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NOTE

Recent invasion of a Florida (USA) estuarine system by lionfish *Pterois volitans* / *P. miles*

Zachary R. Jud[1,*], Craig A. Layman[1], Jessica A. Lee[1], D. Albrey Arrington[2]

[1]Marine Sciences Program, Department of Biological Sciences, Florida International University, 3000 NE 151st Street, North Miami, Florida 33181, USA

[2]Loxahatchee River District, 2500 Jupiter Park Drive, Jupiter, Florida 33458, USA

ABSTRACT: The invasion by lionfish *Pterois volitans* and *P. miles* throughout the western Atlantic and Caribbean is emerging as a serious ecological problem. While lionfish have been identified on coral reefs and in other marine systems, additional ecosystems may be affected as the invasion spreads. Here we identify the first estuarine intrusion by lionfish in their invasive range. Lionfish (n = 211) were captured in the Loxahatchee River estuary (Florida, USA) between August 2010 and April 2011, with some individuals located as far as ~5.5 km from the ocean. Multiple size classes were documented (standard lengths ranged from 23 to 185 mm), and post-settlement juveniles were present throughout the sampling period. All individuals were found in close association with anthropogenically created habitats (e.g. docks, sea walls, submerged debris), suggesting that human-driven changes in habitat availability may facilitate estuarine invasion. Fifteen prey taxa were found in lionfish stomachs, with diets dominated by small shrimp. Since estuaries are already highly threatened by human impacts, and provide critical habitat for numerous commercially, recreationally, and ecologically important species, establishment of lionfish in these ecosystems is of particular concern.

KEY WORDS: Invasive species · Anthropogenic impacts · Habitat modification · Nursery habitat · Estuary · Diet · Fish · Loxahatchee River

INTRODUCTION

Estuaries are highly productive systems that provide some of the most valued ecosystem services at a global scale (Costanza et al. 1997, Granek et al. 2010), including habitat for numerous commercially, recreationally, and ecologically important species (Beck et al. 2001, Adams et al. 2006, Courrat et al. 2009, Jud et al. 2011). Despite their importance, estuaries may be among the most impacted types of ecosystems. Certain impacts (e.g. shoreline development, pollution, dam construction, dredging) have led to precipitous declines in marine and estuarine fauna. The overwhelming cause of these declines has been habitat alteration/destruction and direct over-exploitation of organisms (Lotze et al. 2006, Halpern et al. 2008). Although estuaries are also affected by invasive species (Ruiz et al. 1997, Cohen & Carlton 1998, Byrnes et al. 2007), non-native organisms rarely have been directly implicated in declines of native fauna in coastal systems (Lotze et al. 2006). Yet because most documented coastal marine invasions are by taxa at relatively low trophic positions, e.g. primary producers, planktivores, detritivores, or deposit feeders (Byrnes et al. 2007), an understanding of the effects of invasive predators in estuarine systems is only starting to emerge.

Here, we identify a new threat to estuarine ecosystems in the western Atlantic and Caribbean, the invasive Indo-Pacific lionfish *Pterois volitans* and *P. miles* (morphologically indistinguishable species, hereafter referred to as lionfish). The spread of invasive lionfish in the western Atlantic and Caribbean has been well documented (Whitfield et al. 2002, Hamner et al. 2007, Freshwater et al. 2009, Schofield 2009), with the invasion considered 1 of the top 15 emerging environmental issues at a global scale (Sutherland et

*Email: zackjud@gmail.com

al. 2010). To date, most lionfish research has focused on invaded coral reefs and other marine habitats. While lionfish have been identified in the lower 1 km of a mangrove-lined creek in the Bahamas (Barbour et al. 2010), the hydrology and ecology of this system are substantially different from true riverine estuaries that receive considerable freshwater input and experience fluctuating salinities (Layman et al. 2007, Valentine-Rose et al. 2007). We have recently identified lionfish utilizing estuarine habitats in the Loxahatchee River, near Jupiter, Florida (USA). This is the first documented intrusion of lionfish into an estuarine system in their invasive range.

Herein we provide information on the lionfish invasion of the Loxahatchee River, including (1) a description of lionfish capture locations, (2) size structure of sampled fish, and (3) basic diet information. These data are a first step towards research on future estuarine invasions by lionfish in the region.

MATERIALS AND METHODS

The Loxahatchee River (26° 57′ N, 80° 06′ W), located near Jupiter, Florida, receives flow from 3 major branches and a number of smaller tributaries (Fig. 1). The river drains a 434 km^2 watershed and flows into the Atlantic Ocean at Jupiter Inlet (VanArman et al. 2005). While the upper reaches of the river are largely composed of natural habitats (e.g. cypress forests, mangrove-lined shorelines, oyster reefs), lower sections of the river have been highly modified by human activities, including construction of seawalls, docks, and channels. The river bottom in the lower section of the estuary is largely composed of sand, without any high-relief features (e.g. rocks, ledges). In this part of the estuary, structurally complex habitats (both natural and human-made) that are favored by lionfish are restricted to shoreline areas.

Despite periodic underwater surveys during the previous 3 yr (for unrelated research projects), we did not detect lionfish in the Loxahatchee River until August 2010. This initial sighting prompted a more thorough search of the system. We identified and captured lionfish while visually surveying (while snorkeling) a belt extending ~30 m from the shoreline, running parallel to the river's edge. Sampling frequency and spatial extent differed between the north and south shorelines of the river. On the north shoreline, our primary sampling location, we surveyed a continuous belt extending from the river mouth to an area ~5.5 km upstream from the ocean (upstream limit of clear water needed for visual surveys) every 11 to 12 wk (Fig. 1). During each of these intensive sampling events (carried out in August 2010, October 2010, January 2011, and April 2011), 100 % of the shoreline in this section of estuary was visually surveyed, including all natural habitats (e.g. mangroves, sandy bottom, seagrass) and human-made structures (e.g. docks, seawalls, rock rip-rap, debris). We attempted to capture and kill all lionfish present along the north shoreline during the course of each survey. Fish were captured using pole spears and hand nets, and all sampling was conducted during daytime incoming tides to maximize visibility. Sampling was also carried out along a shorter (~1.5 km) section of the south shoreline as part of an ongoing mark–recapture study (Fig. 1). Opportunistic sampling of the south shoreline was conducted throughout the study period (August 2010 to April 2011), rather than at fixed time intervals.

Standard lengths (SL) were measured for all collected lionfish (north and south shorelines). We conducted stomach content analyses (direct microscopic examination of stomach contents) on individuals captured along the north shoreline during our surveys in August and Octo-

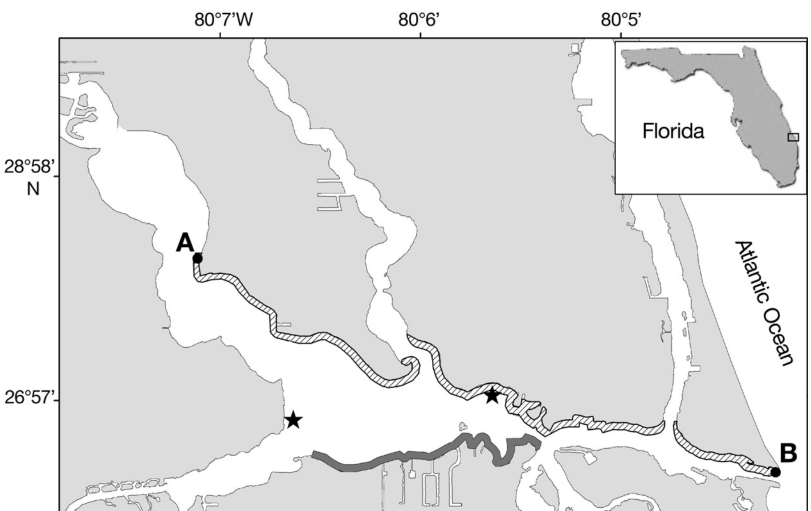

Fig. 1. Lower Loxahatchee River, near Jupiter, Florida (USA). Hatching indicates the section of the north shoreline that was intensively surveyed for lionfish *Pterois volitans* / *P. miles* every 11 to 12 wk. Dark gray shading indicates the section of the south shoreline that was opportunistically sampled as part of an ongoing mark–recapture study. Width of the survey belt was ~30 m (exaggerated slightly for clarity). Lionfish were found throughout the survey belt. The upstream limit of lionfish capture (A) was ~5.5 km from the ocean, while the downstream limit (B) was ~0.1 km from the ocean. Stars indicate the location of salinity and temperature datasondes

ber 2010 (see Jud et al. 2011 for methods). To obtain an overall description of lionfish diet, we calculated the following values for each prey taxon present in the sampled stomachs: percent frequency of occurrence (%O), percent composition by number (%N), and percent composition by wet mass (%M) (Morris & Akins 2009). Based on these values, an index of relative importance (IRI) was calculated for each prey taxon *i*, where $IRI_i = \%O_i\ (\%N_i + \%M_i)$. The IRI is a compound index that incorporates quantity, mass, and frequency of occurrence into a single numerical measure, facilitating dietary comparisons and providing a more accurate estimate of 'dietary importance' of prey items (Hynes 1950, Hyslop 1980, Cortés 1997).

Temperature and salinity measurements for the period January 2010 (the potential time of lionfish arrival in the estuary based on age estimates) to April 2011 were obtained from a pair of datasondes (600XLM, YSI Hydrodata) located ~1 m below the surface, in the section of river where lionfish were collected (Fig. 1).

RESULTS

In total, 211 lionfish were captured in the Loxahatchee River between August 2010 and April 2011. Collection sites were ~0.1 to 5.5 km from the ocean (Fig. 1). All fish were found in close association with human-made structures along the river's shoreline (Fig. 2). Lionfish were frequently observed hovering around or resting on debris under docks (e.g. cinder blocks, concrete slabs, discarded fish traps) or near the base of rock rip-rap. Some individuals were found resting in a vertical orientation against dock pilings or corrugated sea walls. All fish were captured ~0.5 to 2 m below the surface. Although we surveyed natural shoreline habitats (mangroves, seagrass, sand bottom), no lionfish were found in these areas. Additionally, no lionfish were observed at >1700 natural sites throughout the estuary that were surveyed during the summer of 2010 as part of an unrelated study (Loxahatchee River District unpubl. data), further emphasizing the species' affinity for human-made structures within the system.

Fig. 2. *Pterois volitans* / *P. miles* utilizing anthropogenically created habitat in the Loxahatchee River (corrugated seawall under a dock)

Mean (±SD) SL of all 211 captured lionfish was 92.1 ± 33.5 mm, with a range of 23 to 185 mm. All individuals were likely ≤12 mo of age at time of capture (J. Morris unpubl. data). Lengths of the 145 individuals captured along the north shoreline during primary sampling events varied by month (Fig. 3). At the time of our first sampling of the north shoreline in August 2010, mean lionfish SL was 96.7 ± 21.7 mm (n = 54). Mean SL along the north shoreline increased to 118.7 ± 34.2 mm in October 2010 (n = 24), decreased to 66.4 ± 38.5 mm in January 2011 (n = 18), and finally increased to 88.4 ± 25.5 mm in April 2011 (n = 49).

Preliminary stomach content analyses were performed on 71 lionfish captured along the north shoreline in August and October 2010, 66 of which (93%) contained prey items. In total, 15 prey taxa were identified. The prey taxa found in the greatest proportion of sampled lionfish stomachs (excluding empty stomachs) were unidentified (i.e. digested) teleosts (59% of sampled stomachs), followed by palaemonid shrimp (58% of stomachs) and penaeid shrimp (58% of stomachs). The remaining 12 prey taxa (Blenniidae, Gerreidae, Lutjanidae, Gobiidae, Panopeidae, Portunidae, Porcellanidae, Paguroidea, Alpheidae, *Lysmata* sp., Amphipoda, and unidentified crabs) were each found in <23% of the sampled stomachs. Overall, 88% of lionfish stomachs contained shrimp, 79% contained fishes, and 23% contained crabs. Palaemonids and penaeids were the numerically dominant prey groups found in lionfish stomachs, while penaeids and 2 teleost taxa (Gerreidae, Blenniidae) were the gravimetrically dominant prey items in lionfish stomachs (based on mass in stomachs). The 3 most important prey taxa based on IRI values were Penaeidae, Palaemonidae, and unidentified (i.e. digested) teleosts.

From January 2010 to April 2011, water temperatures in the section of river where lionfish were collected ranged from 12.2 to 34.4°C, and salinities (~1 m below surface) varied from

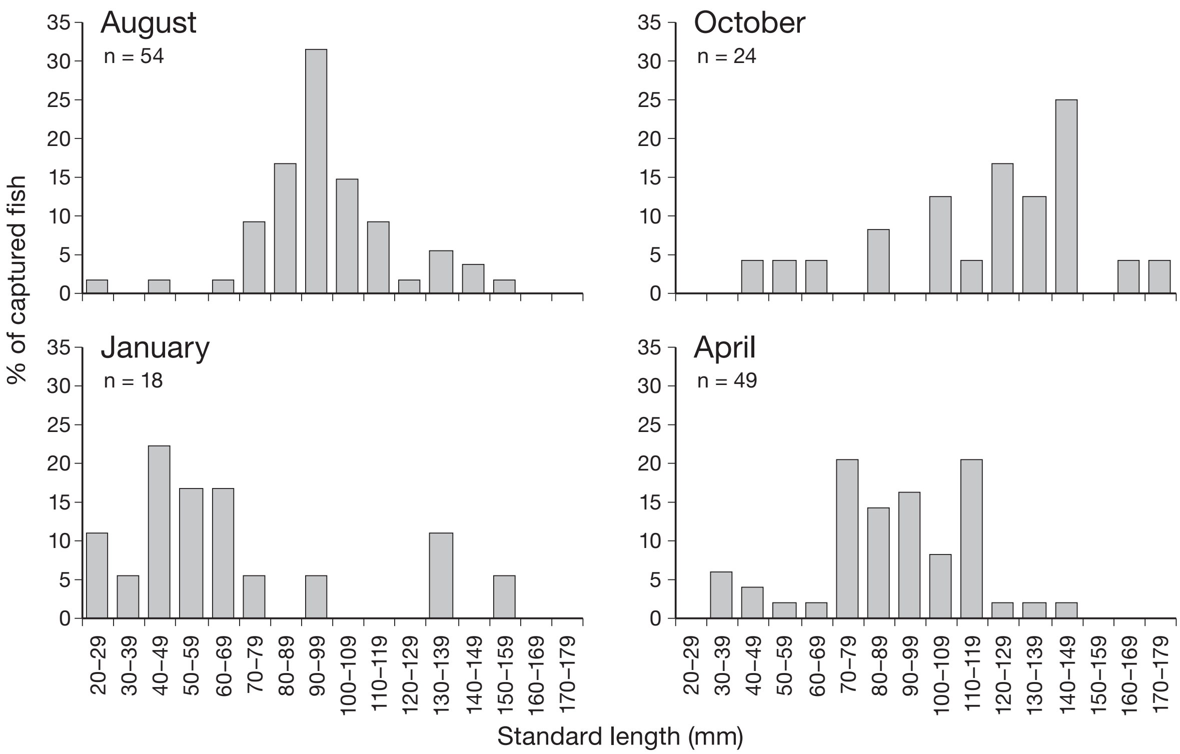

Fig. 3. *Pterois volitans* / *P. miles*. Size distribution of 145 lionfish captured during 4 primary sampling events along the north shoreline of the Loxahatchee River (Jupiter, FL) in August 2010 (n = 54), October 2010 (n = 24), January 2011 (n = 18), and April 2011 (n = 49). An additional 66 lionfish were opportunistically captured along the south shoreline between August 2010 and April 2011, but are not included here because sampling dates did not match north shoreline sampling dates

5.8 to 38.6‰. Lower salinities were common during the wet season (June to October), concurrent with the first third of our lionfish sampling period. Extreme low salinities (i.e. <10‰) were limited both temporally (hours to <1 d) and spatially (the upstream datasonde only). During the wet season, the estuary was stratified, with a thin (~0.25 to 0.5 m) layer of turbid freshwater floating over a layer of clear, higher-salinity water.

DISCUSSION

Our initial findings suggest that the presence of lionfish in the Loxahatchee River estuary is more than just a short-term phenomenon. Based on observed size distributions (Fig. 3), it appears that successful recruitment may have occurred multiple times throughout 2010 and early 2011. Small post-settlement juveniles were captured on each sampling date, suggesting that recruitment may occur year round. We initially predicted that recruiting lionfish would settle in the lower reaches of the estuary, closer to the ocean; however, several of the smallest individuals we captured (SL ≤ 28 mm) were located >4 km upriver, indicating that small juveniles may possess the ability to settle well into estuarine systems.

While there is no published record for salinity tolerance in lionfish, their presence in the Loxahatchee River suggests that the species may be able to behaviorally (or physiologically) handle fluctuating estuarine salinities. We believe a salt wedge and associated salinity stratification, common in estuaries (Simpson et al. 1990), may have provided a stable high-salinity benthic refuge for lionfish when surface salinities were reduced. All lionfish were captured at ≥0.5 m in depth, suggesting they may avoid lower-salinity surface waters. Even during a period of extremely high freshwater inflow associated with a passing tropical storm, we continued to observe lionfish in the Loxahatchee River.

Despite record cold water temperatures during the winter of 2010 (Loxahatchee River District unpubl. data), water temperatures in the section of river inhabited by lionfish remained above the species' lethal minimum temperature of 10°C (Kimball et al. 2004). As such, wintertime low temperatures appear to be an insufficient barrier to the permanent establishment of lionfish in South Florida and Caribbean estuaries. Additional laboratory experiments are needed to determine physiological tolerances (salinity, temperature) in estuarine lionfish.

Human activities may facilitate the successful invasion of estuaries by lionfish through the creation of structurally complex artificial habitats that the species appear to favor, particularly in systems that lack natural high-relief habitats. With a unique set of muscles attached to the swim bladder that allows them to assume a vertical orientation (Hornstra et al. 2004), lionfish are highly adapted to exploit vertical surfaces, including numerous anthropogenically created structures found in estuaries (e.g. sea walls, pilings). Rapid establishment of lionfish in the Loxahatchee River estuary may represent another example of artificial structures facilitating the spread of invasive species (Sheehy & Vik 2010).

Although no significant predation of lionfish has been documented in the Atlantic, the large predators (e.g. serranids) that may occasionally consume lionfish (Maljkovi et al. 2008) are typically rare in estuarine systems compared to coral reefs (Dorenbosch et al. 2009). The most abundant estuarine predators (e.g. juvenile lutjanids and carangids) are gape-limited and would only be able to consume the smallest lionfish. There are no reports of larger estuarine predators (e.g. centropomids) feeding on lionfish. We observed 1 instance of a green moray eel *Gymnothorax funebris* consuming a wounded lionfish in the Loxahatchee River, but moray eels are likely far less abundant in estuaries than on coral reefs.

Without additional research, it is difficult to predict the future impacts of lionfish in estuaries. The species' rapid rate of prey consumption (Fishelson 1997) may alter prey communities, particularly since feeding rates in the lionfish's invasive range appear to be even greater than in their native range (Côté & Maljkovi 2010). Although lionfish in their native range frequently have empty stomachs (Fishelson 1997) — a common pattern among piscivorous fishes (Arrington et al. 2002) — the fish we sampled almost always had prey in their stomachs. This low percentage of empty stomachs has been observed across the lionfish's invasive range (Albins & Hixon 2008, Morris & Akins 2009, Barbour et al. 2010), suggesting that these invasive predators feed frequently, perhaps in response to prey naïveté and a consequent increase in prey capture success rates. Additionally, release from predation in their invaded range may allow lionfish to spend more time foraging and less time sheltering from predators.

On coral reefs, invasive lionfish have been shown to reduce recruitment of native fishes by nearly 80 % over a 5 wk period (Albins & Hixon 2008); similar predation rates in estuaries could have major, yet undocumented, effects, particularly for species that rely on estuarine systems as nursery habitat. The continued presence of lionfish in estuarine nursery habitats may threaten the early life history stages of a number of commercially, recreationally, and ecologically valuable fish species, either through indirect interactions (e.g. prey depletion), or as a result of direct predation (Morris & Akins 2009). Although preliminary, our diet data have already revealed some consumption of commercially and recreationally important lutjanid species by lionfish in the Loxahatchee River.

Colonization of an estuary by lionfish provides an example of the rapidly expanding range (and potential ecological impacts) of the species in the region. The invasion by lionfish will undoubtedly have broad-reaching effects which are of particular concern for highly threatened ecosystems like estuaries. Since lionfish are often found in turbid bays in their native range (A. Anton unpubl. data), estuaries may become another major site of invasion as regional populations continue to grow. At this point in the invasion, efforts to control lionfish populations should remain focused on the most critical or threatened ecosystems, i.e. those systems where direct removal of lionfish would have the greatest ecological benefits (e.g. in nursery habitats). Since lionfish are less likely to be observed and reported in estuaries than on coral reefs, it is possible that estuarine invasions may go undetected for considerable periods of time. Early detection and control of lionfish in estuaries may be crucial to offset their long-term ecological impacts in these critical ecosystems.

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