Biology, Ecology, Control and Management of the Invasive Indo-Pacific Lionfish: An Updated Integrated Assessment

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Cover image: Image of lionfish invasion in a Bahamian coral reef. Photo courtesy Richard Carey.

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Biology, Ecology, Control and Management of the Invasive Indo-Pacific Lionfish: An Updated Integrated Assessment

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Summary

Venomous Indo-Pacific lionfish (*Pterois miles* and *P. volitans*) are now established along the Southeast U.S.A. and parts of the Caribbean and pose a serious threat to reef fish communities of these regions. Lionfish are likely to invade the Gulf of Mexico and potentially South America in the near future. Introductions of lionfish were noted since the 1980s along south Florida and by 2000 lionfish were established off the coast of North Carolina. Lionfish are now one of the more numerous predatory reef fishes at some locations off the Southeast U.S.A. and Caribbean. Lionfish are largely piscivores that feed occasionally on economically important reef fishes. The trophic impacts of lionfish could alter the structure of native reef fish communities and potentially hamper stock rebuilding efforts of the Snapper –Grouper Complex. Additional effects of the lionfish invasion are far-reaching and could increase coral reef ecosystem stress, threaten human health, and ultimately impact the marine aquarium industry. Control strategies for lionfish are needed to mitigate impacts, especially in protected areas. This integrated assessment provides a general overview of the biology and ecology of lionfish including genetics, taxonomy, reproductive biology, early life history and dispersal, venom defense and predation, and feeding ecology. In addition, alternative management actions for mitigating the negative impacts of lionfish, approaches for reducing the risk of future invasions, and directions for future research are provided.

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Introduction

Invasive species are capable of competing with native organisms, altering habitats (Mack et al. 2000; Kolar and Lodge 2001; Rahel 2002; Olden et al. 2004), reducing biodiversity (Olden et al. 2004), and even causing extinctions of indigenous plants and animals (Clavero and García-Berthou 2005). Extreme economic costs have resulted from many invasions, e.g., Formosan termite, which causes an estimated $300 million in damage annually in New Orleans alone (NISC 2001). Recent estimates suggest that the cost of invasive species to the U.S. economy is $137 billion annually (Pimentel et al. 2000; 2005).

The increase in the frequency of bioinvasions over the last century is astounding. Bioinvasions have increased significantly since the beginning of the industrial revolution and are strongly correlated with economic growth (Lin et al. 2007). As a result of increased shipping traffic and world travel, the species composition of our diverse ecosystems is being homogenized causing direct and indirect changes to our natural resources.

The number of introductions of nonindigenous species[1] into estuarine and coastal marine environments is small compared with terrestrial and freshwater systems. Owing to the rapid increase in coastal development and shipping over the past several decades, marine introductions are accelerating with more than 400 invasions reported along the

[1] Invasion ecology is replete with adjectives describing nonindigenous species, some of which have a negative connotation for the local environment (i.e., invasive, weedy) or on humans (i.e., noxious, nuisance) (Colautti and Maclsaac 2004). The term 'invasive species' used throughout this report follows the definition provided in the federal register as an organism that is: 1) non-native (or alien) to the ecosystem being considered; and 2) likely to cause economic or environmental harm or harm to human health (Invasive Species Executive Order No. 13112). By this definition, range extensions of native species or nonindigenous species that exhibit no potential for ecological or economic impacts are not considered invasive species.

Pacific, Gulf, and Atlantic coasts of the U.S.A. (Ruiz et al. 1997). Species introduced into nearshore environments of the U.S. East Coast, such as the European green crab (Behrens Yamada 2001), tunicates (Lambert 2007), and more recently ornamental finfish (Semmens et al. 2004), are nearly impossible to eradicate once established, given the expansive habitats, high connectivity and complexity of estuarine and oceanic currents, and constant propagule pressure (Drake and Lodge 2006). Over the past century, more than 68 marine introductions have occurred in Florida, the Caribbean, and the Gulf of Mexico (USGS 2009). The taxonomic diversity of these introductions is high (Figure 1) and few studies have assessed their vectors and potential impacts.

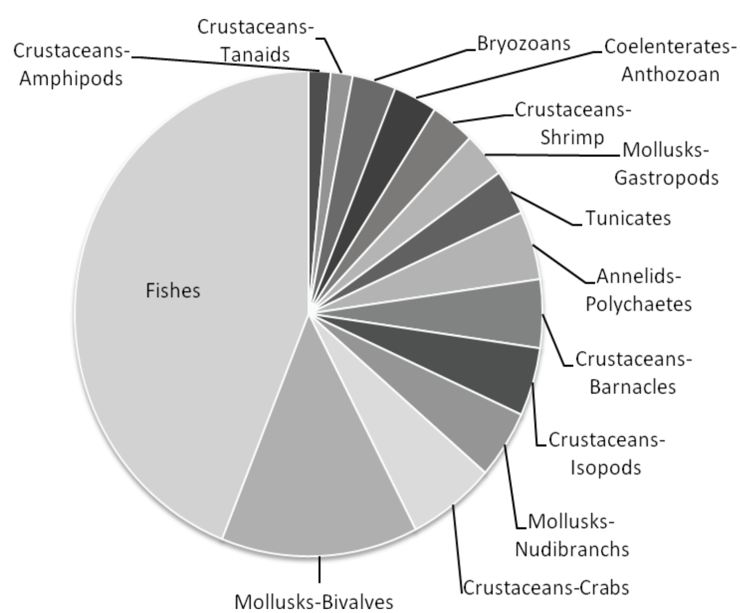

Figure 1. Summary of marine introductions (n=68) sorted by taxa for Florida, Caribbean, and Gulf of Mexico regions from 1887 – 2009. Data courtesy of the U.S. Geological Survey Nonindigenous Aquatic Species Database (USGS-NAS 2009).

While fewer marine fish introductions have occurred relative to freshwater systems, marine fish invasions are considered highly consequential and capable of displacing native species, and altering biodiversity and community structure (e.g., Grozholz et al. 2000; Streftaris et al. 2005). Baltz (1991) provides a review of non-native marine fish introductions and reports that well over 100 species have been introduced worldwide. Many of these introductions are the result of transplantations for fisheries enhancement, canal construction, or ballast water releases.

Since Baltz's report, some reef fishes have become established in Hawaii including the peacock grouper (*Cephalopholis argus*), bluestripe snapper (*Lutjanus kasmira*), and blacktail snapper (*Lutjanus fulvus*) following their intentional release in the 1950s (Randall 1987). Two of these species are causing economic or ecological harm. Bluestripe snapper are considered a nuisance by commercial fishermen who attribute the reduction in catches of valuable goatfishes (*Parupeneus porphyreus* and *P. multifasciatus*) to the overabundance of bluestripe snapper (Randall 1987). Since Randall's (1987) assessment, the peacock grouper has undergone significant population growth and it is one of the most dominant near shore reef predators in the main Hawaiian Islands (Dierking 2007). Consumption of the standing stock biomass of the reef fish community by peacock grouper now exceeds 11%; thus, they are likely altering community structure (Dierking 2007). No negative impacts of the blacktail snapper have been reported, likely a result of their low abundance (Randall 1987).

The Mediterranean provides abundant examples of the profound impacts of non-natives. Over 60 Red Sea fish species have entered the eastern Mediterranean via the Suez Canal and are either established or undergoing rapid colonization (Golani 1993;

Goren and Galil 2005). The extent of the changes in marine fish assemblages resulting from these invasions is wide-reaching and well documented (Goren and Galil 2005). The most alarming impact is the irreversible domination of community structure (50-90% of fish biomass) and alteration of the food web (Goren and Galil 2005). Species-specific examples include the non-native rabbitfishes (*Siganus rivulatus* and *S. luridus*) that have replaced native herbivores and drastically changed the dynamics of energy flow through the food web (Galil 2007). The goldband goatfish (*Upeneus moluccensis*) has replaced the native red mullet (*Mullus barbatus*) in commercial fisheries, providing a classic example of niche takeover by a non-native species following a failed year-class of a similarly trophic-positioned native species (i.e., occupation of a vacant niche) (Galil 2007).

In North and South America, anadromous salmonids have been introduced either intentionally or unintentionally as a result of releases from aquaculture operations. One highly problematic example is the Chinook salmon (*Oncorhynchus tshawytscha*) that was intentionally introduced into Chile from 1978 to 1989. It is now spreading across a large part of South America and poses an ecological concern during both the freshwater (increased nutrient release in upwater streams) and marine (trophic imbalance) components of its life history (Correa and Gross 2008).

The interactions of invasive species with other stressors, such as global climate change, have long been a concern. Perhaps the most poignant example of how small changes in water temperature can influence the invasiveness of a non-native is the lizardfish (*Saurida undosquamis*). After being introduced into the Mediterranean via the Suez canal, the lizardfish exhibited a rapid increase in abundance in 1955, which has been attributed largely to a 1-1.5°C rise in seawater temperature (Galil 2007). Lizardfish in the eastern Mediterranean displaced the native hake (*Merluccius merluccius*) and became so abundant that they constituted more than one fifth of the total landings along the Mediterranean coast of Israel (Galil 2007). Given the forecasted increases in seawater temperature owing to global climate change, concern should be given to how small changes in water temperature could influence both the abundance and scale of impacts of invasive species. Understanding the invasiveness of invaders will require an integrated approach, encompassing many aspects of biology, ecology, and their interactions with abiotic influences.

A recent introduction of the tropical marine reef fishes, the red lionfish (*Pterois volitan*) and devil firefish (*P. miles*) (Scorpaenidae, order Scorpaeniformes) into the western North Atlantic, has resulted in a rapid rate of establishment (Figure 2). Lionfish[2] were first reported in the 1980s along South Florida and have now spread along the Southeast U.S.A. and well into the Caribbean (Figure 2). The eventual distribution of lionfish is likely to be restricted by thermal tolerance (Kimball et al. 2004) and will ultimately include the Gulf of Mexico, the entire Caribbean, and as far south as the temperate regions of the east coast of South America (Figure 3).

As a venomous scorpionfish native to the Indo-Pacific, lionfish are considered invasive (Invasive Species Executive Order No. 13112) because of their probable

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[2] *Pterois miles* and *P. volitans* are valid (Schultz 1986), sympatric species with overlapping meristic characters, definitively distinguishable only by genetics (Hamner et al. 2007). The term "lionfish" in this integrated assessment refers collectively to both species.

Figure 2. Progression of the lionfish invasion from 2000 to 2009. Sightings data courtesy of the U.S. Geological Survey Nonindigenous Aquatic Species Database, NOAA, and the Reef Environmental Education Foundation.

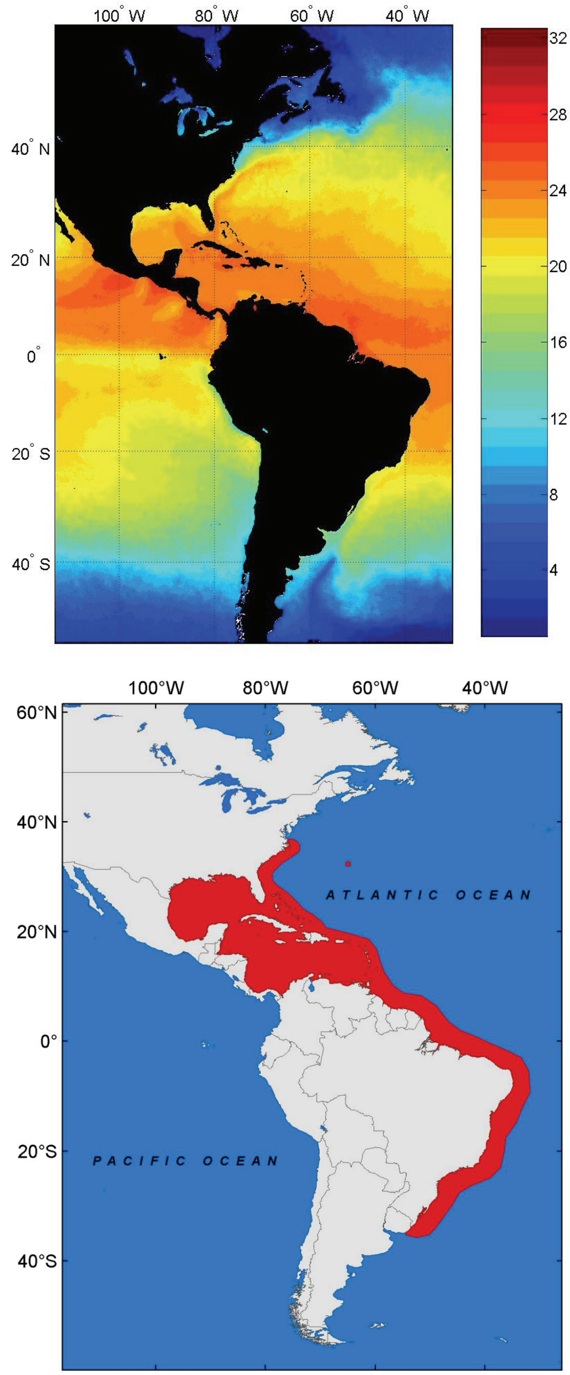

Figure 3. Composite 9 km resolution image of average annual sea surface temperatures (°C) collected by Aqua MODIS in 2008 for North, Central, and South America (top) and potential future range of lionfish based on the lethal thermal minimum of 10°C (bottom) (Kimball et al. 2004).

impacts to native reef fish communities (Albins and Hixon 2008; Morris et al. 2009) and to human health (Vetrano et al. 2002). Prior to the introduction of lionfish, little information on their biology and ecology was available. As a result, much of what has been learned about lionfish in their invaded range is new information for the species or genus. An early integrated assessment for lionfish conducted by researchers at the National Oceanic and Atmospheric Administration (Hare and Whitfield 2003) gathered what little life-history information was available and predicted the likely introduction source, dispersal method, and probable ecosystem impacts. Emerging evidence indicates that many of the early predictions by Hare and Whitfield (2003) are being realized including: 1) the aquarium trade is the probable primary vector (Semmens et al. 2004; Ruiz-Carus et al. 2006); 2) the east coast of Florida is the likely the source of introduction (Hamner et al. 2007; Freshwater et al. 2009); 3) dispersal is accomplished by ocean currents during pelagic egg and larval stages of lionfish; and 4) ecosystem impacts are likely to result from predation interactions. In addition, Hare and Whitfield (2003) predicted that without management action lionfish densities along the Southeast U.S.A. shelf would continue to increase and that ecosystem effects of this increase would become more noticeable. The incidence of envenomation is also predicted to become more common. To minimize these potential impacts, a three-pronged approach was recommended that included lionfish population control, outreach and education, and research. Since 2003, much progress has been made on all three recommendations and a large body of research on lionfish has ensued. Further, many of the research topics provided in this assessment were driven by requests from coastal managers for information about lionfish and the inherent need to develop management approaches.

Documentation of Status and Trends

The following information represents the most complete and up-to-date summary of the following aspects of lionfish biology and ecology.

Lionfish density and distribution

Lionfish were first reported along the east coast of south Florida in 1985 (Schofield 2009; Morris and Akins 2009). Sporadic sightings[3] and collections occurred from that time in South Florida until 2000 and 2001 when NOAA researchers documented multiple lionfish off the coast of North Carolina and off South Carolina, Georgia, Florida and Bermuda (Whitfield et al. 2002). Over the next two years, lionfish densities and reportings off the Southeast U.S.A. shelf continued to increase (Hare and Whitfield 2003). In 2004, lionfish were first detected in the Bahamas (Snyder and Burgess 2006; Whitfield et al. 2007; Schofield 2009; Schofield et al 2009a) and have since systematically increased their range throughout much of the Caribbean (Chevalier et al. 2008; Guerrero and Franco 2008; Freshwater et al. 2009; see Schofield et al. 2009a for the current status). As of this writing, lionfish have not invaded the Gulf of Mexico, however, an invasion is likely to be forthcoming (Figure 3).

The first estimates of lionfish densities in the Atlantic were reported by Whitfield et al. (2007) who observed a mean of 21 lionfish per hectare across 17 locations off North Carolina in 2004. By 2008, mean lionfish densities were approximately 150 lionfish per hectare with some sites exhibiting nearly over 350 lionfish per hectare (>450 lionfish per

[33] Some reports have implied that the release of six lionfish into Biscayne Bay, Florida during Hurricane Andrew (Courtenay 1995) was the initial source of lionfish in the western North Atlantic. It should be noted that while Courtenay (1995) did provide the first published record of lionfish releases in the Atlantic,

hectare was observed in 2007) (Figure 4). Green and Côté (2009) reported similarly high densities of lionfish in the Bahamas. These results suggest that lionfish are thriving in both the warm temperate and subtropical reaches of the Atlantic. Lionfish densities in the Atlantic appear orders of magnitude higher than observed in their native range (Green and Côté 2009; Grubich et al. 2009).

Factors controlling lionfish densities in their Indo-Pacific native range are unknown. Lionfish are reported to have few natural predators, a likely consequence of their venomous spines (Bernadsky and Goulet 1991; Morris 2009). Native sea basses (*Centropristis striata*) in the Atlantic demonstrated avoidance for lionfish as prey in laboratory experiments (Morris 2009). Malijkovic et al. (2008), however, reported that three grouper individuals consumed lionfish in the Bahamas. It is uncertain at present if groupers or any other reef predators will feed with regularity on lionfish and if this consumption will be significant enough to provide predation mortality capable of reducing the lionfish population.

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the number of reports off Florida prior to Hurricane Andrew suggests that lionfish establishment could have been the result of multiple releases in both time and space.

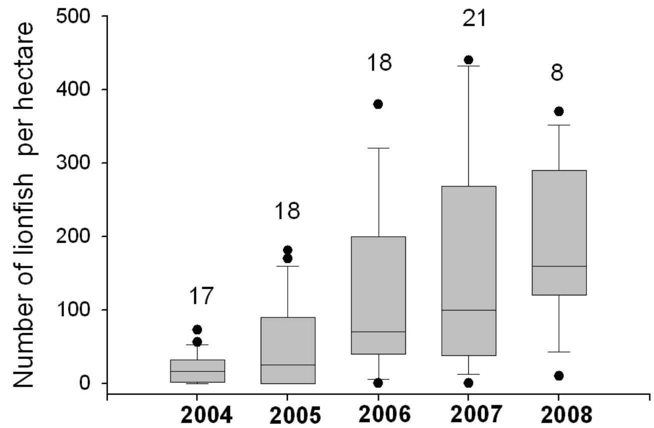

Figure 4. Lionfish density estimates at hardbottom and wreck sites off North Carolina from 2004 – 2008 using a 50-m belt transect. Surveyed locations include depths from 95 to 150 feet. All sites were not surveyed each year. Number of sites surveyed per year is provided above box plots. Box plots display the interquartile range (box), median (center line in box), 10th and 90th percentiles (whiskers), and outliers (black dots).

Genetics and Taxonomy

Two species of lionfish, *Pterois miles* and *P. volitans* were introduced into the Atlantic (Hamner et al. 2007). *Pterois miles* are much less abundant than *P. volitans* off North Carolina (Hamner et al. 2007) and have not been found in the Bahamas (Freshwater et al. 2009). In their native range, *P. miles* are distributed in the Red Sea, Persian Gulf, and the Indian Ocean (excluding Western Australia). *Pterois volitans* are observed in both the Western and Central Pacific and Western Australia (Schultz 1986). At the margins of their native range, *P. miles* and *P. volitans* are distinguishable by meristics (*P. volitans* exhibits one additional dorsal and anal fin ray). Overlapping meristics are common in regions co-occupied by both species making their identification to species difficult without genetic analysis. It is unknown if *P. miles* and *P. volitans* hybridize, although

Morris (2009) observed no differences in their reproductive biology. Recent assessments have confirmed that lionfish in the Atlantic have low genetic diversity typical for invasive species in the early stages of the introduction (Hamner et al. 2007; Freshwater et al. 2009).

Reproductive biology

Lionfish are gonochoristic pair spawners that exhibit a complex courtship prior to spawn release. In their native range, lionfish courtship occurs shortly before dark and may extend well into the nighttime hours (Fishelson 1975). Towards the end of the courtship, the female ascends toward the surface and releases two egg masses, one from each ovarian lobe (Morris 2009). Lionfish spawn throughout the year at a frequency of approximately every four days in North Carolina and the Bahamas (Morris 2009). This spawning frequency equates to an annual fecundity of over two million eggs (Morris 2009).

Lionfish females mature around 180 mm total length, while male lionfish mature at approximately 100 mm total length (Morris 2009). Based on unvalidated estimates of daily age using otoliths, lionfish are capable of becoming sexually mature within their first year of life (Ahrenholz and Morris, unpub. data).

Early life history and larval dispersal

Lionfish embryos develop at the ocean surface within the gelatinous egg mass. Lionfish larvae are grouped among an unresolved “morph B” morphotype for scorpaenid larvae (Leis and Rennis 2000). This morphotype is distinguishable by a large head, long triangular snout, serrated head spines, large pelvic spine, and pigmented pectoral fins. At hatching, pteroine larvae are approximately 1.5 mm (Mito and Uchida 1958; Mito 1963). Recent assessments of the lionfish larval duration suggests that settlement occurs around 26 d post hatch (Ahrenholz and Morris, unpub. data), a pelagic larval duration that facilitates dispersal via oceanographic currents (i.e., Gulf Stream, Gulf of Mexico loop current, Caribbean current) throughout the Southeast U.S.A., Gulf of Mexico, and Caribbean (Cowen et al. 2006). The specific larval duration of lionfish is likely to vary depending on factors such as temperature.

Venom defense and predation on lionfish

Lionfish dorsal, ventral, and anal spines are venomous. The lionfish venom apparatus consists of two glandular grooves extending from the base of the spine three quarter distance towards the tip (Halstead et al. 1955). The apocrine-type glands release venom when the tissue is disturbed, typically the result of the spine entering the victim. This penetration pushes the spine integumentary sheath ventrally, exposing and tearing the glandular tissue and releasing the venom (Saunders and Taylor 1959).

Lionfish venom is composed of acetylcholine and a neurotoxin (Cohen and Olek 1989) that causes pain and other physiological problems in humans (Kizer et al. 1985; Vetrano et al. 2002). Lionfish stings in humans can be treated using heat (Ventrano et al. 2002) and antivenom from the closely related stonefish (*Synanceia* spp.) (Shiomi et al. 1989; Church and Hodgson 2002).

Lionfish venom defense as a predation deterrent is not well understood. Lionfish venom can kill other fish species (Allen and Eschmeyer 1973), however, anecdotal observations suggest that this is rare. Large top-level predators have been observed to avoid juvenile lionfish as prey in the laboratory (Morris 2009), however, Malijkovic et al. (2008) reported three juvenile lionfish in the stomach contents of two grouper species. At the present time, it is unknown whether grouper predation on lionfish is common and if grouper predation could cause significant reductions of lionfish populations.

Feeding ecology

Adult lionfish in the Bahamas feed on more than 40 species of prey fishes including small gobiids, labrids, grammatids, apogonids, and pomacentrids as well as juveniles of larger serranids, mullids, lutjanids and others. These teleosts are among the abundant forage fishes in coral reef environments and are important diet constituents for economically important species such as snappers and groupers (Morris and Akins 2009).

In the Indo-Pacific, *Pterois miles* also feed on benthic reef fishes including damselfish, cardinal fish, and anthias (Fishelson 1975; 1997) and *P. lunulata* feeds primarily on penaeid and mysid shrimps (Matsumiya et al. 1980; Williams and Williams 1986). Lionfish's ability to withstand long periods of fasting is possibly explained by the expansion of the stomach to over 30 times the initial volume after consuming a large meal (Fishelson 1997). This feeding pattern has been observed in the Atlantic where lionfish have been collected with over 20 haemulids in the stomach and exhibit large volumes of visceral fat.

Description of Potential Causes and Consequences of the Lionfish Invasion

Potential sources of the lionfish introduction

The number of lionfish reported from 1985 to 2000 in south Florida provides strong evidence that the east coast of southern Florida could have been the location of the first introduction(s). South Florida is a known hot-spot for other marine introductions (Semmens et al. 2004) with over 30 species of non-native marine and estuarine fish reported within the last decade (Schofield et al. 2009b). Lionfish are popular ornamental fish that are heavily imported into the U.S.A. for the aquarium trade. Ruiz-Carus et al. (2006) noted that lionfish are one of the top ten most valuable marine fish imported into the U.S. (7,562 in six months through the Tampa airport alone in 2003). Genetic analysis suggests that the introduced lionfish originated from Indonesia, a common origin for many lionfish imported into the U.S.A. (Hamner et al. 2007).

Recent genetic research found no differences between Bahamian and Southeast U.S.A. lionfish specimens (Freshwater et al. 2009). This genetic similarity, combined with the invasion lag time (2000 NC, 2004 Bahamas), support the initial source location of the lionfish introduction as the Florida east coast. This also is evidence of larval connectivity between Florida and the Bahamas (Freshwater et al. 2009, C. Paris, University of Miami, pers. comm.). Thus far, lionfish dispersal southward into the Caribbean follows a pattern that closely resembles the Caribbean connectivity model developed by Cowen et al. (2006) for damselfish.

Lionfish ecological impacts

The future expansion of lionfish into the coastal waters of the southern Caribbean, Gulf of Mexico, and eastern South America is probable and troublesome. Coral reef environments in the Caribbean basin are presently under stress because of environmental and anthropogenic factors including coral bleaching, fishing pressure, pollution, global climate change, and disruptive algal growth (Wilkinson and Souter 2008). The addition of a nonindigenous, predatory reef fish along with the existing coral reef stressors could cause irreversible changes in these systems. Probable impacts include a reduction of forage fish biomass (Albins and Hixon 2008), possible increase in algal growth owing to herbivore removal by lionfish (Morris 2009), and competition with native reef fish. Lionfish are considered to be among the influential reef predators known to impact prey community structure (Fishelson 1997). This influence could cause cascading trophic impacts on economically important species and result in niche takeover by lionfish.

Lionfish densities in the Atlantic are much higher than reported for their native range (Whitfield et al. 2007; Green and Côté 2009; Grubich et al. 2009). Recent visual census surveys indicate that lionfish at their present densities are capable of removing all of the forage fish biomass produced in some reef systems (S. Green, Simon Fraser University, pers. comm.). Future monitoring of lionfish diets could indicate prey switching whereby more crustaceans enter their diet as forage fish abundance declines. An increase in crustacean consumption by lionfish could directly impact some economically important species as crustaceans are a staple in the diet of some juvenile and adult serranids (Eggleston et al. 1998).

Lionfish are piscivores and thus could compete with other native reef fish for food resources. The Snapper-Grouper Complex (i.e., snappers, groupers, porgies, triggerfish, jacks, tilefishes, grunts, spadefishes, wrasses, and sea basses) is heavily exploited by commercial and recreational fisheries possibly resulting in niche vacancy in the reef fish community (Huntsman et al. 1999). The occupation of this vacated niche by lionfish could be problematic for stock rebuilding programs presently underway for the Snapper-Grouper Complex of the Southeast U.S.A. and Caribbean. There are classic examples of niche takeover by one fish species following the removal of another (Botsford et al. 1997). It is unclear if niche takeover by lionfish will impact stock recovery of threatened species such as Nassau grouper. Lionfish impacts will likely be the highest in locations that are heavily stressed, such as coral reef environments of the Caribbean. Reduction of lionfish densities via control measures is a possible way to protect native stocks.

Understanding and predicting lionfish impacts will ultimately depend on baseline knowledge of the communities that lionfish invade. Future research emphasis and collection of baseline data is needed to elucidate lionfish ecological impacts especially for locations where no estimates of the long term variability (seasonally, inter-annually, etc.) of small-bodied finfish exists.

Lionfish socio-economical impacts

The socio-economic impacts of lionfish have not been considered to date and could include impacts on commercial fisheries, the aquarium trade, or coastal tourism industries of the Southeast U.S.A. and Caribbean (Table 1). Lionfish feed directly on juveniles of some commercial fishery species such as yellowtail and vermilion snapper and at least one threatened species, Nassau grouper. Attributing declines in these or other economically important species to interactions with lionfish is difficult given high annual variability in recruitment and fishing pressure. Furthermore, economically important species are of relatively low importance in lionfish diet (Morris and Akins 2009). Lionfish diet shifts, however, could result in higher predation on juvenile economically important species as densities of lionfish increase and as foraging pressure by lionfish alters the prey fish community. Lionfish predation on juveniles of commercially important species is also more likely to occur in tropical coral reef environments where lionfish inhabit the nursery areas of these species more frequently. Monitoring efforts to assess changes in lionfish diet and frequency of predation on economically important species are needed to assess the long-term impacts of lionfish on commercially important species.

The harvesting of lionfish presents an opportunity to develop a new fishery and thus could result in some local economic benefits. Given the present status of the snapper-grouper stocks of the Southeast U.S.A. and Caribbean, lionfish harvesting could provide an alternative fishery. Lionfish are venomous, not poisonous[4]; therefore, special handling precautions to avoid envenomation are only needed during collection and immediately post-mortem.

During the early stages of the invasion, some reports of lionfish as a dive attraction were also observed. It is unknown if this activity has resulted in substantial gain for the dive tourism industry. Over the last few years, however, the focus among most dive operators has shifted towards a removal ethic rather than attraction. In heavily invaded areas such as the Bahamas, many divers are tiring of witnessing the large

[4] The lionfish neurotoxin located within the venomous spines and is not found elsewhere in the body. Lionfish meat is thus nonpoisonous.

abundance of lionfish and relative low abundance of other native species. Further, some resort locations have now posted signs warning swimmers of possible envenomation risks.

Anecdotal observations also suggest that aquarium sales of lionfish have fallen since the lionfish invasion. Given that lionfish was one of the most valuable marine ornamental fish, this economic impact is likely to be significant. Future assessments of the combined economic impacts of the lionfish invasion could find that the negative effects of this invasion far exceed any economic benefits.

Table 1. Description of potential economic impacts of lionfish.

Potential Economic Impact	Impact Type	Pos. or Neg.
Reduction in landings of economically important species	Fishery	-
New fishery species	Fishery	+/-
Increase/decrease in dive/snorkel tourism	Tourism	+/-
Incidence of marine envenomations	Tourism; recreation	-
Decrease in aquarium sales of lionfish	Aquarium industry	-

Forecasts of Future Conditions With No Management Action

Presently, there are no region-wide management plans for invasive lionfish in the coastal waters of the Southeast U.S.A., Gulf of Mexico, or Caribbean Sea. Lionfish are increasing in both their new range distribution and local densities. Lionfish distribution will likely expand southward and will be limited by cooler water temperatures along the east coast of South America (Figure 3). Lionfish densities will also likely continue to increase until resources become limiting, either by exceeding the carrying capacity of the local environment or through competition with native species. Lionfish are already one of the more numerous reef predators at some locations in the Atlantic. The impacts of this predation pressure on the forage fish community and ultimately competition with economically important species is a tangible concern. While it is presently difficult to forecast the final densities and distribution of lionfish, the following general predictions can be made based on observed trends:

1. Lionfish densities will continue to increase and expand to new locations throughout the Caribbean. Lionfish will likely invade the Gulf of Mexico and the east coast of South America. North of Florida, lionfish will continue to be limited in their nearshore distributions owing to winter bottom water temperatures that exceed thermal limits. Lionfish will not become established north of southern Virginia also owing to their lethal thermal limit.
2. Lionfish densities could continue to increase unless population growth is checked by interspecific or intraspecific competition expressed as limited reef space or food resources.

3. Lionfish competition with native species could hamper stock rebuilding efforts for the Snapper-Grouper Complex of the Southeast U.S.A.
4. Indirect impacts of lionfish (e.g., alterations of community structure) could cause changes in the reef fish communities, especially in coral reef environments that are already heavily stressed.
5. Lionfish interactions with humans will continue to increase as lionfish densities increase. The number of envenomations of recreational swimmers, fishers, and divers will increase.

Possible Alternative Management Actions

The Management of Invasive Lionfish

The creation of wide-scale lionfish control strategies is problematic given the broad geographic distribution, high densities, and mode of lionfish reproduction. Control strategies for smaller, local populations such as the Florida Keys and parts of the Caribbean where lionfish are found in shallow and near shore waters, are likely more practical. Human consumption of lionfish is a plausible option for creating harvest pressure as lionfish meat is mild and firm, two necessary qualities for edible and palatable fish. Scorpionfishes are considered a delicacy in French and Mediterranean cuisine and are the basis for common dishes such as rascasse and bouillabaisse. Further development of markets, both locally and regionally, could create a demand for lionfish providing high market value and additional incentives for harvesting.

Lionfish harvest by divers could be an efficient removal and control strategy especially for locations with high numbers of lionfish and high ecological importance. Locations with high ecological importance include National Marine Sanctuaries, National Parks, or marine protected areas. Lionfish capture methods by divers such as spear fishing and net collecting are the most promising harvest techniques given their absence of bycatch. Recent efforts to focus collections by divers has resulted in over 1400 lionfish collected in one day during derby-style events and up to 19 lionfish collected in 14 minutes by one dive team (L. Akins, Reef Environmental Education Foundation, pers. comm.). Thus, the harvesting of lionfish by divers can provide significant local control, especially in locations that are easily accessible from shore or by boat.

Hook and line catches of lionfish have been reported along the Southeast U.S.A. (K. Brennan, National Marine Fisheries Service, pers. comm.) and Bermuda (C. Flook, Bermuda Aquarium Museum and Zoo, unpub. data); however, these catches have been low in number relative to the densities of lionfish reported in some of these locations. Bermuda fishermen are reporting regular catches of lionfish, however, in lobster traps, suggesting that lionfish could be harvested as a bycatch.

The development of regional strategies for lionfish control in the Southeast U.S.A., Gulf of Mexico, and Caribbean should also be considered. Strategies that employ existing snapper-grouper fishery resources could help offset the economic impacts of recent closures while simultaneously helping with lionfish control measures. The creation of a federal fishery for lionfish is problematic, because a "fishery" by definition invokes species protection under the Magnuson-Stevens Fishery Conservation and Management Act (16 USC 1801 et seq). Further, the precedent of establishing a formal fishery for an invasive species could increase illicit introductions. The creation of a long term economic dependence on lionfish is also not desirable, because the objective is to reduce lionfish populations to levels where their presence no longer impacts other fisheries (Morris 2009). When developing lionfish control strategies, which could include commercial harvest, it would be prudent at the onset to consider the long-term economic implications (e.g., economic dependence could result in lionfish stock protection, i.e., the Magnuson-Stevens Fishery Conservation and Management Act). A list of possible regional management options for invasive lionfish are provided in Figure 5.

Considerations should also be given to the indirect impacts that harvesting lionfish for human consumption could cause. For example, a spear fishery for lionfish would increase the spear fishing effort and could increase the incidental takes of protected stocks. This could be especially a concern in protected and no-take areas. Bycatch of native species and impacts of lionfish harvesting on reef habitats should be fully considered when developing lionfish harvest strategies given the stock status of many snapper and grouper and the stressed status of many reefs.

Alternative initiatives could also be used to support control strategies for invasive lionfish. Below are some examples of initiatives that could compliment management efforts:

1. Support incentives for developing novel strategies with low bycatch (i.e., snapper and grouper) specifically for collecting lionfish. Novel strategies might include traps with bait types that attract lionfish such as the use of live baits, decoys, and potentially pheromones.
2. Develop seafood marketing incentives for lionfish. Conduct workshops and develop educational materials on proper handling/cleaning of lionfish. Develop outreach initiatives on the benefits of eating lionfish as a “green” alternative to overfished species of the Snapper-Grouper Complex.
3. Integrate lionfish monitoring into existing fisheries-independent and dependent monitoring programs and identify additional funding to support monitoring where needed.
4. Develop removal teams in areas of high ecological/economic importance.

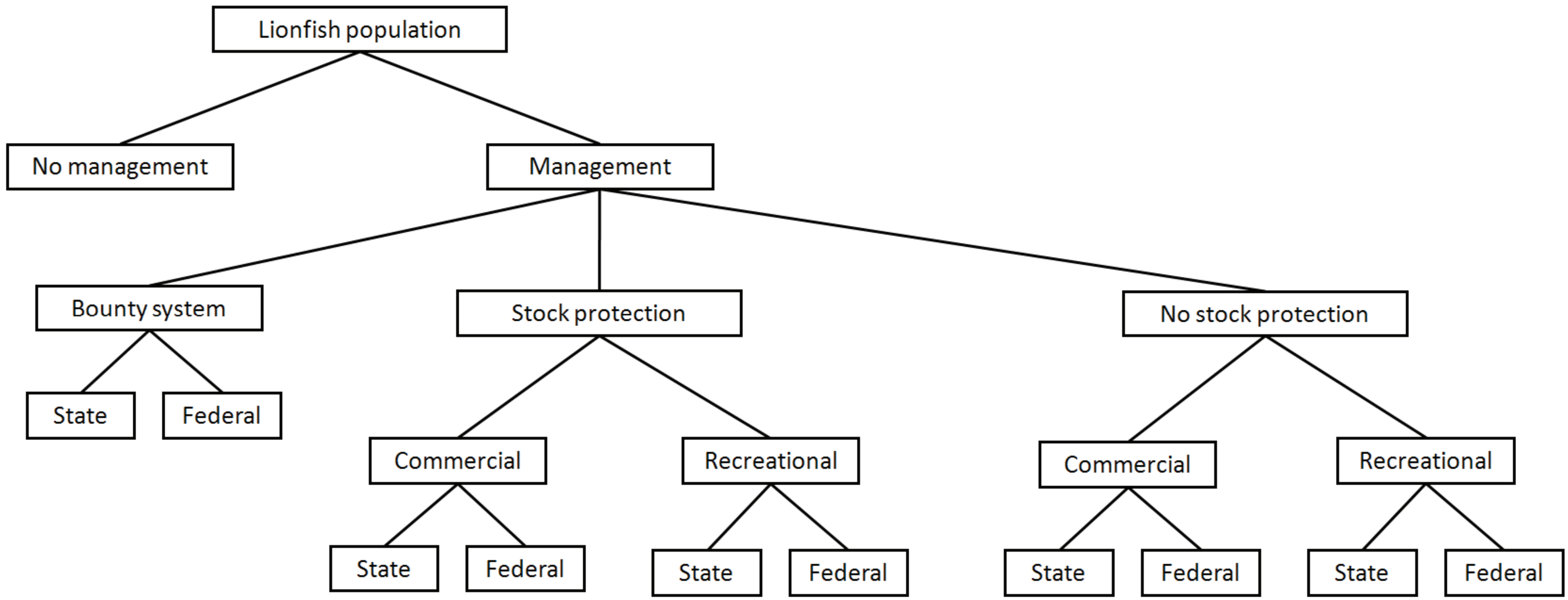

Figure 5. Management considerations for invasive lionfish in U.S. waters. Options may be combined to achieve multiple management goals or control strategies.

Population assessments

Documenting the effectiveness of lionfish control measures will require population-level abundance assessments. While some studies have documented the increase in lionfish densities at a few sites off North Carolina (Whitfield et al. 2007) and in the Bahamas (Green and Côté 2009), there are presently no efforts underway to comprehensively monitor the size or growth rate of lionfish population(s). Furthermore, without population assessment, it will be difficult to ascertain when lionfish approach or reach ecological carrying capacity.

The existing indices of abundance for reef fishes of the Southeast U.S.A. and Gulf of Mexico are not likely to provide adequate data for lionfish population assessment. Reef fishes are assessed in these regions largely using fisheries-dependent surveys (headboat sampling, logbooks, etc.) and some fisheries-independent surveys by the Marine Resources Monitoring, Assessment, and Prediction program (MARMAP). MARMAP surveys include the use of chevron fish traps and short longlines. Surveys of hook and line catches by headboats have produced only a few lionfish catches ($n<40$) in the Southeast U.S.A. since 2004 (K. Brennan, National Marine Fisheries Service, pers. comm.). The size of lionfish collected by hook and line suggests high sampling bias for the larger (male) lionfish (J. Morris, unpub. data). MARMAP chevron trapping surveys have not captured lionfish to date (M. Reichart, South Carolina Department of Natural Resources, pers. comm.); however, recent efforts to develop trapping methods for lionfish using live bait have been successful (J. Morris, unpub. data). The integration of lionfish sampling into existing MARMAP trapping efforts could result in a reliable index of abundance for MARMAP areas. Other fisheries independent indices and site-based monitoring programs (e.g., state and other federal monitoring programs, REEF, and university researchers, etc.) could collectively provide useful information on changes in lionfish densities. Further, the establishment of a central reporting database and funded assessments could be useful in developing wider-scale abundance estimates.

Future research directions

Much has been learned from biological invasions since the mid-1800s. Some of the fundamental principles of ecology (e.g., evolution, speciation, dispersal, population and island ecology, etc.) that limit species distributions and structure communities within ecosystems were developed from observations on biological invasions (Sax et al. 2007).

The lionfish introduction likewise represents “a natural experiment” capable of providing new information on fundamental ecological processes of the Southeast U.S.A., Caribbean, and Gulf of Mexico including dispersal, competition, and ultimately community structure. For example, the growing distribution of lionfish provides a model of dispersal as lionfish larvae are utilizing oceanographic currents and islands as stepping-stones throughout the Caribbean and ultimately into the Gulf of Mexico (Freshwater et al. 2009; Morris et al. 2009). This information could benefit future management of native reef fisheries through improved understanding of dispersal and connectivity (Cowen et al. 2006). Critical chokepoints should also be investigated for preventing new introductions or controlling the spread of established invaders (Hare and Whitfield 2003).

The lionfish invasion represents the first marine invasive finfish to become established along the Southeast U.S. coast, the Caribbean, and predictably in the Gulf of

Mexico. Little information is available on lionfish biology and ecology from the native range. For this reason, much of the research on lionfish represents new information for the species and genus and for marine invasive finfish in these regions. Hence, a major portion of biology, ecology, and population studies performed on fishes are relevant for lionfish in addition to questions related to invasive species ecology. The following research directions are provided below (Table 2).

Table 2. Future research directions for invasive lionfish (not prioritized).

Research needs

Zoogeographical studies
Tracking of sightings and establishment
Forecasting of future distribution

Population dynamics
Density estimates in native range
Density estimates in invaded range
Density forecasts for invaded range
Population abundance assessments
Factors controlling lionfish in native range
Dispersal mechanisms
Estimates of propagule pressure
Settlement rates
Genetics to determine dispersal pathways

Impacts
Local community and ecosystem impacts
Baseline community assessments
Diet across temporal and spatial scales
Competitive interactions
Venom effects on native predators
Ecological carrying capacity indicators
Interactions with global climate change
Consumption estimates

Control
Development of collection/harvest techniques
Identification of lionfish refuges
Assessment of removal strategies
Management options

Reproductive potential
Fecundity estimates and change over time
Rates of maturation and change over time
Spawning season/frequency by location

General fish biology
Parasitology
Genetics
Epigenetics
Bioenergetics
Age and growth
Bioenergetics

Invasiveness and lionfish

Past efforts have attempted to understand and even predict the likelihood for a species to become established outside of its native range. Using approaches such as 'species profiling' (Moyle and Light 1996; Ricciardi and Rasmussen 1998; Kolar and Lodge 2002) and quantitative analysis (Kolar and Lodge 2001; Marchetti et al. 2004a), risk assessments of invasiveness for many freshwater fish species have been developed (Ricciardi and Rasmussen 1998; Kolar and Lodge 2002). Given the high number of freshwater fish introductions over the past century, quantitative approaches are becoming possible, and are providing valuable insights into both abiotic and biotic characteristics that have enabled the establishment of past invaders.

There is, however, an inherent uncertainty in distinguishing between the abiotic and biotic factors that drive invasions (Kolar and Lodge 2001). Given the high variability of introductions among habitat types, the taxonomic diversity of invaders, and the lack of information on unsuccessful introductions (many of which are unreported), much can be gained through meta-analysis across many introductions and taxa of fishes. This approach increases the detectability of invasive characteristics and highlights the most invasive characteristics by virtue of their repeated occurrence (e.g. Ross 1991; García-Berthou 2007).

Lionfish possess multiple life history and ecological traits that together (Marchetti et al. 2004a) have enabled their rapid establishment along the Southeastern U.S.A. and Caribbean. It is unclear whether any individual component of lionfish life history has contributed more than others towards invasiveness. Lionfish have many of the same life-history traits that are known to be main predictors of invasiveness for freshwater fish (Table 3).

Table 3. Summary of main predictors of invasiveness for established nonindigenous freshwater fish species that are relevant to lionfish. The presence (Y) or absence (N) of each predictor is noted for lionfish. Predictor summary was adapted from a comprehensive review by Garcia-Berthou (2007).

Main predictor	Reference	Lionfish	Reference
Broad diet	1,7	Y	Morris and Akins 2009
High physical tolerance	1,2,3,8	Y	Kimball et al. 2004
Prior invader	1,2,3,10	Y	Golani and Sonin 1992
Fast growth	1	Y	Morris, unpub. data
Large native range	2,3	Y	Schultz 1986
High adult trophic status	2	Y	Morris 2009
High propagule pressure	2,3,5,6	Y	Ruiz-Carus et al. 2006
Long life span	3	Y	Morris, unpub. data
High fecundity	6,8	Y	Morris 2009
Large egg diameter	6	Y	Morris 2009
Long reproductive season	4	Y	Morris 2009
Young age at maturity	8	Y	Morris 2009
Large body size	2,9,10,5	Y	Morris 2009
Short distance to native source	2,10	N	Schultz 1986
Parental care	2,3,6	N	Morris 2009

1, Kolar and Lodge 2002; 2, Marchetti et al. 2004b; 3, Marchetti et al. 2004a; 4, Alcaraz et al. 2005; 5, Colautti 2005; 6, Jeschke and Strayer 2005, 2006; 7, Ruesink 2005; 8, Vila-Gispert et al. 2005; 9, Duggan et al. 2006; 10, Ribeiro et al. 2008.

Early Detection and Rapid Response

Prevention, early detection, and rapid response are the least expensive options for managing invasive species (Simberloff 2009). As observed with lionfish, invaders often exhibit a lag time before establishment that can sometimes consist of years to decades (Crooks 2005). It is during this lag time that early detection and rapid response (ED/RR) programs can be most effective, removing the invader before it has reached critical mass and exponential growth rate (Drake and Lodge 2006).

Development of ED/RR programs for coastal marine environments is perhaps more difficult than terrestrial and freshwater systems owing to the challenges of accessibility and expansiveness of marine systems (Locke and Hanson 2009). For marine ornamental fish introductions, ED/RR is a viable option, considering past introductions have been closely correlated with highly developed coastlines (Semmens et al. 2004). These areas often have intensive recreational dive tourism and recreational fishing activities that are capable of providing early detection. Education and outreach to local coastal resource managers and the public is important in establishing rigorous early detection.

Protected areas, such as National and State parks, National Marine Sanctuaries, and the National Estuarine Research Reserves are robust resources for early detection and should be viewed as sentinel locations. These areas typically have ongoing volunteer-based monitoring programs, locally trained staff or volunteers capable of detecting non-native species, and legislative mandates or Executive Orders intended to ensure protection of trust resources, e.g. Marine Protected Areas Executive Order (No. 13158), Marine Protection, Research, and Sanctuaries Act (16 U.S.C. 1431 et seq., 1447 et seq.;

33 U.S.C. 1401 et seq., 2801 et seq), National Marine Sanctuaries Act (Title III 16 USC 1431-14445c-1), Estuary (Estuarine) Protection Act (16 USC 1221-1226), Coral Reef Protection Executive Order (No. 13089), and the Coral Reef Conservation Act (16 USC 6401-6409). These mandates require managers of protected areas to work towards maintaining the biotic integrity of the resources that they manage.

The lionfish invasion has provided a stark example of the looming threat of marine invasive species and the consequences of delayed action. Protected area managers of National Parks and National Marine Sanctuaries, in the regions impacted by lionfish, are presently working to develop management plans capable of mitigating the impacts of lionfish (Appendix I). These plans will require the use of volunteer and park staff to monitor and detect early arrival and the impacts of invasive lionfish.

Examples of promising early detection and rapid responses are seen in South Florida, the Cayman Islands, and Cozumel, Mexico. South Florida is a region that has been inundated by marine ornamental introductions over the past decade (Semmens et al. 2004). In 2008, a team of researchers from the National Oceanic and Atmospheric Administration, the U.S. Geological Survey, and the Reef Environmental Education Foundation, organized a workshop to coordinate ED/RR among over 30 stakeholders and government agencies in South Florida. In under two years, this program has resulted in approximately 60 marine non-native fish sighting reports, 19 of which were confirmed and the fish removed within a few days of detection.

The Reef Environmental Education Foundation, in partnership with NCCOS, has been conducting workshops throughout the Caribbean to develop in-country early detection and rapid response programs. In the Cayman Islands, over 200 dive professionals have been trained and licensed to remove lionfish when they are sighted, resulting in the removal of over 300 yearling lionfish in the first seven months of the program. Marine park and resource managers in Mexico and Honduras have also implemented programs for ED/RR resulting in the removal of over 100 early arrivals in the first few months following initial reports of lionfish.

Considerations for import limitations

The unprecedented invasion of lionfish demonstrates the urgency for reviewing the present importation requirements for marine ornamental fishes. As of January 2009, the U.S. Congress is reviewing the Non-native Wildlife Invasion Prevention Act (H.R. 669), an Act that will require the Secretary of the Interior to develop a process for assessing the risk of all non-native wildlife species proposed for importation into the United States. This Act would expand upon the existing mandates aimed at preventing non-native introductions (e.g., Invasive Species Executive order (No. 13112), the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 (16 USC 4701-4751), and the National Invasive Species Act of 1996 (P.L. 104-332) to include a screening process based on invasiveness and the likelihood of establishment. This new legislation is different in that it takes a “guilty until proven innocent” rather than an “innocent until proven guilty” approach. In the present state, a species must be declared “injurious” under the Lacey Act of 1998 (18 USC §42), a classification that can take years to achieve before importation and interstate commerce is banned (see Lodge et al. 2006).

Predicting the invasiveness of marine ornamental finfish might be possible. For example, the life history characteristics exhibited by lionfish (Table 2) are found among other non-natives being imported in high volume into coastal regions of the U.S. and could be used as a starting point for risk assessment. At a minimum, those species that are expected to rapidly outgrow the living space provided by aquaria should be considered a high risk for intentional release (Duggan et al. 2006).

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Appendix I. Invasive Lionfish Control and Management Action Plan Florida Keys National Marine Sanctuary[5]

3.4.5 Invasive Lionfish Control and Management Action Plan

Introduction

Invasive lionfish (*Pterois miles* and *P. volitans*) are now well established along the Southeast U.S.A., Bahamas, and much of the northern and western Caribbean. Lionfish sightings and collections in the Florida Keys National Marine Sanctuary (FKNMS) were first reported in 2009, likely owing to larval dispersal into the FKNMS. Lionfish are piscivorous and are capable of reaching higher densities than native top-level predators in coral reef environments. The potential for lionfish impacts on sanctuary resources is far reaching from increased envenomations of commercial and recreational fishers, divers and swimmers to alteration of the structure of the reef fish community and thus the biotic integrity of the FKNMS.

Over 20 species of non-native fishes have been documented in South Florida over the past decade. Aquarium dumping has been identified as the likely source of these introductions given that most of the species are popular ornamental fish. Sightings and collection reports for these introductions can be found in a central depository database maintained by the United States Geological Survey (USGS) Nonindigenous Aquatic Species Program. Sightings information is frequently submitted into this database from sources such as the National Oceanic and Atmospheric Administration (NOAA), the Reef Environmental Education Foundation (REEF), Mote Marine Lab, the State of Florida, and the general public. In addition to tracking sightings, the USGS database also provides an automated alert system to subscribers. These resources are valuable assets to the FKNMS as services that are available and in kind.

In June 2008, representatives from approximately 30 state, federal, and non-profit institutions met during a workshop to develop an early detection and rapid response (ED/RR) program for non-native marine fish introductions in south Florida. This program identified ED/RR processes from sighting to removal. Since then, staff from NOAA's Office of National Marine Sanctuaries (ONMS) and NOAA's National Center for Coastal Ocean Sciences (NCCOS) have been partnering with USGS, REEF, and Mote Marine Lab to test and further refine ED/RR protocols for South Florida.

Invasive lionfish control and management in the FKNMS will benefit from the ED/RR program already in place and from refinements and revisions as the invasion progresses. To every extent possible, this action plan will draw upon existing resources to support the detection and removal of lionfish and other non-native fishes in the FKNMS.

[5] This Action Plan was collaboratively developed by S. Morton (FKNMS), S. Donahue (FKNMS), K. Carnes (FKNMS), L. Akins (REEF), C. Walters (MML), and J. Morris (NCCOS) and will be implemented into the Florida Keys National Marine Sanctuary Revised Management Plan pending further review.

Goals and Objectives

The goals of the Lionfish Control and Management Action Plan are to:

- Detect and control Lionfish abundance in the FKNMS;
- Identify and prioritize FKNMS marine zones requiring vigilant Lionfish control;
- Promote and build public awareness of the damaging ecological impact of Lionfish;
- Promote protection and sustainable use of Sanctuary resources;
- Facilitate uses of the Sanctuary that are consistent with resource protection;
- Ensure coordination and cooperation between Sanctuary managers and other Federal, state, and local authorities with jurisdiction within or adjacent to the Sanctuary

The objective of the Action Plan is to:

- Develop a detection, control and management strategy for lionfish that will reduce the densities and impacts of invasive lionfish in the FKNMS.

Implementation

The Invasive Lionfish Control and Management Action Plan will be implemented through a coordinated framework of federal, state, and local agencies, in cooperation with academic and research institutions. However, the FKNMS, NCCOS, and REEF will have the lead responsibility for overall program implementation.

Accomplishments

- Between January and September 2009, thirteen lionfish sightings have been reported to the FKNMS, of which ten were confirmed as lionfish, and eight of those successfully captured and removed.

Strategies

There are six strategies in this Invasive Lionfish Control and Management Action Plan.

- Strategy P.1 Lionfish and invasive species outreach
- Strategy P.2 Develop Lionfish collection and handling training and workshops for targeted users and partners, also using available multimedia technologies (e.g., DVDs, on-line video, etc.)
- Strategy P.3 Coordination of early detection and rapid response
- Strategy P.4 Issuance of lionfish collection permits to facilitate removal of lionfish in no-take areas
- Strategy P.5 Resource protection
- Strategy P.6 Scientific data collection

Each of these strategies is detailed below for three predicted phases of the lionfish invasion into the FKNMS. The criteria for each phase are provided in Table A.1.

Table A.1 Criteria and management objectives for three phases of the lionfish invasion into the FKNMS.

Invasion phase	Criteria	Management objective
Initial	<25 confirmed reports per year	Minimize or delay establishment in FKNMS
Early	>25 confirmed reports per year abundance low (1 individual per report)	Minimize or delay establishment; initiate impact mitigation strategies
Intermediate	> 200 confirmed reports per year abundance high (more than 1 individual per report	Minimize and mitigate lionfish impacts in all FKNMS zones
Advanced	>200 confirmed reports per year Evidence from resource protection strategies indicate control strategies are no longer efficient	Minimize and mitigate lionfish impacts to the extent possible in critical FKNMS zones

The estimated cost for implementation of these strategies over the next five years is provided in Table A.2 for each phase of the lionfish invasion.

Table A.2 Estimated Costs of the Lionfish Control and Management Action Plan for the invasion phases. Phases are not finite, thus for budgeting purposes they have overlapping considerations.

Lionfish Control and Management Action Plan phases	Estimated Annual Cost (in thousands)*					Total Estimated 5 Year Cost
	YR 1	YR 2	YR 3	YR 4	YR 5	
Phase 1 - Initial	80	30	-	-	-	110
Phase 2 - Early	-	120	120	-	-	240
Phase 3 - Intermediate	-		200	200	-	400
Phase 4 - Advanced	-	-	-	120	200	320
Total Estimated Cost	80	150	320	320	200	1,070
* Contributions from outside funding sources also anticipated						

STRATEGY P.1 LIONFISH AND INVASIVE SPECIES OUTREACH

Strategy Summary
The purpose of this strategy is to conduct outreach and education about lionfish and invasive species to stakeholders and the general public. Lionfish is an excellent tool for educating the public about invasive species.

Activities (1)

(1) ***Produce and Distribute outreach information*** on lionfish to promote awareness, detectability and central reporting of lionfish in the FKNMS. This includes distribution of stickers, flyers, and other outreach materials to dive shops, NGOs, state and federal agencies, and sanctuary staff.

Initial invasion

Status: Implemented and ongoing
Implementation: Lionfish stickers and flyers are being distributed in by the Reef Environmental Education Foundation, the Mote Marine Lab, and NCCOS. A June 2008 workshop in Marathon, FL, hosted by NCCOS, REEF, and USGS provided direct outreach on lionfish to representatives from over 30 institutions in South Florida. Various media outlets have covered the lionfish invasion along the Southeast U.S.A. and the Caribbean including newspapers, magazines, and major networks news coverage (Fox, NBC, CBS, Discovery).

Early invasion

Status: Initiated
Implementation: Organize and execute training workshops on lionfish awareness to promote detection and removal. Workshops should be targeted for dive operators, NGOs, and state and federal agency field staff. Outreach materials should be developed on threats to human health and distributed to USCG, medical staff, and the public through the print media and public service announcements. Bilingual outreach products are required.

Intermediate invasion

Status: TBD
Implementation: Development of an online awareness module for the general public including awareness and reporting, safe handling, and processing of lionfish for human consumption. Organize and execute lionfish collection events including derbies and tournaments.

Advanced invasion

Status: TBD
Implementation: Continue previous outreach efforts and evaluate effectiveness for supporting resource protection strategies. Include updated information and emerging strategies.

STRATEGY P.2 LIONFISH COLLECTING AND HANDLING TRAINING

Strategy Summary
The purpose of this strategy is to educate, enable key users in best collection and handling practices to aid in opportunistic removal of lionfish from frequented sites including no-take areas.

Activities (1)

(1) ***Develop and implement collection and handling training programs to facilitate community involvement in removing lionfish.***

Initial invasion

Status: Initiated
Implementation: Few individuals are trained and available to respond to early sighting reports. These responses include effective removal of fish as well as gathering of important ecologicial and biological data including dissections and archiving of early arrival specimens. Data will be forwarded to MEERA, REEF, NCCOS, or FKNMS for further distribution.

Early invasion

Status: Initiated
Implementation: Training is developed for key users to effectively remove lionfish considering effective and allowed gear restrictions. Training will be targeting key user groups and include best collecting and handling practices as well as reporting requirements.

Intermediate invasion

Status: TBD
Implementation: Evaluate effectiveness of removal by current permit holders and potentially broaden training to include private individuals and recreational users.

Advanced invasion

Status: TBD
Implementation: Consider lifting of individual permitting and movement towards blanket regulations on removal of lionfish.

STRATEGY P.3 PERMITTING REMOVALS OF LIONFISH

Strategy Summary
The purpose of this strategy is to develop a method for tracking lionfish removals, the impacts of lionfish removal in the FKNMS, and to ensure best collection and handling practices.

Activities (1)

(2) ***Establish permitting requirements for lionfish removal*** that will encourage the reporting of lionfish from existing permit holders and allow the collection of lionfish in no-take areas in consideration of gear restrictions and reportingrequirements.

Early invasion

Status: Initiated
Implementation: Few individuals are authorized via a letter of authorization (LOA) to remove lionfish from no take areas (gear restrictions apply). All researchers with permits and LOAs should be requested to report all lionfish sightings and include lionfish information in permit communications. No FKNMS permit required for removal of lionfish from areas other than no-take (SPAs, RO, and ER). Gear restrictions are applicable and should be enforced.

Intermediate invasion

Status: Initiated
Implementation: Permits should be developed for trained responders to remove lionfish from no take areas with gear restrictions. Individual names should be listed on the permit. No blanket permits for dive shops or organizations.

Advanced invasion

Status: TBD
Implementation: Evaluate permitting requirements and consider additional resources for improving efficiency of collection strategies and

reducing impacts of collections to the FKNMS. This may include adjusting gear restrictions.

Established invasion

Status: TBD
Implementation: Evaluate permitting requirements and consider additional resources for improving efficiency of collection strategies and reducing impacts of collections to the FKNMS. This may include adjusting gear restrictions.

STRATEGY P.4 COORDINATION OF EARLY DETECTION AND RAPID RESPONSE

Strategy Summary
The purpose of this strategy is to develop a coordinated network for the early detection of and rapid response (ED/RR) to lionfish and other non-natives in the FKNMS. This ED/RR network will utilize early detection resources from the recreational and commercial fishing/diving industries, NGOs, and state and federal agencies. Rapid responders will be trained to effectively remove invaders.

Activities (2)

(1) Develop a framework for ED/RR in South Florida. A framework for ED/RR is required in South Florida to coordinate collection of information on non-native sightings and initiate a response to reports. This framework should be inclusive of all organizations capable of detecting non-native marine organisms in the FKNMS.

Status: Initiated. Partially ongoing
Implementation: In June 2008, representatives from over 30 institutions developed a framework for ED/RR (Figure A1) for the entire South Florida region. This framework is operational and has resulted in over 20 reports of non-native sightings in the first year. FKNMS ED/RR activities will benefit from incorporation of this framework into Action Plan activities. The designation of a regional ED/RR coordinator is highly recommended to facilitate information sharing among state/federal agencies, NGOs, and other ED/RR partners and to assure data quality of sightings reports and collections.

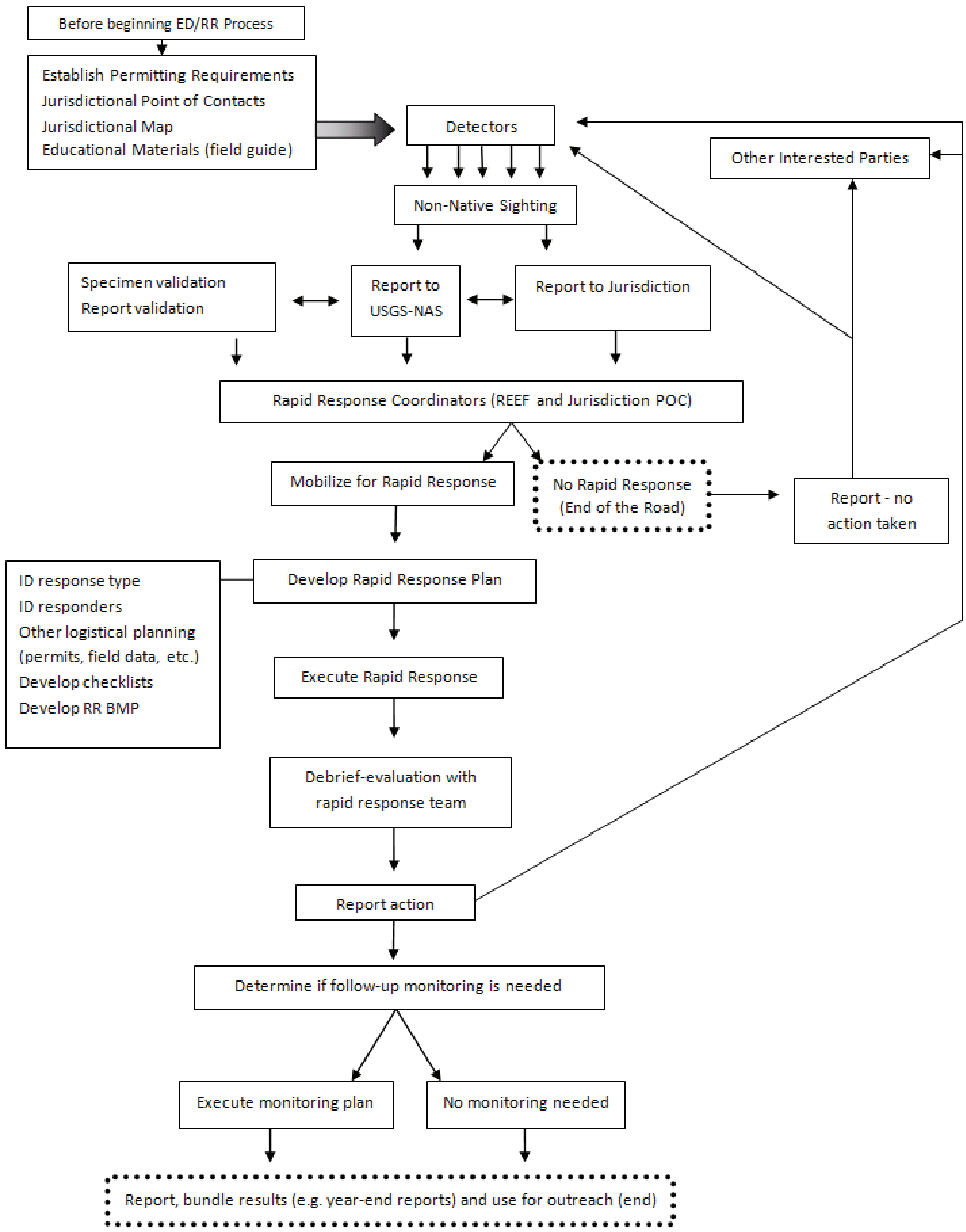

Figure A1. Conceptual model for an early detection and rapid response network.

(2) ***Conduct training workshops on ED/RR for lionfish and other non-natives.*** Workshops are needed to train early detectors and rapid responders on ED/RR protocols relating to lionfish and other non-native species.

> Status: Ongoing
> Implementation: Staff from the FKNMS, REEF, and NOAA/NCCOS are planning workshops. The specific objectives of the workshops are to train on lionfish detection and removal strategies and reporting protocols. Attendance to workshops should be required before permitting lionfish removal from no take areas during the early and intermediate phases of the lionfish invasion. Tools such as listservs, a website, and other methods may be used to facilitate communication to and among trained responders.

STRATEGY P.5 RESOURCE PROTECTION

Strategy Summary

The purpose of this strategy is to develop measures to assess effectiveness and maximize efficiency of lionfish control strategies leading to more effective resource protection. Resource protection measures will vary depending on the level of invasion, measureable impacts to the native coral reef community and human health and available control resources.

Activities (3)

(1) ***Surveys and removal of lionfish***. Field surveys directed at detecting and removing lionfish are needed to monitor the status of the invasion and protect FKNMS resources from lionfish impacts.

Early invasion

Status: Initiated. Partially ongoing.
Implementation: Removal of lionfish early arrivals is occurring in the FKNMS using existing ED/RR resources outlined in Strategy P.3. All data on lionfish location, capture success, and life history information is being archived by REEF staff in cooperation with NCCOS and FKNMS. Outside monitoring (REEF, NURC, FWC, others) is taking place incidentally with removal and reporting of lionfish sightings.

Intermediate invasion

Status: Initiated.
Implementation: Removal of lionfish from no take areas using trained and permitted rapid responders should be encouraged. Permitting requirements are provided in Strategy P.3. Training of rapid responders is provided in Strategy P.2. Additional efforts directed at highly invaded

areas or areas of high invasion probability should be implemented. Additional invasion data (micro habitat, genetics, etc) should be gathered during collections.

Advanced invasion

Status: TBD
Implementation: Development of dedicated lionfish removal teams capable of large-scale removal of lionfish from priority sites and critical habitats of the FKNMS.

Established invasion

Status: TBD
Implementation: Organize and execute regular lionfish tournaments and other events aimed at large-scale, but controlled, removal of lionfish from the FKNMS.

(2) Identify and prioritize FKNMS marine zones requiring vigilant Lionfish control. The lionfish invasion requires assessment of critical and priority habitat towards which mitigation resources should be focused. As demonstrated in the Bahamas and some parts of the Caribbean, lionfish are capable of reaching high densities within a couple of years. It will be prudent to assess beforehand which habitats of the FKNMS ED/RR resources should be focused, especially during the intermediate and advanced stages of the invasion.

Status: Initiated
Implementation: Previous efforts to characterize critical habitats within the FKNMS can provide guidance on focusing rapid response resources. FKNMS partners, including NCCOS, REEF, academic institutions can provide high-resolution data sources. Data mining efforts to assess the availability of this information based on permitted activities could help in this assessment.

(3) ***Development of a lionfish fishery.*** One of the most promising control strategies for lionfish is development of a fishery. Lionfish are a common foodfish in their native range and represent a eco-beneficial alternative to many of the overfished reef fish species of the Snapper-Grouper Complex.

Status: TBD
Implementation: The NMFS and FWC will have the lead responsibility. The FKNMS will benefit greatly from human consumption of lionfish as it will create intense fishing pressure and thus large-scale removal of this invader. The FKNMS is possibly the most promising location for this control strategy given the shallow water and diver accessible habitats and

large number of recreational and commercial divers. Lionfish can easily be marketed as an exotic and edible reef fish. This strategy will be best implemented during the advanced and/or established phases of the invasion given possible issues. Concern should be given to possible negative impacts that intense fishing pressure may cause if a lionfish fishery is developed in the FKNMS.

(4) ***Investigation and Development of Emerging Control Strategies*** – Research and development of new and emerging control strategies should be encouraged including those coinciding with potential market use or compatible with existing or potential commercial activities..

STRATEGY P.6 DATA NEEDS AND COLLECTION

Strategy Summary

The purpose of this strategy is to identify the data needs and collection criteria for forecasting the spread of lionfish and their impacts to FKNMS resources. This information will be used to develop impact mitigation measures and can be used as a guide for other protected areas including other sanctuaries, MPAs, and national parks.

Activities (1)

(1) Data collection and sample processing. The creation of a central reporting location for lionfish data collected from the FKNMS is needed to facilitate data collection and assure data quality. At present, the USGS Nonindigenous Aquatic Species database is the central repository for international sightings information. Additional database resources are needed to ensure collection of information on the biology, ecology, and ultimately impacts of lionfish in the FKNMS.

<u>Status</u>*:* Initiated and ongoing.
<u>Implementation</u>*:* FKNMS partners NCCOS and REEF have extensive research experience and data sets describing the biology and ecology of lionfish in coral reef habitats of the Bahamas. These resources are invaluable for predicting the impacts of lionfish and developing sampling criteria for assessments. A centralized database should be created complete with information for each lionfish collection (e.g., size, location captured, micro-habitat type, tissue samples, etc.). A centralized datasheet or web-based reporting form are needed to streamline data acquisition. These data and the previous data collected by NCCOS/REEF can be used to identify data gaps and focus research priorities. During the advanced stages of the invasion, research on the efficacy of control strategies and development of new strategies will likely be needed.

Appendix II. Electronic educational resources on the lionfish invasion

Informational websites

NOAA National Centers for Coastal Ocean Science lionfish webpage
http://coastalscience.noaa.gov/education/lionfish.html

NOAA National Ocean Service lionfish educational website
http://oceanservice.noaa.gov/education/stories/lionfish

USGS Nonindigenous Species Database lionfish factsheet
http://nas.er.usgs.gov/queries/FactSheet.asp?speciesID=963

Reef Environmental Education Foundation lionfish program
http://www.reef.org/programs/exotic/lionfish

Television and Videos on lionfish

Children's TV Show AquaKids
http://www.youtube.com/watch?v=5-DyaV8UQfw

CBS Evening News
http://www.cbsnews.com/video/watch/?id=5265536n

NBC Nightly News
http://www.msnbc.msn.com/id/3032619/#25462218

Associated Press
http://www.youtube.com/watch?v=Ar0CX8dj948

Cayman Island Morning Television
http://www.cayman27.com.ky/news/item/1243

United States Department of Commerce
Gary F. Locke
Secretary

National Oceanic and Atmospheric Administration
Jane Lubchenco
Undersecretary of Commerce for Oceans and Atmosphere

National Ocean Service
John H. Dunnigan
Assistant Administrator for Ocean Service and Coastal Zone Management