		March 2002	
		June 2002	
		August 2003	
Miami	October 1998	May 1999	None taken
	October 2003	August 1999	
		September 2001	

channels with shallow backwaters and dense vegetation near the point where it empties into Tampa Bay. In this study, the Little Manatee River was only sampled west of US-301 and east of I-75 in 2001 and 2005, which was in the vicinity of a tropical fish farm that had reportedly raised swamp eel possibly as early as the 1960s (C. A. Watson, University of Florida Tropical Aquaculture Laboratory, personal communication).

MATERIAL AND METHODS

Data Collection

Multiple canals were sampled using electrofishing and blocknetting procedures. Snake Creek Canal was sampled the most, followed by the Biscayne and Miami canals (Table 1).

Occurrence and Abundance

Three canals (Snake Creek, Biscayne, and Miami canals) were repeatedly sampled using standardized methods to monitor the spread and changes in abundance of Asian swamp eel through time. The number of eels observed but not collected was recorded for each sample in order to calculate capture efficiencies. Capture efficiencies were calculated by dividing the number collected by the sum of the number collected and number observed multiplied by 100. Beginning in late 1998, other canals in coastal southeast Florida were electrofished to determine the presence and relative abundance of Asian swamp eel.

Electrofishing was conducted using a Smith-Root™ Model GPP-7.5 or GPP-9.0 electrofisher (Vancouver, WA) adjusted to 680 volts DC (direct current) and 120 pps (pulses per second) that generated 8–10 amps between 6.4-mm diameter stainless steel cable electrodes. Two 1.3-m anodes and three 3.1-m cathodes were suspended from two fiberglass booms that extended 2.5 m in front of the 5.5-m aluminum jon boat. All electrofishing was conducted using one person to dip fish and one to drive the boat.

Standardized electrofishing in Snake Creek Canal consisted of the same transects electrofished for 15 min (900 sec) of pedal time at 12-month intervals, some of which were conducted during the day and others at night. In daytime October 1998–2008 samples (3 transects) all fish species were collected; however, only Asian swamp eel were targeted during February 1998–2002 and 2008 samples (6 day and 6 night transects, no samples taken during February 2003–2007; Table 1).

Annual electrofishing catch rates for Asian swamp eel and co-occurring fishes were analyzed using coefficients of correlation (r) as a preliminary screen to determine if the presence of swamp eel might be detrimentally affecting the abundance of other fishes. For the purposes of this study, strong correlations were arbitrarily defined as those with coefficient values greater or less than ± 0.60 and p-values ≤ 0.05, while those between ± 0.50 to ± 0.60 were considered to be moderately correlated.

When only Asian swamp eel were targeted, a 5-mm ace-mesh dip-net was used, which retained most eels >159 mm total length (TL). When all fish species were targeted, a larger, 13-mm ace-mesh dip-net was used, but this netting permitted swamp eel as large as 350-mm TL to pass through.

In the Biscayne Canal only Asian swamp eel were targeted in quarterly standardized samples taken at 11 transects (5 daytime, 6 nighttime) between December 1999 and August 2003. This directed effort was done to monitor the dispersal of Asian swamp eel after a localized population was discovered at the west end of this canal in May 1999. Similarly, a 1999 standardized Miami Canal electrofishing sample was repeated in 2001. The Aerojet, C-113, and other southeast Florida canals were electrofished between 1998 and 2008, and the Little Manatee River was sampled twice (2001 and 2005), but these samples were performed primarily to determine only the presence or absence of swamp eels. Sampling was not standardized nor nearly as extensive in the Aerojet Canal, C-113, or the Little Manatee River as it was in Snake Creek, Biscayne, and Miami canals.

Fish Community Analyses

Standing crop estimates of fishes in the main Snake Creek Canal were calculated using data from a single 0.185-ha shoreline blocknet sample taken in June 1987, four in January 1999 and May 2000, and two in May 2001 and 2005 using the concussion methodology described by Metzger and Shafland (1986).

In these samples, we attempted to kill all the fishes within the netted-off area using 50-grain detonating cord. Floating fish were picked up for three days, sorted by species, measured, counted, and weighed.

Early electrofishing data indicated Asian swamp eel were most abundant in shallow, shoreline, vegetated areas; hence, fish communities in areas with more vegetation were compared to those with less vegetation. In 2002 the amount of vegetation was more carefully quantified than in previous years by using a tape measure to estimate the areas of coverage and using a grappling hook to collect vegetation in water too deep for it to be seen. That year the more-vegetated site contained 3–4 m of dense shoreline Fanwort (*Cabomba caroliniana*), which extended into and covered about 26% of the blocknetted area, plus an additional 10% was covered with less dense Fanwort. At the same time, the less-vegetated site had a 1-m wide shoreline fringe of Torpedo Grass (*Panicum repense*), very small amounts of Soft Rush (*Juncus effusus*), Duck Potato (*Sagittaria lancifolia*), and some filamentous algae, but no submersed aquatics were recovered from the remainder of the blocknetted area during 14 throws of a grappling hook.

Life History

Electrofished Asian swamp eel were immediately placed on ice and later measured (mm), weighed (g), and sexed. Stomach contents of swamp eel (>250-mm TL) were excised by cutting along the abdomen from the head to the anus and the contents identified. The digestive tract was pinched off as close to the head as possible and then slit to the valve separating the stomach from the intestines and the contents removed. The stomach is a straight, thin-walled, elastic tube, visually discernable only when containing food. Volumetric measures of each prey type (nearest 0.1 ml) were determined for all eels that had identifiable stomach contents in order to calculate Index of Relative Importance values,

$$\text{IRI} = \%F(\%N + \%V) \times 100$$

where F is frequency of occurrence in stomachs, N is total number, and V is volumetric displacement of prey organisms (Liao et al., 2001).

Asian swamp eel were collected quarterly from Biscayne Canal and their gonads were removed by dissection. Immature testes were distinguished by their uniform thread-like appearance, but transitional males required microscopic examination to determine the presence of both eggs and testicular tissue. Fecundity (total number of ready-to-spawn eggs) was gravimetrically estimated for 12 ripe females by weighing a subsample of about 100 eggs/fish.

Lower lethal temperatures of Asian swamp eel collected from Snake Creek Canal (TL = 272–739 mm) were identified between February 24 and March 29, 1999, using the same temperature control system and methods described in Shafland and Pestrak (1982). Three swamp eel were acclimated in each of six 190-l experimental and two control tanks at the water temperature from which they were collected (22°C); however, one swamp eel died of unknown causes, reducing the number of test eels to 17, plus 6 were used for controls. Swamp eel were fed live earthworms, and, after the acclimation period, water temperatures in the experimental tanks were decreased 1°C/day until all test fish had died.

Asian swamp eel exhibit two color varieties, the darker olive-drab brown variety dominates the much less frequently encountered lighter variety, some of which are distinctively spotted or blotched with black (Nichols, 1943). The ratio of darker- to lighter-colored swamp eel found in different canal populations was calculated.

Asian swamp eel ($n = 10$, mean = 695-mm TL and 542 g, range = 600- to 813-mm TL, and 348 to 831 g) collected from Snake Creek Canal in February 2002 were analyzed for total mercury. These fish were electrofished, immediately placed on ice, frozen within a few hours, and shipped to the Florida Fish and Wildlife Conservation Commission's Eustis Fisheries Research Laboratory to be analyzed for total mercury concentrations in their edible muscle tissue per EPA Method 245.6 (U.S. Environmental Protection Agency (USEPA), 1991).

RESULTS

Occurrence and Abundance

Overall electrofishing capture efficiency for Asian swamp eel was 48%, with 2,012 being caught out of a total 4,211 observed (i.e., 2,199 avoided capture). Capture efficiencies ranged from 25–52% from six canals, but the two canals sampled most (Snake Creek and Biscayne) yielded similar capture efficiencies of 48% ($n = 2{,}488$) and 52% ($n = 1{,}316$).

Snake Creek Canal

Asian swamp eel have been widespread and abundant throughout Snake Creek Canal since 1998, but none have been collected on the west side of the S-30 water control structure where it intersects with the L-33 Canal (Figure 1). Catch rates were highest and sometimes exceeded 2.00 eels/min in transects having a shallow (<1 m deep) shelf comprised of sand or silt substrate covered with aquatic vegetation and a shoreline fringe of Torpedo Grass. The mean Snake Creek Canal catch rate when only swamp eel were targeted was 1.10 eels/min ($n = 6$; SD = 0.17) for standardized samples taken from 1998–2002 and again in 2008. During these same 6 years, annual swamp eel catch rates were 1.00 (167 min), 1.00 (182 min), 1.14 (184 min), 1.20 (184 min), 1.37 (181 min) and 0.88 eels/min (181 min; Figure 2). The 1998–2002 5-year mean was 1.14 fish/min (SD = 0.15), which was considerably higher than the 2008 catch rate of 0.88 eels/min.

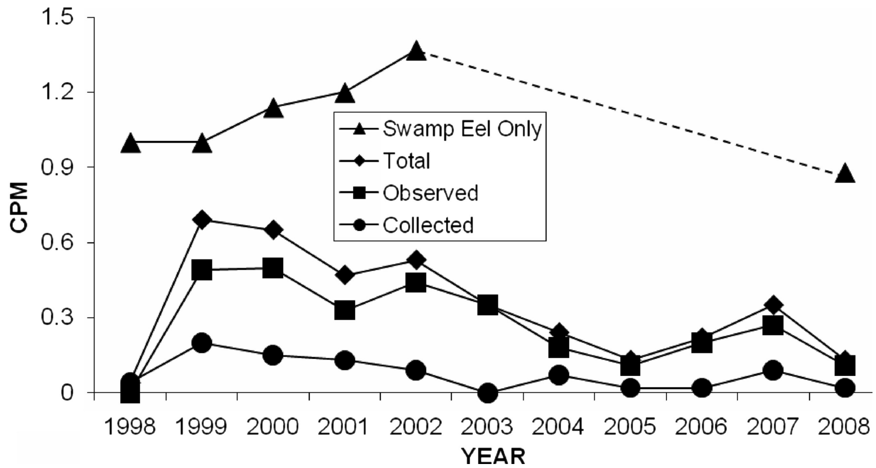

Figure 2 Standardized Asian swamp eel electrofishing catch rates from Snake Creek Canal, Florida, from 1998 to 2008 (CPM = catch per pedal minute; total is number of swamp eels collected plus number observed; swamp eel "only" refers to standardized electrofishing samples, wherein only swamp eel were targeted; dashed line indicates sampling not done).

Snake Creek Canal standardized multi-species samples yielded Asian swamp eel catch rates of 0.00–0.20 eels/min (mean = 0.08; SD = 0.06; Figures 2 and 3). This 11-year sampling period was arbitrarily divided into two time periods, and the first five annual samples yielded a mean of 0.12 (range = 0.04–0.20; SD = 0.06) eels/min versus the last six-year mean of 0.04 (range = 0.00–0.09; SD = 0.04) eels/min. In these same samples, the combined number of swamp eel collected and observed ranged from 0.04–0.69 (mean = 0.35; SD = 0.22) eels/min, and the first five versus last six-year mean was 0.48 (range = 0.04–0.69; SD = 0.26) versus 0.24 (range = 0.13–0.35; SD = 0.10) eels/min. No strong or moderately negative correlation coefficients existed between the catch rates of swamp eel and any other fish species present in Snake Creek Canal, although their abundance was positively correlated with Spotted Sunfish (*L. punctatus*) of all sizes ($r = +0.74$, $p = 0.01$).

Biscayne Canal

The 5-year (1999–2003) single-species composite catch rate for Asian swamp eel in the western six transects of the Biscayne Canal was 0.93 eels/min (729 pedal min). No swamp eel were collected in the eastern half of this canal until August 2003, when five were caught (0.07 eels/min) and eight observed (collected plus observed = 0.12 eels/min). The five-year catch rates at six transects in the western half of this canal, starting at the westernmost transect where the swamp eel was first found and

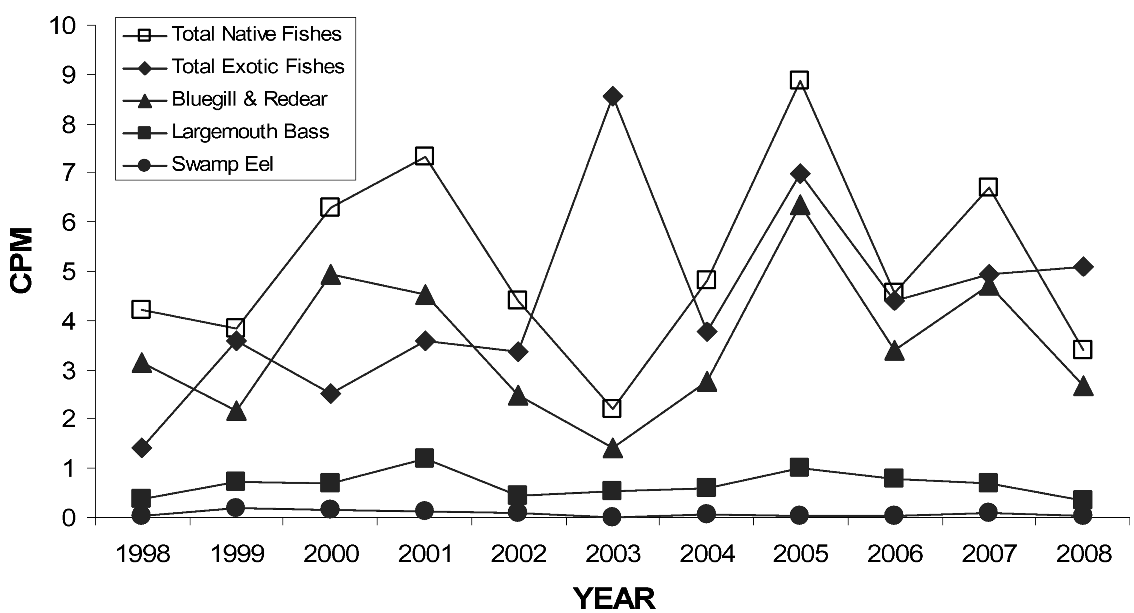

Figure 3 Standardized annual daytime electrofishing catch rates for selected fishes from Snake Creek Canal, Florida (CPM = catch per pedal minute; all samples taken annually in October or November at same three 15-minute transects).

Table 2 Main Snake Creek Canal standing crop estimates from 1987–2005 based on one blocknet in 1987, the composites of four each in 1999 and 2000, and two each in 2001, 2002, and 2005 (KG/HA = kilograms per hectare; N/HA = number per hectare; no Asian swamp eels were collected in these samples)

Parameter	June 1987	January 1999	May 2000	May 2001	May 2002	May 2005	Mean (SD)
KG/HA	221[a]	84[b]	76[c]	216[d]	115[e]	35[f]	125 (77)
Native fish	129	24	41	72	49	14	55 (42)
Gamefish	48	26	40	61	30	14	37 (17)
Redear sunfish	19	9	18	19	8	8	14 (7)
Bluegill	11	5	11	20	5	5	10 (6)
Largemouth bass	15	3	5	7	5	0.4	6 (5)
Bluefin killifish	0.01	0.04	0.20	0.10	0.01	0.03	0.07 (0.07)
N/HA	5,135	1,369	3,661	3,870	2,768	2,776	3,263 (1,273)
Native fish	2,735	856	3,064	3,594	2,130	1,873	2,375 (970)
Gamefish	1,811	669	1,488	1,619	1,365	1,546	1,416 (395)
Redear sunfish	492	219	373	308	311	257	327 (96)
Bluegill	892	201	538	968	630	1,143	729 (341)
Largemouth bass	162	14	81	162	65	24	85 (65)
Bluefin killifish	54	111	742	297	19	54	213 (278)
Total species	22	28	28	25	24	24	25 (2)
Native species	18	19	21	20	16	16	18 (2)
Exotic species	4	9	7	5	8	8	7 (2)

[a] 1987: 2% of total biomass contributed by one Orinoco sailfin catfish (*Pterygoplichthys multiradiatus*); <1% by number); no grass carp (*Ctenopharyngodon idella*) collected; spotted tilapia (*Tilapia mariae*) made up 38% of biomass (46% by number); spotted tilapia, striped mullet (*Mugil cephalus*), and Florida gar (*Lepisosteus platyrhincus*) collectively made up 70% of biomass.
[b] 1999: 25% of total biomass contributed by one grass carp (<1% by number); 18% by 20 Orinoco sailfin catfish (2% by number).
[c] 2000: 8% of total biomass contributed by five Orinoco sailfin catfish (<1% by number); no grass carp collected.
[d] 2001: 46% of total biomass contributed by six grass carp (<1% by number), 15% by 18 Orinoco sailfin catfish (1% by number), and 5% by one tarpon (*Megalops atlantica*; <1% by number); therefore, 25 fish (<2% by number) made up 67% of total biomass.
[e] 2002: Most of biomass increase due to Orinoco sailfin catfish (45 kg/ha; $n = 23$), Florida gar (13 kg/ha; $n = 4$), grass carp (10 kg/ha; $n = 2$), and common snook (*Centropomis undecimalis*; 8 kg/ha; $n = 2$). Collectively, these species comprised 66% of total biomass but only 3% by number.
[f] 2005: 23% of total biomass contributed by five Orinoco sailfin catfish (1% by number); no grass carp collected.

progressing eastward were 2.23 (122 min), 1.56 (138 min), 0.79 (100 min), 0.23 (104 min), 0.39 (130 min), and 0.32 (136 min) eels/min. Similarly, the annual catch rates of swamp eel from the western six transects combined were 0.54 (131 min) in 1999, 1.08 (178 min) in 2000, 0.89 (167 min) in 2001, 1.05 (169 min) in 2002, and 1.07 (84 min) eels/min in 2003.

Miami Canal

In the easternmost 34 km of the Miami Canal between water control structures S-26 and S-32, the catch rate of Asian swamp eel in 1999 was 0.66 eels/min (114 min). This value remained unchanged two years later when the same six transects were again sampled. In both of these samples (1999 and 2001), the three same and otherwise similar transects yielded 83 and 99% of all the eels collected. Four years later (October 2003), swamp eel had dispersed throughout this section of the Miami Canal, although they remained most abundant in the same areas they had been previously.

Aerojet Canal

Asian swamp eel were collected in small numbers ($n = 0$–5/sample) from the lower portion of the Aerojet Canal from 2000 to 2002 until August 2003, when 18 were caught and 45 observed (caught plus observed = 1.11 eels/min). The abundance of swamp eel continues to slowly increase in this canal.

Other Areas

Three Asian swamp eel were collected (0.04 eels/min; 70.1 pedal min) and six observed in the Little Manatee River in 2001, and six more were collected (0.23 eels/min; 26.4 pedal min) in 2005. The first record of swamp eel in Tamiami Canal was in October 2007 (one collected and three observed).

Snake Creek Canal Standing Crop Estimates

Standing crop estimates taken between 1987 and 2005 for the Snake Creek Canal fish community averaged 125 kg/ha (SD = 77) and 3,263 fish/ha (SD = 1,273; Table 2). Although 40 fish species were collected (10 exotic), no Asian swamp eel were recovered in these samples.

Vegetated sites sampled in 1987, 2001, and 2002 yielded the highest standing crop estimates (216–341 kg/ha; 3,340–5,351 fish/ha; Table 3). Between 1999 and 2005, the number of fishes collected from the vegetated sites collectively averaged approximately three times more than those from less-vegetated areas (Table 3). In 2002, when the amount of vegetation was more carefully assessed (see methods), the more-vegetated sample

Table 3 Comparison of fish communities in more- versus less-vegetated shoreline areas of Snake Creek Canal from 1999 to 2005 (KG/HA = kilograms per hectare; N/HA = number per hectare; no Asian swamp eel collected in these samples)

	More Vegetated						Less Vegetated						Overall
Parameter	1999	2000	2001	2002	2005	Mean	1999	2000	2001	2002	2005	Mean (SD)	Mean (SD)
KG/HA[a]	127	82	341	216	34	160 (121)	40	69	90	14	36	50 (30)	105 (102)
Native fish	31	45	95	90	16	55 (35)	17	37	49	9	12	25 (17)	40 (31)
Gamefish	36	44	82	51	17	46 (24)	17	37	39	8	11	22 (15)	34 (22)
Redear sunfish	12	21	24	10	7	15 (7)	6	15	15	5	8	10 (5)	12 (6)
Bluegill	6	14	25	10	7	12 (8)	3	8	16	1	3	6 (6)	9 (7)
Largemouth bass	6	3	8	10	1	6 (4)	0.4	8	6	1	0.1	3 (4)	4 (4)
Bluefin killifish	0.02	0.4	0.2	0.03	0.04	0.14 (0.16)	0.05	0.03	0.06	–	0.01	0.03 (0.03)	0.09 (0.13)
N/HA	1,538	5,857	5,351	5,211	3,340	4,259 (1,796)	1,200	1,465	2,389	324	2,211	1,518 (832)	2,889 (1,957)
Native fish	889	5,027	5,065	4,006	2,470	3,491 (1,797)	881	1,100	2,124	254	1,276	1,127 (678)	2,309 (1,787)
Gamefish	781	2,078	1,957	2,486	2,070	1,874 (643)	557	897	1,281	243	1,022	800 (406)	1,337 (760)
Redear sunfish	305	481	389	546	341	412 (100)	132	265	227	76	173	175 (75)	294 (150)
Bluegill	203	814	1,276	1,205	1,632	1,026 (544)	200	262	660	54	654	366 (276)	696 (535)
Largemouth bass	24	97	141	108	38	82 (49)	3	65	184	22	11	57 (75)	69 (61)
Bluefin killifish	57	1,373	449	38	49	393 (575)	165	111	146	—	60	96 (67)	245 (416)
Total species	22	26	21	24	21	23 (2)	22	19	18	11	19	18 (4)	20 (4)
Native species	13	19	16	16	13	15 (3)	15	12	14	7	14	12 (3)	14 (3)
Exotic species	9	7	5	8	8	7 (2)	7	7	4	4	5	5 (2)	6 (2)

[a]Values are composites of two vegetated and two non-vegetated blocknet sites for 1999 and 2000; only one blocknet site sampled in 2001, 2002, and 2005; 1999 samples were done in January, all others in May.

yielded 24 species and >15 times the number and weight of fishes than did the 11 species collected from the less-vegetated area (Table 4). Moreover, the 2002 more-vegetated site yielded 30 times more small fish (<60-mm TL; 3,719 versus 124 fish/ha) weighing 12 times more than those collected from the less-vegetated site (8.9 versus 0.73 kg/ha). Overall, the composite standing crop estimates for fishes <60-mm TL (1999–2002, 2005) from the more- versus less-vegetated sites were 2,480 versus 756 fish/ha and 5.5 versus 2.4 kg/ha.

Table 4 Comparison of fish communities in a more- versus less-vegetated shoreline area of Snake Creek Canal based on two 0.185-ha blocknet samples in May 2002 (KG/HA = kilograms per hectare; N/HA = number per hectare)

Parameter	More Vegetated	Less Vegetated	Difference (%)
KG/HA	216	14	202 (−94)
Native fish	90	9	81 (−90)
Gamefish	51	8	43 (−84)
Redear sunfish	10	5	5 (−50)
Bluegill	10	1	9 (−90)
Largemouth bass	10	1	9 (−90)
N/HA	5,211	324	4,887 (−94)
Native fish	4,006	254	3,752 (−88)
Gamefish	2,486	243	2,243 (−79)
Redear sunfish	546	76	470 (−86)
Bluegill	1,205	54	1,151 (−96)
Largemouth bass	108	22	86 (−80)
Total species	24	11	13 (−54)
Native species	16	7	9 (−56)
Exotic species	8	4	4 (−50)

Life History

Stomach Contents

Of the 729 Asian swamp eel stomachs examined, 199 (27%) contained food items, 107 (15%) of which contained prey that could be identified to species level (Table 5). The percentage of stomachs with food and relative importance of the major prey groupings were similar for swamp eel collected during the day or at night (Table 6). Fish and fish remains were found in 111 of 199 (56%) swamp eel stomachs containing food, followed in decreasing frequency by crustaceans (32%) and insects (27%; Table 5). Fish also were the most common prey category numerically, making up 44% of the 299 prey items identified, followed by crustaceans (24%) and insects (21%). Swamp eel consumed more Swamp Darter (*Etheostoma fusiforme*), Bluefin Killifish (*Lucania goodie*), crayfish, and dragonfly nymphs than other species, along with a wide variety of other prey species that included a small turtle (32 × 16 × 10 mm) and head of a snake.

The highest IRIs in the 107 Asian swamp eel containing identifiable prey items were fish (5,145), crustaceans (1,564), and insects (576), and 49% of these stomachs contained fish that made up 40% by number and 65% by volume of the prey consumed (Table 7). In swamp eel <400-mm TL, insects were proportionately more important than crustaceans, ranking second to fish. Overall, fish was also the most important prey category being found in 56% of the stomachs ($n = 199$) and making up 44% by number of all the prey consumed (Table 5). The smallest swamp eel that had eaten a fish measured 266-mm TL. Positively identified fish in swamp eel stomachs included 14 species and 46 individuals, the most abundant (65%) of which

Table 5 Identifiable stomach contents from Asian swamp eel collected from Snake Creek, Biscayne, and Miami canals between September 1998 and February 2002 (199 of 729 stomachs contained prey, FO = frequency of occurrence or number of stomachs containing identifiable prey; N = total number of identified prey from all stomachs)

	Stomachs with Identifiable Prey Items			
Prey Category	FO	%FO	N	%TN
Fish	111	56	133	44
Unidentified fish	72	35	87	29
Swamp darter	10	5	12	4
Bluefin killifish	8	4	13	4
Eastern mosquitofish	5	3	5	2
Asian swamp eel	3	2	3	1
Golden topminnow	2	1	2	1
Fat sleeper	2	1	2	1
Largemouth bass	2	1	2	1
Mayan cichlid	1	<1	1	<1
Tadpole madtom	1	<1	1	<1
Bluegill	1	<1	1	<1
Jaguar guapote	1	<1	1	<1
Jewelfish	1	<1	1	<1
Black acara	1	<1	1	<1
Spotted sunfish	1	<1	1	<1
Crustaceans	63	32	72	24
Crayfish	37	19	37	12
Grass shrimp	26	13	35	12
Insects	54	27	64	21
Unidentified insects	23	11	23	8
Dragonfly nymph	29	14	40	13
Mayfly nymph	1	1	1	<1
Beetle	1	1	1	<1
Molluscs	7	4	9	3
Snail	7	4	9	3
Other	5	3	6	2
Frog	2	1	2	1
Turtle	1	1	1	<1
Snake's head	1	1	1	<1
Fish eggs	1	1	2	1
Unidentified prey	12	6	15	5
Total[a]	199		299	
Invertebrates	124	62	145	48
Fish	111	56	133	44
Other	5	3	6	2
Unidentified prey	12	6	15	5
Stomachs with food	199	27		

[a]Since more than one category of prey item were found in some stomachs, the total number of stomachs containing prey items (FO) is not a simple sum.

were Bluefin Killifish (n = 13), Swamp Darter (n = 12), and Eastern Mosquitofish (*Gambusia holbrooki* (n = 5; Table 5).

Seven hundred Asian swamp eel stomachs were examined from Snake Creek Canal (n = 476) and Biscayne Canal (n = 224). The percentages of stomachs containing food (25% versus 30%), frequency of fish present (55% versus 48%), and percentage of prey items represented by fish (46% versus 47%) were similar in both of these canals. However, the frequency and percentage by number of crustaceans was greater in the stomachs of Biscayne Canal eels (43% and 36%) than the Snake Creek Canal fish (26% and 21%). Overall, IRI values for fish and crustaceans in Snake Creek Canal were 5,936 and 1,188, while in Biscayne Canal these components were similar in magnitude though reversed in relative importance (2,449 for fish and 3,198 for crustaceans).

Predator-Prey Sizes

A total of 65 minimally digested fish with a mean standard length (SL) of 34 mm (range = 6–202-mm SL, SD = 29) were recovered from Asian swamp eel stomachs. The mean ratio of prey SL to predator TL (range = 303–756, mean = 496-mm TL, SD = 112, n = 54) expressed as a percentage was 7.0% (range = 1.7–44.1%, SD = 6.5; Table 8). The standard lengths of only two prey fish were >13% of the swamp eel's length that ate them, and the prey eaten in both of these cases were cannibalized swamp eel measuring 145 and 202 mm (38.6% and 44.1% of the consuming swamp eels' length). The overall mean percentage decreased from 7.0% to 5.9% when three cannibalized swamp eels were omitted from this calculation. Mean SL:TL of prey to predator expressed as a percentage decreased with increasing swamp eel size from 8.2, 7.0, and 5.5% for eels measuring 250–399, 400–599, and >599-mm TL. The longest identifiable fish that was not a swamp eel was a 68-mm SL Bluegill (*Lepomis macrochirus*) eaten by a 751-mm TL swamp eel (SL:TL = 9.1%; Table 8).

Length/Sex Relationships

Of 665 Asian swamp eel that were positively sexed, 93% (n = 620) were females, 6% (n = 42) were males, and <1% (n = 3) were transitioning from females to males. In Snake Creek Canal, 90% (n = 367) of sexed swamp eels were females, 9% (n = 38) were males, and 1% (n = 3) were transitioning from females to males. In Biscayne Canal, 98% (n = 213) were females and 2% (n = 4) were males. All 40 sexed swamp eel examined from Miami Canal were females.

In Snake Creek, female Asian swamp eel ranged from 229- to 774-mm TL and males from 505- to 855-mm TL, and all six swamp eel >774-mm TL were males. The smallest mature female swamp eel measured 318-mm TL, while the smallest male was 537-mm TL. Swamp eel transitioning from female to males (n = 3) ranged from 694- to 782-mm TL. Of the sexed fish >300-mm TL (n = 390), 10% were males, while 23% of the sexed fish >500-mm TL were males. The percentage of males typically increased with each 50-mm TL group >500-mm TL from 6, 5, 13, 30, 42, 71, and 100% (Figure 4).

In Biscayne Canal, female Asian swamp eel ranged from 241- to 680-mm TL, and males from 434- to 688-mm TL. The smallest mature female swamp eel measured 330, and the only mature male captured measured 688-mm TL. Only four of 217 (2%) sexed swamp eel were males, and these averaged 550-mm TL (SD = 124 mm). The smallest mature female Asian swamp eel in all canals was 318-mm TL, and of 602 swamp eel >318-mm TL, 93% (n = 560) were females. Similarly, the smallest mature male observed was 434-mm TL, and of 387 swamp eel

Table 6 Day-night comparison of identifiable prey from 729 Asian swamp eel stomachs, 107 of which contained identifiable prey from Snake Creek, Biscayne, and Miami canals (parentheses indicate total number of stomachs containing specified prey, total number of prey identified, or total volume of prey category in stomachs)

	Day				Night				
Food Category	Frequency	Number	Volume	Day IRI	Frequency	Number	Volume	Night IRI	Overall IRI
Fish	50 (26)	39 (36)	75 (47.4)	5,700	47 (26)	41 (31)	57 (45.6)	4,606	5,145
Crustaceans	35 (18)	22 (20)	15 (9.3)	1,295	33 (18)	28 (21)	26 (20.8)	1,782	1,564
Insects	35 (18)	27 (25)	6 (3.9)	1,155	15 (8)	12 (9)	2 (1.5)	210	576
Molluscs	6 (3)	5 (5)	1 (0.6)	36	4 (2)	3 (2)	1 (0.8)	16	25
Other[a]	—	—	—	—	7 (4)	7 (5)	11 (8.7)	126	36
Unidentified prey	10 (5)	7 (6)	3 (1.8)	100	13 (7)	9 (7)	4 (3.0)	169	121
Totals	52	92	63.0		55	75	80.4		
Total stomachs	171				156				
Stomachs w/food	52 (30%)				55 (35%)				

[a]Other = small turtle, head of a snake, fish eggs, frog.

Table 7 Index of relative importance and percent composition of six major prey categories based on 729 Asian swamp eel stomachs examined, 107 of which contained identifiable prey (swamp eels were collected from the Snake Creek, Biscayne, and Miami canals from 1998–2002; parentheses indicate total number of prey identified, total number of stomachs containing specified prey, or total volume of prey category in stomachs)

Prey Category	Frequency of Occurrence	Percentage of Prey Items	Percentage of Prey Volume	Index of Relative Importance
All eels ($n = 107$)				
Fish	49 (52)	40 (67)	65 (93.0)	5,145
Crustaceans	34 (36)	25 (41)	21 (30.1)	1,564
Insects	24 (26)	20 (34)	4 (5.4)	576
Molluscs	5 (5)	4 (7)	1 (1.4)	25
Other[a]	4 (4)	3 (5)	6 (8.7)	36
Unidentified prey	11 (12)	8 (13)	3 (4.8)	121
Total	107 stomachs	167 prey items	143.4 ml	
<400-mm TL				
Fish	57 (12)	40 (14)	53 (4.6)	5,301
Crustaceans	24 (5)	20 (7)	24 (2.1)	1,056
Insects	38 (8)	29 (10)	18 (1.6)	1,786
Molluscs	5 (1)	9 (3)	3 (0.3)	60
Unidentified prey	5 (1)	3 (1)	1 (0.1)	20
Subtotal	21 stomachs	35 prey items	8.7 ml	
400- to 599-mm TL				
Fish	43 (26)	36 (33)	58 (45.0)	4,042
Crustaceans	37 (22)	26 (24)	25 (19.6)	1,887
Insects	22 (13)	18 (16)	4 (2.7)	484
Molluscs	5 (3)	3 (3)	1 (0.5)	20
Other[a]	5 (3)	4 (4)	7 (5.7)	55
Unidentified prey	17 (10)	12 (11)	6 (4.6)	306
Subtotal	60 stomachs	91 prey items	78.1 ml	
≥600- mm TL				
Fish	54 (14)	49 (20)	77 (43.4)	6,804
Crustaceans	35 (9)	24 (10)	15 (8.4)	1,365
Insects	19 (5)	20 (8)	2 (1.1)	760
Molluscs	4 (1)	2 (1)	1 (0.6)	12
Other[a]	4 (1)	2 (1)	0.2 (0.1)	10
Unidentified prey	4 (1)	2 (1)	5 (3.0)	40
Subtotal	26 stomachs	41 prey items	56.6 ml	

[a]Other = turtle, head of a snake, fish eggs, frog.

Table 8 Ratio of prey length to predator length for 65 measureable prey fish found in stomachs of Asian SWAMP Eels (prey SL/predator TL × 100). Number in parenthesis is the number of specimens that could be measured in all stomachs examined

	Prey Standard Length/Swamp Eel Total Length Ratio (%)		
Fish Category	Mean (*n*)	Minimum	Maximum
Asian swamp eel	30.6 (3)	10.1	44.1
Bluegill	9.1 (1)	—	—
Fat sleeper	8.6 (2)	7.3	9.9
Largemouth bass	8.2 (1)	—	—
Jewelfish	8.0 (1)	—	—
Spotted sunfish	7.6 (1)	—	—
Black acara	7.5 (1)	—	—
Swamp darter	7.2 (12)	4.2	10.9
Golden topminnow	7.0 (2)	6.3	7.8
Tadpole madtom	6.4 (1)	—	—
Unidentified fish	5.4 (23)	2.2	13.1
Mosquitofish	5.3 (4)	4.7	6.1
Bluefin killifish	4.5 (12)	1.7	6.3
Mayan cichlid	3.3 (1)	—	—
Overall	7.0 (65)	1.7	44.1

>434 mm, 11% were males, while 31% of the 110 swamp eel >600-mm TL and 56% ($n = 34$) >700-mm TL were males. The percentage of males generally increased with each 50-mm group from 500- to >800-mm TL from 4, 3, 14, 30, 42, 56, and 100%.

Fecundity

The estimated number of eggs in 12 ripe female Asian swamp eel (450- to 576-mm TL) averaged 439 (range = 268–642). The number of eggs per gram body weight for whole ripe females ranged from 1.6 to 3.5 and averaged 2.7. Swamp eel eggs from ripe females were slightly oval in shape, light yellow in color, and averaged 2.9 mm long and 2.6 mm wide. Fourteen of 15 ripe female Asian swamp eel were collected in June (2000 and 2001) and one in March (2001), suggesting some spawning occurs during these months.

Lower Temperature Tolerances, Coloration, and Mercury Concentration

Individual Asian swamp eel reduced feeding between 16–17°C, stopped feeding at 14–16°C, and died at 8–9°C. Snake Creek Canal contained 8% (82 of 1,051) lightly colored swamp eels, while Biscayne Canal contained 2% (14 of 702). No light-colored swamp eel were collected from C-113 ($n = 120$), Miami Canal ($n = 50$), or Aerojet Canal ($n = 23$). Mercury concentrations in edible muscle tissue from large Snake Creek Canal swamp eel ranged from 0.05 to 0.22 ppm (T. R. Lange, Florida Fish and Wildlife Conservation Commission, personal communication).

DISCUSSION

After being discovered in Snake Creek Canal in 1997 (USGS, 1998), the Asian swamp eel was subsequently found in several canals further south (e.g., Little River—October 1998, Miami—October 1998, Biscayne—May 1999, C-113—late 1999, Aerojet—January 2000, and Tamiami—October 2007); however, no swamp eel have been collected north or west of Snake Creek Canal in southeast Florida, even though they have water access to these areas. The primary reason for this is the physical barriers (i.e., water control structures) that block the swamp eel's movement when closed and apparently become impassable when opened due to the resultant "downstream" current.

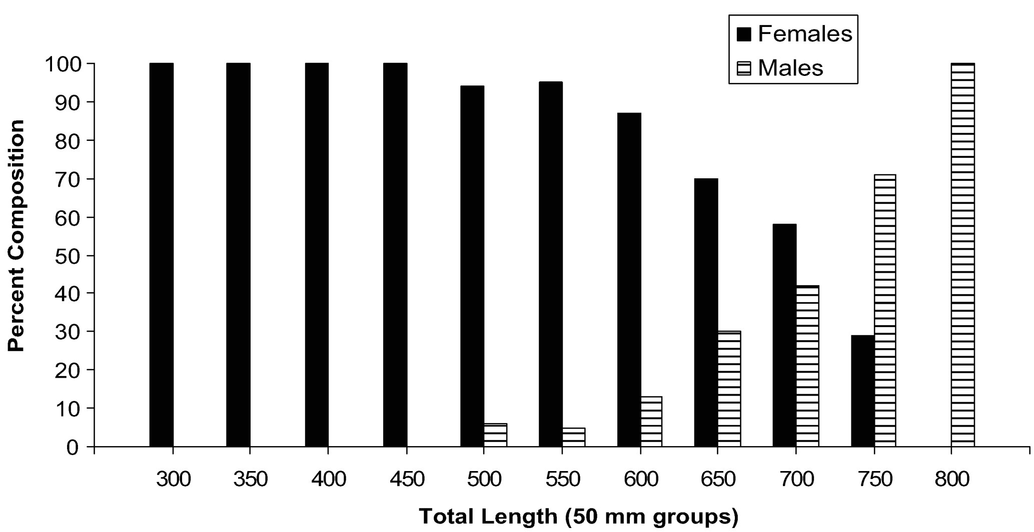

Figure 4 Percent composition of male and female Asian swamp eel ($n = 390$) from Snake Creek Canal, Florida, by 50-mm TL size groups ($n = 36, 47, 50, 52, 68, 40, 38, 27, 19, 7$, and 6). Three swamp eel measuring 694-, 770-, and 782-mm TL were "transitioning" from female to male and are not included in this histogram.

Based on electrofishing catch rates, Snake Creek Canal supports the largest population of Asian swamp eel in Florida and possibly the U.S. When only swamp eel were collected from this canal, their catch rates generally increased from 1999 to their highest level of 1.37 eels/min in 2002 (Figure 2), but when sampled again in 2008, the catch rate was 0.88 eels/min. Although it is possible the swamp eel densities were higher sometime between 2003 and 2007, these data suggest the maximum density of swamp eel in Snake Creek Canal correspond to electrofishing catch rates of around 1.40 eels/min. If so, this population would have peaked somewhere between 5 and 11 years after being discovered, and possibly as long as 10–20 years after being introduced.

In general, canal populations of Asian swamp eel have slowly increased in abundance and range even in the absence of physical barriers. For example, the 1999–2003 composite catch rate at the two westernmost transects of the 23-km long Biscayne Canal was 1.89 eels/min; yet, nearly inexplicably, none were captured in the eastern half of this canal until early 2003. Similarly, swamp eel were first collected from Everglades National Park marshes in December 2007 (M. Robinson, National Audubon Society, personal communication), even though they had direct access to these marshes for more than seven years. This slow expansion into Everglades' marshes was unexpected because the general consensus was that swamp eel would be quickly attracted to and flourish in these habitats (USGS, 1998; Prok, 2000; Bricking, 2002; Aquatic Nuisance Species Task Force (ANSTF), 2008).

Some reasons Asian swamp eel are slow to increase in abundance and spread to new areas may be due to their slow growth, sedentary nature, and the presence of very few males that need first to mature as females. Biscayne Canal is the best example of this slow-to-spread characteristic in that they had direct and uninterrupted water access throughout this 23-km long canal, yet for $\geq$5 years swamp eel were limited to the western half of the Biscayne Canal, where only 6% were $>$700-mm TL and 3% were males compared to 14% $>$700-mm TL and 9% males in the Snake Creek Canal population. Interestingly, the smallest male swamp eel collected in this study was 434-mm TL, and it came from Biscayne Canal, while the smallest male collected from Snake Creek Canal was 505-mm TL. This suggests males might start maturing at smaller sizes in younger populations than they do in more mature populations. Although slow to develop, given time, swamp eel can and do become quite abundant as evidenced by their presence in Snake Creek Canal.

The only exception to the slow-to-spread behavior of the Asian swamp eel was its southward expansion into the lower portion of the Aerojet Canal south of the S-18C water control structure (Figure 1). In 1999, swamp eel were discovered in the C-113 Canal, yet in January 2000 they began showing up $>$20 km south of this area, and DNA analyses confirmed they came from the C-113 population (Collins et al., 2002; T. M. Collins, Florida International University, personal communication). This exceptionally rapid range extension (i.e., $>$19 km in $<$12 months) was facilitated by large volumes of water flowing through two water control structures (S-177 and S-18C) that almost certainly carried swamp eel downstream, extending their range much more quickly than they would have otherwise.

Although Asian swamp eel were first found in Snake Creek in 1997 (USGS, 1998; Fuller et al., 1999; Collins et al., 2002), they were abundant there in 1998 when this study was initiated, suggesting they had gone undetected for several years. Swamp eel ($n = 43$, 75- to 607-mm TL) ages in Georgia were estimated to be up to 7–9 years (Freeman and Burgess, 2000), and eight large Florida eels (mean = 783-mm TL; range = 682- to 806-mm TL, 375–618 g) averaged 8.9 presumed annual growth rings in their otoliths (range = 5–16 rings; authors' unpublished data). Liem (1963) reported Asian swamp eel grew to 18- to 19-, 29- to 31-, 41- to 44-cm TL after 12, 24, and 36 months in the laboratory, and that these growth rates corresponded to those observed under natural conditions. Although the growth rate of swamp eel in Florida is likely faster than those reported by Liem (1963), their abundance when first discovered suggests they may have been first introduced into southeast Florida as early as the mid to late 1980s or more than a decade before being discovered in 1997.

Liem (1980) found that Asian swamp eel fed on small fishes, prawns, crayfish, snails, insect larvae, insects, frog eggs, tadpoles, and frogs in their native range. Yang et al. (1997) reported that, in addition to the previously mentioned prey items, swamp eel consume phytoplankton, benthic algae, and organic debris. Preliminary swamp eel studies in Georgia led to speculation that their food habits might vary depending on the presence or absence of other top predators because, in one pond with other predators, they fed nearly exclusively on aquatic insects, yet, in the absence of other predators, stable isotope analyses suggested larger swamp eel had become primary predators (Freeman and Burgess, 2000; Freeman et al., 2005; Straight et al., 2005; Hill and Watson, 2007).

In this study, Swamp Darter and Bluefin Killifish made up 54% by number (25 of 46) of the 14 identifiable fish species found in Asian swamp eel stomachs (Table 5), and these eels generally consumed relatively small prey with SLs that were 4–9% of their TL (Table 8). Due to the swamp eel's comparatively small mouth, the largest prey that a large eel (755-mm TL) can eat is about the same size as what a much smaller native largemouth bass (*Micropterus salmoides*; 220-mm TL) can eat (Lawrence, 1958; Hill and Watson, 2007).

Concern has been expressed that when the Asian swamp eel extends its range into the Everglades, it might seriously impact the small native fishes living there (USGS, 1998). The primary reason for this was that swamp eel have been described as voracious predators (Liem, 1998, p. 173; Starnes et al., 1998); however, about three-fourths of the Asian swamp eel stomachs examined in this study were empty, and the ones with food contained an average of only 1.5 prey items (299 items in 199 stomachs; Table 5). Freeman and Burgess (2000) stated their preliminary diet studies indicated Georgia swamp eel would have minimal direct impacts on other fishes. Hill and Watson (2007) examined Asian swamp eel from tropical fish culture ponds and found that more than 50% were empty. Based on these findings, we conclude that the swamp eel will likely have less detrimental effects on small native fishes than was once anticipated (see also Freeman and Burgess, 2000; Hill and Watson, 2007).

Asian swamp eel have been found in the stomachs of several largemouth bass collected from the wild, and largemouth bass will eat swamp eel in laboratory aquaria (authors' observations). Moreover, on two occasions, piscivorous wading birds have been observed eating swamp eel, and Freeman et al. (2005) similarly observed native predators (fish and wading birds) preying on swamp eel in Georgia. Some native species at least occasionally prey on swamp eel in Florida; however, to what extent they do remains an important question to be answered.

The Asian swamp eel's ability to live out of water when kept moist has intrigued scientists for more than 100 years (Day, 1899, and others cited in Wu and Liu, 1940; Chew et al., 2005). Swamp eel also commonly live in burrows beneath shallow waters (e.g., rice fields) in southern China, where it was "not uncommon to find dead specimens on muddy land in the dry season or living specimens wriggling over drying water holes to reach another nearby waterway, which is highly possible in the close agricultural network of rice farming in the region" (S. T. H. Chan, University of Hong Kong, retired, personal communication). The swamp eel is well adapted to these conditions because they breathe air, can go long periods without food, and are able to cope with high levels of accumulated ammonia (Ip et al., 2004; Chew et al., 2005). It has also been commonly reported that this species makes voluntary overland movements (Graham, 1997; USGS, 1998; Bricking, 2002; Gulf States Marine Fisheries Commission (GSMFC), 2003; Reinert et al., 2006); however, we could find no firsthand account of this behavior other than Liem's (1967, p. 382–383; brackets added) anecdotal observation that the swamp eel ". . . migrates in schools of 10–50 individuals across land from one [water] body to another . . . the exact distances covered during such migrations are unknown" (see also Liem, 1980, 1987, 1998).

In Florida, swamp eel have been observed along shallow edges of flooded roadside ditches (J. E. Hill, University of Florida Tropical Aquaculture Laboratory, personal communication), stranded in a small puddle of water (W. F. Loftus, U.S. Geological Survey, personal communication), and involuntarily leaving the water for brief periods to avoid being shocked by the electrofisher (authors' observations). We have never observed swamp eel making voluntary overland movements, nor did any of the scientists we contacted familiar with the swamp eel have any definitive evidence of this occurring. Hence, we question whether the swamp eel actually makes such voluntary movements over land (i.e., in the absence of at least some standing water), although they may attempt to do so if their immediate survival is threatened (e.g., during droughts or when dropped on land by a bird). Of course, in areas with differing climates, agricultural and water management practices, soil conditions, etc., they may do so, but, even so, such movements are likely much less frequent than is commonly assumed.

No Asian swamp eel were recovered in blocknets using detonating cord as the killing agent, and live swamp eel were electrofished from within the blocknetted areas immediately after the concussion even though the concussion did kill test eels suspended from fish stringers (authors' observations). Furthermore, dead swamp eel put into blocknetted areas after detonation were not recovered, even though a majority floated within three days when placed in covered control cages, ponds, or aquaria. Hence, concussion sampling is an ineffective tool for estimating the abundance of swamp eel.

Reducing or eliminating aquatic vegetation has been suggested as a means of controlling Asian swamp eel (ANSTF, 2008) because it is often abundant in shallow vegetated areas (Prok, 2000). However, our data and observations suggest this would be ineffective, as large concentrations of swamp eel in Snake Creek Canal were found in areas nearly devoid of vegetation, not to mention the beneficial effect of aquatic vegetation on small native fishes (Table 3). Furthermore, unrelated to this study, more than 32,000 triploid grass carp (*Ctenopharyngodon idella*) were stocked into Snake Creek Canal from 1999–2003 (G. Baker, South Florida Water Management District, personal communication). While triploid grass carp reduced aquatic vegetation, swamp eel remained abundant, indicating the intentional removal of vegetation to control swamp eel would be ineffective and more deleterious to small native fishes than to swamp eel.

Single-pass electrofishing is effective at capturing Asian swamp eel during the day and night (6-year means 1.12 eels/min during day versus 1.07 eels/min during night). However, the overall electrofishing capture efficiency for swamp eel was only 48%, and this was calculated based only on those eels that were seen and not collected, while numerous others surely got away unnoticed. Even though electrofishing is the best tool available for capturing and estimating the relative abundance of swamp eel in canals, it obviously underestimates their actual abundance (especially those smaller than 350-mm TL), although estimates of their actual abundance may be obtained using multi-pass depletion or mark-recapture methodologies (for discussions related to sampling swamp eel, see Reinert et al., 2006, and Schofield and Nico, 2007).

The laboratory-identified lower lethal temperature for the Asian swamp eel was 8°C, suggesting their potential range will be restricted to an area south of Jacksonville, FL (Shafland and Pestrak, 1982); however, swamp eel have unexpectedly survived for several years in a northern Georgia pond where temperatures have dropped below 5°C (Freeman and Burgess, 2000). Swamp eel may be able to survive further north than expected since they burrow into the substrate where the water temperatures may be warmer, or the genetically distinct Georgia population may have a different lower lethal temperature than those we tested from Snake Creek Canal (Collins et al., 2002).

To date, the longest unsexed Asian swamp eel we have collected measured 864-mm TL (683 g), while the longest male measured 855-mm TL (694 g) and the longest female was 774 mm (485 g), and the heaviest overall eel was a 910-g (766-mm TL) female. Only three of the 665 sexed swamp eel were transitioning from female to male, suggesting this transitional phase is of short duration (2–4 months, per Chan and Phillips, 1967); however, the three transitional fish from Florida (694- to 782-mm TL) were much larger than those reported from Hong Kong (350–450 mm; Chan and Phillips, 1967).

Some populations of Asian swamp eel contain individuals whose coloration differs from the typical dark olive-drab brown, with a light yellow-orange underside, suggesting genetic differences may also exist. Color differences range from a few light-colored spots to a calico pattern to an almost uniform pink to white coloration. In Florida, Snake Creek Canal contained the most light-colored swamp eel (8%), followed by Biscayne (2%), and no lightly colored swamp eel were collected from the other canals sampled.

The Asian swamp eel is a highly esteemed food in its native range (Smith, 1945), and, for this reason, it was deliberately released in Hawaii in the 1800s, where it is reported to have had negligible impacts on native species (Maciolek, 1984; Welcomme, 1988; Devick, 1991). The most common health advisory concerning human consumption of freshwater fishes in Florida is for mercury concentrations >0.5 ppm in their edible flesh. Mercury concentration in edible muscle tissue of all 10 swamp eel tested was <0.23 ppm. Based on what we now know, properly cooked swamp eel from Florida waters are safe for human consumption (Florida Department of Health (FLDOH), 2003). Live swamp eels are occasionally sold in Asian food markets and aquarium stores in the United States (Starnes et al., 1998; Prok, 2000; Collins et al., 2002), and though circumstantial, the swamp eel now in Florida waters likely originated from either or both of these sources.

Exotic fishes alter the energy flow within ecosystems wherever they exist, and some outside of Florida have had serious deleterious effects. Yet whether an exotic species is detrimental, innocuous, or even beneficial is based more on the observers' values than value-neutral scientific assessments (Shafland, 1996; Slobodkin, 2001). Partly because of this and the Asian swamp eel's unusual eco-morphological adaptations and catchy common name, the discovery of this species quickly led to sensationalized predictions that it would assuredly have serious detrimental effects. Unfortunately, such responses suggest the science of introduced species has progressed little since the walking catfish (*Clarias batrachus*) was discovered in Florida nearly 40 years ago (Idyll, 1969; Lachner et al., 1970; Santiniello, 2005; Morgan, 2009).

CONCLUSIONS

The Asian swamp eel was likely introduced into Florida waters in the mid to late 1980s or possibly early 1990s, and it is now abundant in four major southeast Florida canal systems, occurs in several others, and is also found in a few locations in coastal, west-central Florida. Since first being discovered in Snake Creek Canal in 1997, swamp eel have slowly increased in abundance and range, yet somewhat surprisingly few have been collected in nearby Everglades' marsh habitats.

No deleterious ecological effects were associated with the Asian swamp eel's illegal presence, although, to be identified, such effects would need to be dramatic because Florida's freshwaters are affected by numerous factors that likely dwarf its effects, if there are any. These factors include urban sprawl, controlled water flows and levels, climatic events such as drought and hurricanes, eutrophication, aquatic plant control operations, human exploitation of fishes via angling, and other land management practices.

Rather than a voracious predator that moves over land, the Asian swamp eel in Florida is better described as being an opportunistic predator that feeds on a wide variety of small fishes, crustaceans, and insects found in water. No swamp eel have been observed moving across land, and its current distribution pattern suggests that it does not do so. Swamp eel will likely continue to spread and increase in abundance during the next several decades, and this is cause for concern and further study. However, due to their relatively small mouths, weak swimming attributes, presumed poor vision, slow growth, other eco-morphological characteristics, and currently available data and observations, it seems unlikely the swamp eel will cause major ecological or economic disturbances in Florida. Nonetheless, given that the effects of illegally and largely randomly introduced species are difficult to predict, every reasonable and practical effort should be made to prevent future introductions of this type.

ACKNOWLEDGMENTS

We thank FWC colleagues Larry Connor, who assisted with statistical analyses, and Ted Lange, who provided the edible muscle mercury analyses. And we thank J. Fury, J. Galvez, S. Hardin, J. Hill, J. Kline, K. Liem, W. Loftus, J. Trexler, J. Williams, and J. Troxel for valuable personal communications. We also thank the following individuals for reviewing and providing valuable comments on early drafts of this paper: S. Hardin, T. Reinert, J. Troxel, C. Watson, and P. Zajicek.

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