Encouraging Results in Tests of New Lionfish Trap Design

Resultados Alentadores en Pruebas de un Nuevo Diseño de Trampa para Pez León

Résultats Encourageants d'essai d'un Nouveau Modèle de Piège à Poisson-lion

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ABSTRACT

Field trials were conducted for prototype lionfish traps designed to capture lionfish and reduce bycatch typically seen in traditional fish trap designs. These "non-containment curtain traps" exploit the tendency of lionfish to aggregate around structures. The prototype traps contain a fish aggregation device (FAD) centered within an open frame. When retrieved, a net curtain is drawn up around the FAD, capturing all fish within the frame. Two pairs of traps were deployed 29 km off Pensacola, Florida in the Gulf of Mexico at a depth of 34 m. One pair was positioned 10 m and another 40 m from existing artificial reefs originally placed to provide habitat for native marine organisms, but which is now dominated by invasive lionfish. Divers counted lionfish, then removed them via spear (to simulate trap retrieval) at different intervals (simulating soak times). The traps attracted 23-40% of lionfish from the existing artificial reefs although not all lionfish were within the trap itself. Longer soak times increased capture rates: 14% of attracted lionfish were within the trap after one day, 35% after two days, and at least 80% for intervals 32 days or longer. Future tests will evaluate the effectiveness of trap modifications, and the effect of varying depths and distances from source populations. Preliminary results from these trials are encouraging and demonstrate that traps can be developed to remove lionfish from deep, remote locations throughout their invaded range, although collaboration with the fishing community will be essential to maximize efficiency.

KEYWORDS: Lionfish, trap, efficiency, aggregation, fishery; pez león, trampa, eficiencia, agregación, pesquería

INTRODUCTION

Both the range and abundance of two invasive lionfish species (*Pterois volitans* and *P. miles*), native to the Pacific and Indian Ocean, continue to increase in the north Atlantic basin (Ballew et al. 2016). *P. miles* is also becoming more abundant in the Mediterranean Sea (Kletou et al. 2016). Experts generally agree that eradication in the invaded range is not possible (Barbour et al. 2011). Though the eventual impacts of the invasion on native ecosystems is unknown, evidence from shallow reefs (< 30 m) suggests it could be substantial (e.g., Albins and Hixon 2008, Arias-González et al. 2011, Green et al. 2012, Albins 2015). Recently, Ballew et al. (2016) used fishery-independent data from three sampling programs to report region-wide impacts of lionfish on the continental shelf of the eastern United States (U.S.). Between 15 and 100 m, they found that Tomtate (*Haemulon aurolineatum*), a native forage species, declined in abundance by 45% from 1990 to 2014, coincident with the rapid population increase of lionfish.

As awareness, interest, and concern over the lionfish invasion has grown among scientists and the general public, there has been considerable effort to respond. Adding to the call for increased capacity for removal is a growing demand for lionfish in the seafood market (Davis 2016). To date, most removals have been conducted by spearfishing; lionfish derbies are regularly held to remove lionfish, but are limited to scuba depths (Barbour et al. 2011). Considerably less effort has been focused on deep water. Though lionfish are also occasionally harvested by hook-and-line at various depths (Akins 2012), harvest from deep water has been primarily as bycatch in lobster traps (Morris and Whitfield 2009, Akins et al. 2012, Gleason and Gullick 2014, Lazarre 2016) and weir traps (Fundación Trichechus 2013). However, existing traps do not capture lionfish in numbers high enough to offer potential in exerting control over deep water populations (as spearfishing can in shallow water; Green et al. 2014). This could be partly because lionfish, which prey on live fish and invertebrates, are not attracted to the baits commonly used in existing traps (Ballew et al. 2016, Lazarre 2016). More likely, they are attracted to the structure of the trap itself (see Pitt and Trott 2013, Lazarre 2016). Thus, over most of their invaded range, lionfish populations in depths beyond 30 m are largely uncontrolled.

There is, therefore, an urgent need for technologies that target lionfish in deeper water (Arias et al. 2011), but which leave other species unharmed (Johnston et al. 2015). Numerous technologies have been proposed or are in development, including modifications to existing lobster traps (Pitt and Trott 2013), traps that open only upon electronic identification of a lionfish, hydraulically powered spears, electrocution devices, and modified suction samplers, among others. Most believe that specialized traps could play a significant role (e.g., Gómez Lozano 2013), but they will need to be designed to avoid both bycatch and ghost fishing (if lost) before being accepted and permitted as suitable for lionfish control (Carballo-Cárdenas 2015). So far, no trap designs have been fully developed to successfully target lionfish exclusively.

Here I report on field trials of a prototype lionfish trap with several design features that reduce impacts and benefit the environment. The design features a structural fish attraction device (FAD), which exploits the attraction of lionfish to structure in deep water (e.g., Reed et al. 2015 and personal observations made in June 2013 from the submersible *Antipodes* offshore Fort Lauderdale, FL). The traps described here are "non-containment," in that they are open and do not entrap fish until the trap is retrieved. The non-containment design and the lack of bait prevent the attraction and/or entrapment of potential bycatch. The prototype is an enclosable "curtain trap" design, in which a curtain of netting is pulled up around the FAD upon retrieval. Lionfish have a very languid response to movement and disturbance around them, and make little attempt to avoid being caught in the trap (personal observations).

METHODS

Four prototype “non-containment, curtain traps” were deployed in 33.5 m of water in the Gulf of Mexico, 29 km southeast of Pensacola, Florida (Figure 1) on July 18, 2016. These waters do not contain high relief natural bottom features, but are known to harbor high abundances of lionfish, particularly around artificial reefs. The depth was chosen due to existing artificial reef material being present in the area and partly due to the documented high densities of lionfish in the waters southeast of Pensacola, FL (Dahl and Patterson 2014). Although these waters are on the deeper end of recreational diving limits, they are still accessible to experienced divers to observe the trap performance throughout the duration of the test.

Each prototype trap (Figure 2) had a cuboid frame (1.2 m x1.2 m x 0.9 m) constructed of PVC pipe, with the top and bottom covered by plastic mesh. Each had a curtain of flexible nylon netting attached to a square frame that could move up and down along the vertical trap supports. The curtain frames were weighted with 4.8 m of 1.6 cm diameter rebar, which provided ballast (~7 kg) to help the traps sink and remain open on the seafloor. Holes were drilled throughout the trap frames to prevent air entrapment. Additional weight (2.5 kg) was added to each FAD to reduce movement within the trap. The moveable frame settles to the bottom of the trap on deployment and opens the trap so that fish can come and go freely for the duration of the deployment. The unbaited FAD in the center of each trap provides structure that attracts lionfish. A four-line bridle is attached to the curtain frame, with one line connecting to each corner, allowing the curtain to be raised and the trap to be recovered using a surface line (not used in these tests), capturing any fish within the trap.

The four prototype traps were positioned at two distances (Figure 3) from existing artificial reef material (chicken transport devices, called “chicken coops” here) that had been placed in the past as habitat for native species, but which are now dominated by lionfish. Two traps were placed 10 m to the SW of the three adjacent chicken coops, and two more 30 m to the SW of the first pair. Given average visibility in the area (about 15 m), a diver can often see the first pair from the chicken coops, but not the second pair, nor can the second pair be seen from the first. A diver navigation line was tied between the traps. To constrain movement in the event of storms, Traps 1 and 3 were anchored, each with two pieces of rebar, bent at one end and driven approximately 0.5 m into the sand; the others were left unanchored to monitor movement over time.

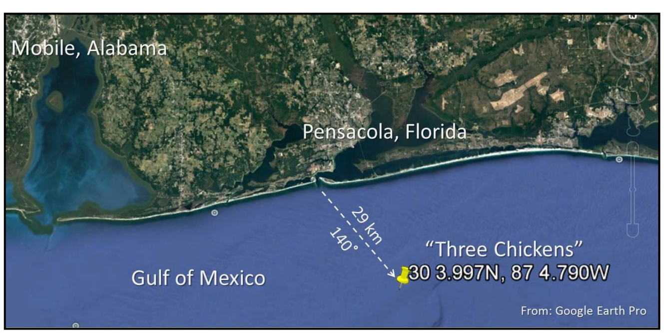

Figure 1. Study site location 29 km southeast of Pensacola Florida. Bottom depth is 33.5 m.

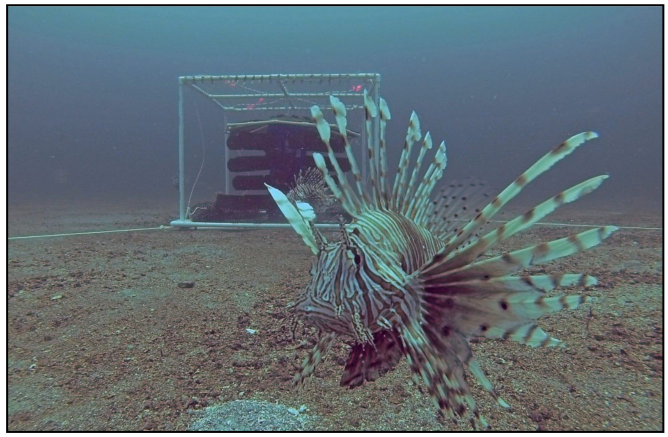

Figure 2. Time lapse image showing lionfish in front of prototype trap. Attached to the trap frame (white PVC) is a FAD that consists of two 5-gallon buckets, plastic garden edging threaded through slots in the buckets, and an umbrella-shaped frame covered with screen mesh. The four-sided frame around the bottom has an attached net that is raised by a four-line harness during retrieval, enclosing the FAD and trapping the fish. White lines lead to other traps at the study site.

Initial observations were made on July 18, 19, and 21, 2016. The numbers of lionfish associated with the chicken coops and lionfish traps (inside and outside) were recorded. Additionally, their vertical orientation (e.g., whether high or low in the trap) and distribution relative to the traps was noted. Swimming and hunting behaviors were also recorded, when observed. Though the test was planned to end on July 21, 2016, the traps were left at the study site for the next three months, and unanticipated observations were made by members of the project team on August 22, September 15, and October 25, 2015. On August 22, 2016, counts were made on the traps, and on one set of chicken coops. On September 15, 2016, a combined count was made on the traps, and an estimate was made of lionfish on the same set of chicken coops. On the final visit on October 26, counts were made on traps and chicken coops, and a new trap design (single trap) was deployed for testing.

Traps were not actually retrieved to assess capture efficiency. During dives, a diver would slowly approach each trap after conducting fish counts and raise the net curtain by pulling up on the lifting harness above the trap. The response of the fish was noted, as was the number inside the enclosed trap (assuming no escapes, these would have been caught if the trap was raised to the surface). After counts were made on July 19 and 21, 2016, and then on September 15 and October 25, 2016, divers removed all lionfish in or around the traps using spears, which simulated actual hauls and resetting of the traps (lionfish were not removed after the counts on August 22, 2016). The interval since the previous removal simulated soak times. This allowed for soak times to be compared, estimate replenishment rate, and detect changes in orientation of fish to the trap and FAD over time. Fish removed from the traps were measured, and notes were made on stomach contents, sex, and deformities.

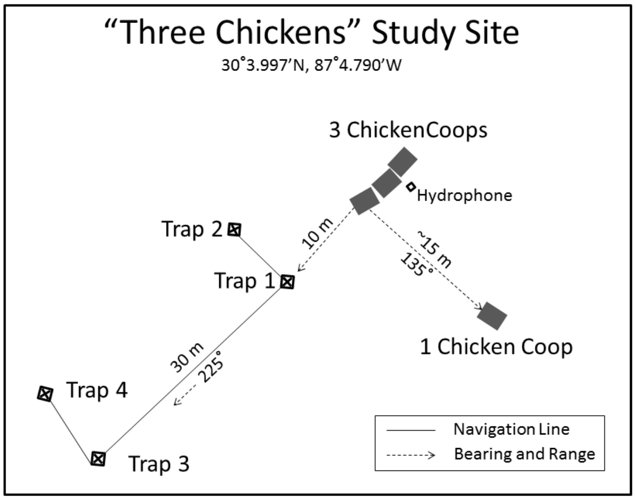

Figure 3. Distribution of artificial reefs (formally called "chicken transport devices" by regulators, but called "chicken coops" here) and lionfish traps at the study site. Solid lines are navigation lines used by divers to locate the traps.

A two-hour time lapse of still images (one per minute between 1100 and 1300 hours) was made at one trap on July 21, 2016. The purpose was to note changes in distribution of fish around the trap in the absence of divers (Figure 2). The camera was positioned on a small tripod approximately 3 m north of Trap #3, with a view that would include most, if not all lionfish associated with that trap.

Because the first trials of these traps were intended to simply determine whether they attracted lionfish, and only a small number of traps (four) were deployed, sample design did not provide adequate replication for statistical rigor. Furthermore, the number of counts made on each location varied due to constraints on dive time and tasking. Thus, data presented here should be considered preliminary and conclusions are derived primarily from combined data and not from statistical analysis.

RESULTS

One to three divers made independent counts of lionfish inside and outside the lionfish traps, as well as around the chicken coops. Mean, actual, and estimated abundances are presented in Table 1, along with totals before the removal of lionfish at the end of each day. No bycatch of commercial interest was observed within the traps, though a few soapfish and smaller fish (cardinalfish, pufferfish, and damselfish) were seen in traps after they had been in the water for three months. By this time, biofouling on the traps had become substantial, making them more attractive to reef fish than during the more realistic soak times they would have as traps. At this site, bycatch could have included primarily Blue and Queen Angelfish, Scamp Grouper, Red Snapper, Gray Triggerfish, and Amber and Almaco Jacks. Red Snapper and jacks were particularly abundant in the area, but almost all remained in the water column rather than aggregating on or around the traps. Two Blue Angelfish and two Red Snapper were the only fish observed to actually swim through a trap (on two occasions), but they continued through and did not remain within the footprint of the trap.

The majority of lionfish observed within the traps prior to simulating haul back were captured, though occasionally a lionfish near the perimeter of the trap would be driven out by the rising curtain. Nevertheless, for those lionfish fully inside the trap footprint, all were successfully captured on every lift.

After a 1-day soak time, 40% of all fish that associated with the chicken coops prior to the deployment of the traps had moved to the vicinity of the traps, and 14% of lionfish attracted to the traps were within the trap (Figure 4). This suggests high attraction by the traps and FADs even after a single day. It is important to note, however, that the traps were placed quite close to the source of lionfish for this first test (one pair was within 10 m). It is not yet known what the attraction rates will be in more remote locations, farther from a source of lionfish. It was also noted that a high percentage (86%) of lionfish attracted to the traps remained outside the frame after the first day in the water (Figure 4). The lionfish associated with the traps appeared to be distributing themselves within about three meters of the traps. Some lionfish appeared to simply be resting; others were clearly focused on hunting. Following the first 24-hour period after placement of the traps, 57 lionfish were removed by spear.

Table 1. Mean, actual, and estimated abundance of lionfish in and around the curtain traps, and around the chicken coops at the study site during each soak interval. * indicates numbers based on estimates provided by diver, and not actual counts. Whole numbers in trap and coop estimates indicate counts that were conducted by a single individual. "n/a" indicates that fish were not removed following counts. "?" indicates that counts were not made.

	TRAPS				COOPS		TOTALS	
Soak Time	Trap 1 In/Out	Trap 2 In/Out	Trap 3 In/Out	Trap 4 In/Out	Triple Coops	Single Coop	Total	After Removal
1-Day	3.5 / 6.0	3.0 / 18.5	1.0 / 15.0	0.5 / 8.0	38.8	44.6	139	82
2-Day	3.2 / 3.6	3.4 / 5.0	3.0 / 6.0	0.3 / 3.7	21.0	34.9	84	51
32-Day	5 / 2	6 / 0	6 / 1	10 / 1	24	?	?	n/a
40-Day	3 / 1	1 / 1	5 / 0	7 / 2	40	27	87	63
56-Day	28 In / 3 Out* (all traps combined)				85*	?	?	?

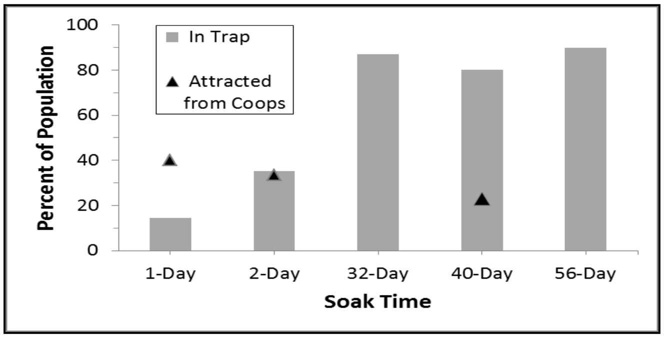

Figure 4. Plot showing increasing concentration of lionfish in traps with longer soak times, and the level of attraction of lionfish from nearby artificial reefs.

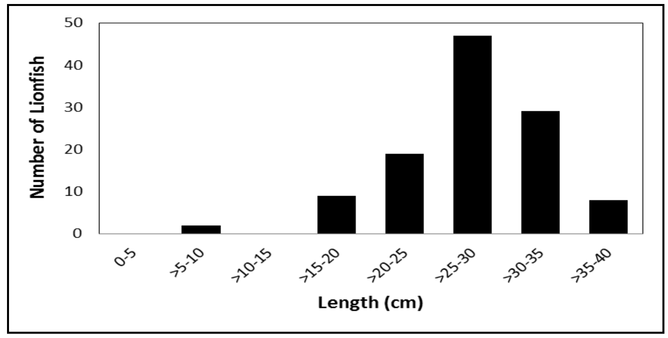

Figure 5. Length frequency data from 111 lionfish removed from within and around traps after 1-day, 2-day, and 40-day soak intervals.

After a 2-day soak time, the percentage of all lionfish attracted to the traps remained close to the 1-day level, at 34% (Figure 4). But a higher percentage of lionfish attracted to the traps (35% vs. 14%) were within the trap footprint. Still, the mean number of lionfish within the trap footprint remained similar (2.0 - 2.5/trap, with a range of 0 - 7/trap). This suggests that lionfish movement from closely located sources may occur within the first day (all traps and artificial reefs at this location were within 50 m of each other). After the two-day soak interval, 33 lionfish were removed from the traps by spear.

After a 32-day soak time, a similar number of lionfish remained associated with the traps (31 in August vs. about 28 on July 21); Table 1), but a much higher percentage of lionfish attracted to the traps resided within the trap footprint (87%). Furthermore, those outside the trap footprint were all within approximately 25 cm, substantially closer than earlier observations. One lionfish was seen on top of one trap, which had not been observed during prior visits. No potential bycatch was associated with the traps. The total number of fish on the three chicken coops (24) plus the traps (31) was 55 (Table 1). Considering that no count was made on the single coop during this visit (it is likely that 30 - 40 lionfish were on it, based on prior counts), and that a total of 51 lionfish were present on all structures after the removal following the 2-day soak interval, a moderate level of recruitment must have occurred during the 30-days since the prior visit.

Longer soak times showed a similar pattern. After a 40-day soak time, 20 lionfish were in or near the traps, representing 23% of the local population, and 80% of those were within the trap footprints (Table 1). After a 56-day soak time, 31 resided within and near the traps, with approximately 90% being within the traps. The higher number of lionfish observed on the chicken coops during the later sampling efforts (see Table 1), as well as the consistent recording by divers of juveniles on both the chicken coops and traps indicates that recruitment is actively occurring on the study site.

The length frequency of the lionfish removed from the site is shown in Figure 5. Mean length of all lionfish was 27.5 cm. Of the 111 fish collected, 51 were female (46%). Of those, most were spawning capable and several were in the actively spawning sub-phase as they contained hydrated eggs. Abnormal development of dorsal spines was observed for four lionfish.

DISCUSSION

These "non-containment, curtain traps" were designed with specific operational, conservation and management goals (Table 2). Early indications are that the current design accomplishes almost every one of these initial goals. The prototype was highly effective in capturing lionfish residing within the trap footprint, and resulted in minimal potential bycatch (almost exclusively small fish that would escape on ascent). If non-targeted fish had been captured, they could be recompressed by sending them down with the net turned upside down (which closes the curtain), then uprighting it by pulling on the surface line before reaching the bottom. Furthermore, there is low likelihood of ghost fishing if the trap is lost, as it has a completely open frame. Finally, the trap itself would have little impact on the

Table 2. Design goals of the prototype lionfish trap, and corresponding characteristics of the traps indicting the extent to which they achieve those goals.

Goal	Trap Characteristics
Capture primarily lionfish	Aggregation behavior of lionfish and lack of similar level of attraction for other species increases likelihood that lionfish alone will be caught
Avoid bycatch	Non-containment prevents capture prior to retrieval, and lack of bait reduces attraction of non-targeted species; lionfish may also deter other species
Prevent ghost fishing if lost	Open design with downward-opening curtain net prevents containment
Prevent habitat damage	Placement is on sand and low relief habitats where snagging is less likely; low center of gravity reduces likelihood of movement
Be easily transportable on fishing boats	Though stackable, the rigid prototype takes up considerable deck space; future designs will be collapsible
Allow for safe release of bycatch	Deployable right side up (open) or upside down (closed). Recompress bycatch by descending in a closed trap. At desired depth, the surface line is pulled to flip the trap upright, which drops the curtain, releasing the fish at depth

habitats in which it is intended for use, with the possible exception being a net or mesh occasionally snagging on hard bottom features.

One drawback of the cubical frame is that it takes up so much space on a vessel. A collapsible trap was fabricated and deployed for testing at the study site on October 25, 2016. Collapsible FADs are also being tested to see if they retain the beneficial characteristics of the prototype. If successful, the new traps and FADs will substantially enhance portability by allowing traps to be stacked, greatly increasing the number that can be carried by a fishing vessel.

Some observations of fish behavior made during this initial test will influence future trap modifications. First, most lionfish found in or around the traps and chicken coops stayed near the bottom. Only two lionfish were observed hovering above traps (1 m above the bottom), and two over the umbrella portion of the FAD. Many lionfish were observed hovering above the chicken coops, which were similar in height but have a much greater footprint than to the traps. Several lionfish were seen about 0.5 m above the bottom within the traps, up against the FAD, and nestled between the plastic extensions threaded through the buckets. This was more evident during longer soak intervals. It was not clear the extent to which the umbrella over the FAD attracted them. Their close association with the buckets and extensions, and seeing only two lionfish using the umbrella for cover suggest a horizontal element like the umbrella may not be an essential feature for future FADs. Further testing would be needed, however, and FAD experiments currently being conducted by NOAA's National Centers for Coastal Ocean Science (NCCOS) and the Reef Environmental Education Foundation in the Bahamas and offshore North Carolina may help answer that question (James Morris, NCCOS, personal communication).

Time lapse images provided insight into the short term spatial distribution of lionfish surrounding the traps. It was clear during the shorter soak times (1-day and 2-day) that lionfish tended not to crowd together within the trap itself, or to aggregate sufficiently to capture a large number in the relatively small traps used in this test. They did not appear to actively compete for space, but most did not stay in close proximity to other lionfish for an extended period. Rather, most lionfish observed tended to move in the vicinity of the traps, some hunting for small fish and invertebrates in the sand (also noted by Dahl and Patterson 2014).

Following the soak periods of 32 or more days, however, as many as ten fish were seen within one trap. Crowding was considerably higher than during the shorter soak times, and even fish outside the traps tended to be very close to the structures. Whether this was due to factors other than soak time is unknown, so more testing will be needed to determine whether densities consistently tend to increase with soak time, and if so, what intermediate soak times might maximize capture efficiency. Regardless, the 32-day, 40-day, and 56-day observations were valuable in providing a longer-term perspective on fish behavior as it relates to trap effectiveness.

Stomach contents of 111 lionfish collected suggested that the lionfish on the traps at this site preyed primarily on sand-dwelling fish and shrimp (e.g., flounder, razorfish, lizardfish, seabass), particularly during the earliest sampling periods. Lionfish are generalist predators, so they consume a large variety of prey. The stomach contents we observed, along with the small sizes of most prey items, suggest the lionfish here may have depleted the fish that would normally occupy the artificial reefs and are now forced to forage more in surrounding sand. Consistent with the findings of Dahl and Patterson (2014) in this area, this could also explain why 40% of lionfish from the artificial reef moved to the traps within a single day of deployment. These observations may also serve as an example of the bigger regional problem with this highly invasive species – quite simply, that they rapidly consume native species. Ironically, this could make trapping them easier, as they need to venture farther and farther over time to find food, and are more likely to encounter traps in locations far from existing artificial and natural reefs, where they would normally shelter and rest.

Interestingly, stomach contents of fish captured during the final sampling effort in October contained a comparatively high number of what appeared to be juvenile tomtates. They also had a few shrimp, crabs, lizardfish, and gobies. The tomtates may have been part of a recent recruitment event and demonstrate the ability of lionfish to adapt easily to changing food availability.

Trap Modifications

The space use of lionfish suggests that the two factors most affecting the number of lionfish caught in a non-containment trap are the footprint of the trap and soak time. It is not clear whether the configuration of the FAD itself would change the attraction characteristics of the trap. It would seem, however, that creating a greater footprint within the trap would result in more lionfish being caught, particularly for shorter soak times. This could be accomplished simply by building a wider trap frame.

Time lapse and diver observations indicate the lionfish perceive the trap frame much like they do the FAD. A few fish are attracted to the uprights of the frame, leaving some fish outside the trap perimeter, and thus not captured when the curtain is raised. Removing the frame, or vertical components that may 'compete' with the FAD itself, to the extent possible, would force fish to orient solely to the FAD. Two new trap designs will be tested that have no uprights, the only vertical structure being the FAD. The first is currently in the water. Both designs will have larger footprints than the prototype. The first has an almost 80% larger footprint (2.63 m^2 vs. 1.47 m^2). Like the prototype, a bridle will be used to pull a curtain of netting around the fish and FAD for retrieval. Additionally, soft bodied FADs are being tested. If effective, they would allow for fully collapsible traps, minimizing deck use on a fishing vessel and simplifying operations for users.

Other modifications to be evaluated include enhancements that may increase lionfish attraction, such as light, bait, and/or sound. There is anecdotal evidence that light attracts lionfish (or bait fish that attract lionfish) under certain conditions (Emma Hickerson, Flower Garden

Banks National Marine Sanctuary, personal communication). Illuminating a FAD may increase the arrival rate for lionfish or alter aggregation behavior in a way that could increase capture rates. Baiting with products likely to attract lionfish (perhaps eggs or other lionfish parts) may increase initial attraction rates. Because bait is likely to attract potential bycatch, sufficient soak time would be needed to ensure that the bait is fully consumed, after which most non-targeted species would depart. Lionfish would be less likely to leave due to their natural attraction to structure (Lazarre 2016). Thus, baiting could enable shorter soak times for the traps and perhaps increase catch rates. Additional work is also needed on lionfish acoustics to determine whether lionfish use specific sounds to find each other or reef habitat. Large aggregations of lionfish have been observed during ROV dives over deep sandy, featureless bottoms (Rich Appledoorn, University of Puerto Rico, personal communication). How they find each other is unknown, but sound is a logical possibility. If particular sounds can be isolated, it may be possible to increase attraction rates or otherwise influence behavior, resulting in improved trapping efficiency. A hydrophone was recently placed at the study site by Dr. Scott Noakes (University of Georgia) in order to collect data on lionfish sounds.

Deep Water Harvesting

Within the range of ocean invaded by lionfish between Cape Hatteras, NC and the mouth of the Orinoco River in Venezuela, the shelf area between 0 m and 30 m is approximately 735,000 km^2 (light blue area on Figure 6). Considering depth alone, lionfish control throughout this area could theoretically be conducted by divers. The area between 30 m and 300 m (beyond typical diving depths) is 665,000 km^2, emphasizing both the challenge of controlling lionfish populations throughout the invaded range (Switzer et al. 2015), and the enormous potential for harvesting a previously unexploited species (Lazarre 2016).

The tests here were conducted in relatively shallow water (33.5 m), but the ultimate purpose is to provide trap designs that allow harvesting in deep water areas containing high densities of lionfish (e.g., Claydon et al. 2012, Nuttall et al. 2014). Surveys in deep water have shown that many such areas exist, including over large expanses of the continental shelf (e.g., Ballew et al. 2016). On the Southwest Florida Shelf, images made during a recent study in the Pulley Ridge area (Reed et al. 2015) show high densities of Red Grouper solution holes 6 - 10 m in diameter at depth of 60 - 80 m (Figure 7). These solution holes, created by the Red Groupers, attract large numbers of fish, including numerous species of potential prey for lionfish (Coleman et al. 2010). ROV dives on some of these holes on the Southwest Florida Shelf showed that many lionfish are also attracted (Figure 7). Rough estimates suggest that approximately136,000 of these holes may exist within the Pulley Ridge Habitat Area of Particular Concern alone (Kimberly Puglise, NOAA, unpublished). Given lionfish feeding habits, this could be devastating to native deep fish and invertebrate communities. But deploying "FAD-based, non-containment, curtain traps" in these areas, the FADs in the traps themselves will provide substantial relief compared to surrounding habitats. This could make these areas productive fishing grounds where we can also protect natural uses of the grouper solution holes by native species.

Regulatory challenges will need to be overcome before these traps are widely adopted to address the lionfish problem. Many protected areas, indeed, entire jurisdictions ban traps in certain waters. Most do so because of problems

Figure 6. Map of areas between Cape Hatteras, NC and the Orinoco River from 0 m to 30 m deep (light blue) and 30 m to 300 m deep (darker blue).

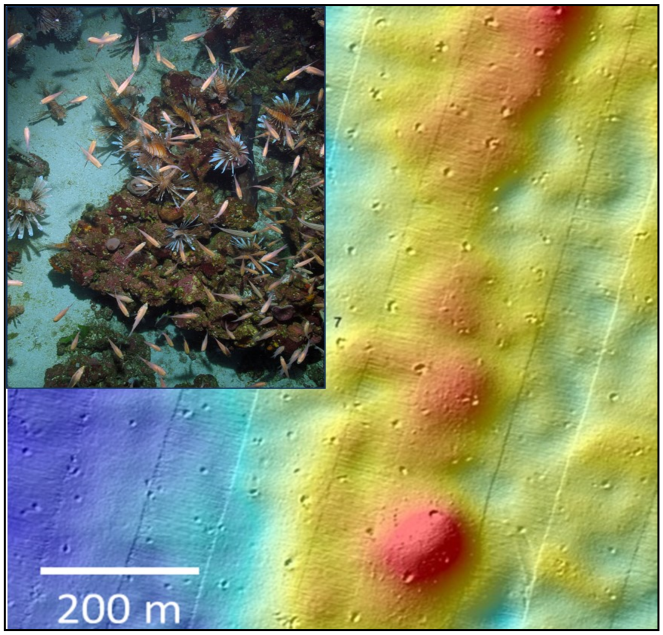

Figure 7. Multibeam sonar image showing many 6-10 m diameter Red Grouper burrows at Pulley Ridge, southwest Florida shelf (from Reed et al. 2015). Inset shows lionfish in a grouper burrow. Most of the smaller fish are anthiids, common in the water column over hard bottoms at these depths. Credit: Coral Ecosystem Connectivity 2014 Expedition.

associated with bottom damage, bycatch, and ghost fishing. While bottom impacts cannot be completely avoided with the proposed traps, both bycatch and ghost fishing appear to be reduced, if not eliminated altogether. Exemptions will need to be sought and justified on the basis of the specialized nature of these traps (Carballo-Cárdenas 2015), and they will have to be negotiated case-by-case, depending on where they are used (Gómez Lozano et al. 2013).

CONCLUSION

The goal of this effort was to determine whether FAD-based, non-containment curtain traps provide an environmentally friendly way to harvest lionfish for purposes of population control and to supply a growing demand in the seafood market. Lionfish are clearly attracted to the traps in habitats that offer little or no alternative structure of equivalent relief, despite the lack of prey on the traps. Many deep water habitats invaded by lionfish have low relief; thus the potential for such traps appears substantial.

Lionfish were attracted to the prototype traps quickly and in fairly high numbers relative to source populations. The traps did not attract or capture non-targeted fish species, and it is unlikely they would be caught under normal fishing conditions. The number of lionfish captured was proportional to soak time, but may be increased, particularly for short soak times, by making the trap footprint larger. A more complete evaluation of their potential will require determining capture rates over intermediate soak times (one to two weeks). These, along with shorter intervals, are the most desirable ones for most actual fishing operations. Other tests using attractants and trap design modifications are also being considered as ways to improve the rate of attraction of lionfish.

Other trap improvements will undoubtedly be made by those who use them and those with much more experience in trap construction that this author. Their changes will increase lionfish yield and trap durability, and simplify operations.

ACKNOWLEDGEMENTS

For field assistance *par excellence*: Alex Fogg, Bryan and Anna Clark, Scott Noakes, Allie Sifrit, Randy Terrell, Mitchell Tartt, Keith Neale, Robert Turpin, and David Mucci. For diving support: Captain Ty McCall, Captain Gene Ferguson, and Chris Thomas from Scuba Shack. For generous project support: Lionfish University (Stacy Frank and Jim Hart), Coast Watch Alliance, Cayman Islands Department of the Environment, and NOAA's Office of National Marine Sanctuaries. For generous submersible support: Stockton Rush and the OceanGate crew. For trap fabrication: Lewis Fortner. For GIS support: Tony Reyer. And for spreading the word and generating interest, Jeremy Morrison (SandsPaper). This research was conducted under a Letter of Acknowledgment issued by NOAA's National Marine Fisheries Service, Southeast Regional Office.

LITERATURE CITED

Akins, J.L. 2012. Control strategies: tools and techniques for local control. Pages 24–50 in: J.A. Morris Jr. (ed.) *Invasive Lionfish: A Guide to Control and Management.* Gulf and Caribbean Fisheries Institute, Special Publication Series 1. Marathon, Florida USA.

Akins, L., D. Lazarre, D. Die, and J. Morris. 2012. Lionfish bycatch in the Florida lobster fishery: first evidence of occurrence and impacts. *Proceedings of the Gulf and Caribbean Fisheries Institute* **65**:329 - 330.

Albins M.A. 2015. Invasive Pacific lionfish *Pterois volitans* reduce abundance and species richness of native Bahamian coral-reef fishes. *Marine Ecology Progress Series* **522**:231-243.

Albins M.A. and Hixon M.A. 2008. Invasive Indo-Pacific lionfish *Pterois volitans* reduce recruitment of Atlantic coral-reef fishes. *Marine Ecology Progress Series* **367**:233-238.

Arias- González J.E., C. González-Gándara, J.L. Cabrera, and V. Christensen. 2011. Predicted impact of the invasive lionfish *Pterois volitans* on the food web of a Caribbean coral reef. *Environmental Research* **111**:917-925.

Ballew, N.G., N.M. Bacheler, G.T. Kellison, and A.M. Schueller. 2016. Invasive lionfish reduce native fish abundance on a regional scale. *Scientific Reports* **6**:32169.

Barbour A.B., M.S. Allen, T.K. Frazer, and K.D. Sherman. 2011. Evaluating the potential efficacy of invasive lionfish (*Pterois volitans*) removals. *PLOS ONE* **6**:*e19666.*

Carballo-Cárdenas, E.C. 2015. Controversies and consensus on the lionfish invasion in the Western Atlantic Ocean. *Ecology and Society* **20**(3):24.

Claydon J.A.B., M.C. Calosso, and S.B. Traiger. 2012. Progression of invasive lionfish in seagrass, mangrove and reef habitats. *Marine Ecology Progress Series* **448**:119–129.

Coleman, F.C., C.C. Koenig, K.M. Scanlon, S. Heppell, S. Heppell, and M.W. Miller. 2010. Benthic habitat modification through excavation by Red Grouper, *Epinephelus morio*, in the NE Gulf of Mexico. *The Open Fish Science Journal* **3**:1-15.

Davis, A. 2016. The consumption of lionfish as a control of an invasive species in Bermuda. Undergraduate Honors Theses. Paper 1045. http://scholar.colorado.edu/honr_theses/1045.

Dahl, K.A., and W.F. Patterson III. 2014. Habitat-specific density and diet of rapidly expanding invasive Red Lionfish, *Pterois volitans*, populations in the Northern Gulf of Mexico. *PLOS ONE* **9** *(8):e105852*

Fundación Trichechus. 2013. Estudios científicos marinos para el vacío de conservación Caribe Sur. Sistema Nacional de Áreas de Conservación, Programa de Naciones Unidas para el Desarrollo y Fondo Mundial para el Medio Ambiente.

Gleason, J. and H. Gullick. 2014. *Bermuda Lionfish Control Plan Version 6.* Prepared by the Bermuda Lionfish Taskforce. 60 pages.

Gómez Lozano, R., L. Anderson, J.L. Akins, D.S.A. Buddo, G. García-Moliner, F. Gourdin, M. Laurent, C. Lilyestrom, J.A. Morris, Jr., N. Ramnanan, and R. Torres. 2013. *Regional Strategy for the Control of Invasive Lionfish in the Wider Caribbean*. International Coral Reef Initiative. 31 pp.

Arias-González, J.E., C. González-Gándara, J. Luis Cabrera, and V. Christensen, 2011. Predicted impact of the invasive lionfish *Pterois volitans* on the food web of a Caribbean coral reef. *Environmental Research* **111**:917-925.

Green S.J., N.K. Dulvy, A.M.L. Brooks, J.L. Akins, A.B. Cooper, S. Miller, and I.M. Côté. 2014. Linking removal targets to the ecological effects of invaders: a predictive model and field test. *Ecological Applications* **24**:1311-1322.

Green, S.J., J.L. Akins, A. Maljković, and I.M. Côté. 2012. Invasive lionfish drive Atlantic coral reef fish declines. *PLOS ONE 7 (3):e32596*.

Johnston, M.A., S.R. Gittings, and J.A. Morris, Jr. 2015. NOAA National Marine Sanctuaries Lionfish Response Plan (2015-2018): Responding, Controlling, and Adapting to an Active Marine Invasion. *Marine Sanctuaries Conservation Series* ONMS-15-01. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, Maryland USA. 55 pp.

Kletou, D., J.M. Hall-Spencer, and P. Kleitou. 2016. A lionfish (*Pterois miles*) invasion has begun in the Mediterranean Sea. *Marine Biodiversity Records* **9**(1) http://DOI: 10.1186/s41200-016-0065-y.

Lazarre, D. 2016. Examining the lionfish invasion: how growth and recruitment relates to connectivity and controls. *Open Access Dissertations*. Paper 1721.

Morris J.A., Jr. and P.E. Whitfield. 2009. *Biology, Ecology, Control and Management of the Invasive Indo-Pacific Lionfish: An Updated Integrated Assessment.* NOAA Technical Memorandum NOS NCCOS 99. 57 pp.

Morris, J.A., A. Thomas, A.L. Rhyne, N. Breen, L. Akins, and B. Nash. 2011. Nutritional properties of the invasive lionfish: a delicious and nutritious approach for controlling the invasion. *Aquaculture, Aquariums, Conservation & Legislation* **5**:99-102.

Nuttall, M.F., M.A. Johnston, R.J. Eckert, J.A. Embesi, E.L. Hickerson and G.P. Schmahl. 2014. Lionfish (*Pterois volitans* [Linnaeus, 1758] and *P. miles* [Bennett, 1828]) records within mesophotic depth ranges on natural banks in the northwestern Gulf of Mexico. *BioInvasions Records* **3:**111-115.

Pitt, J., and T. Trott. 2013. Efforts to develop a lionfish-specific trap for use in Bermuda waters. *Proceedings of the Gulf and Caribbean Fisheries Institute* **66**:188-190.

Reed, J.C., S. Farrington, S. Harter, H. Moe, D. Hanisak, and A. David. 2015. Characterization of the mesophotic benthic habitat and fish assemblages from ROV dives on Pulley Ridge and Tortugas during 2014 R/V Walton Smith Cruise. Project Grant: NA11NOS4780045. 133 pp.

Switzer, T.S., D.M. Tremain, S.F. Keenan, C.J. Stafford, S.L. Parks, and R.H. McMichael Jr. 2015. Temporal and spatial dynamics of the lionfish invasion in the eastern Gulf of Mexico: perspectives from a broadscale trawl survey. *Marine and Coastal Fisheries* **7**(1):1-8.