AN APPETITE FOR LIONFISH: EMPIRICALLY EVALUATING A SUSTAINABLE FISHERY THROUGH TWO CASE STUDIES, ARUBA AND TEXAS

A Dissertation

by

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ABSTRACT

Indo-Pacific lionfish (*Pterois volitans* and *P. miles*) are an invasive marine fish that were introduced off the coast of Florida in the 1980s and became the first established marine fish species to have invaded the Atlantic Coast, Caribbean Sea, and Gulf of Mexico. Once established, an invasive species is not likely to be eradicated, therefore, the goal becomes population suppression through organized control. Commercial harvest of lionfish has been proposed as a long-term strategy; however, until now had not been quantitatively evaluated. This dissertation created a sustainable, lionfish fishery model that balances native reef-fish recovery, lionfish population suppression, and economic viability for commercial fishers through two case studies, Aruba and Texas. To holistically evaluate the commercialization of lionfish harvest, I gathered social data to determine the acceptance, or lack thereof, of the fish in the market; ecological data to assess population-level demographics of the fish; and economic data to aid in determining the financial viability of the fishery. In both case studies, social support for commercial harvest of lionfish was evident and the catch per unit effort values computed from the parsimonious models matched diver removal statistics from field trials, suggesting the fishery could be viable. Additionally, current market dynamics appeared to have the capabilities to support the fishery.

Current regulatory policies would need to be adjusted, likely with an amendment to the Magnuson-Stevens Fishery Conservation and Management Act, that seeks an optimum sustainable yield (OSY) for commercial harvest of invasive marine fish. OSY

prioritizes the state of the environment and economic viability of fishers, such that both work in concert to benefit ecological and social systems together. An OSY would be unique to each species, require multi-stock assessments, and integrate stakeholder engagement, social welfare, and economic interests, such that the fishery was designed to benefit the entire human-environmental system. The long-term sustainability of global marine fish production will require a diversification of species, whereby the inclusion of under-utilized and/or invasive fish may yield a supportive alternative. This dissertation holistically addressed a serious environmental issue with an innovative solution that can be widely applicable to other marine invasive species.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Professor Glenn Jones [advisor], Assistant Professor(s) Ashley Ross and Meri Davlasheridze of the Department of Marine and Coastal Environmental Sciences, and Professor Jay Rooker of the Department of Marine Biology.

The analyses depicted in Section 3 were conducted in part by Alex Fogg, Marine Resource Coordinator at Okaloosa County Board of County Commissioner in Walton Beach, FL. Fogg was the second reader for my age analysis, greatly contributing to the successful completion of that section.

All other work conducted for the dissertation was completed by the student independently.

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Ethics Statement

All of the surveys conducted with human subjects in Aruba and Texas Gulf Coast counties received pre-approval by Texas A&M University's Internal Review Board for Human Subjects Research (IRB2014-0355D) and all of those surveyed provided informed consent to participate. No Animal Use Protocol (AUP) was required for this dissertation, as determined by Texas A&M University's Animal Welfare Assurance Program Institutional Animal Care and Use Committee. The locations visited during this study required specific permissions, of which were obtained for each sampling year (Table 4.1). No endangered or protected species were involved in this study.

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1. INTRODUCTION

Although conservation efforts and sustainable management practices have been implemented in recent years [1], overexploitation of target species remains a major problem in the commercial fishing industry [2-4], with approximately 33% of global fisheries being harvested at biologically unsustainable levels [5]. Due to rising market demand, fisheries are being mismanaged, overfished, and collapsed while destroying valuable ocean habitats [4]. In addition to these stressors, the accidental or intentional introduction of non-native species has accelerated in magnitude in recent years, and presents a serious long-term problem for the environment and economy [6]. To meet these challenges, it is imperative to develop a form of sustainable fisheries that provides food security in the future, which results in positive ecological responses, generates viable monetary security for fishers, and aids in meeting the seafood market demand.

To address the need for such a comprehensive solution, this dissertation was developed to fill an unmet niche in marine biology and marine resource management by quantitatively modelling a sustainable lionfish fishery that holistically evaluated socio-economic and ecological factors that were believed to be associated with the creation of this long-term strategy. As a result, the conception of managing a marine invasive fish species at an optimum sustainable yield was developed, by which on a broader scale could restructure the management of commercially and recreationally important marine fish in the United States.

Human-mediated biological introductions occur when an organism is moved to a new environment, accidentally or intentionally [7], and overcomes barriers to survive, proliferate, and naturally disperse [8, 9]. Organisms that establish self-sustained, localized populations through reproduction become naturalized species [10, 11]. Once a naturalized species disperses from its point of introduction, increasing in abundance over larger spatial scales, it becomes an invasive species [9].

The fate of invasive species is varied, such that, few survive stochastic and chronic forces that allow naturalization into the introduced environment. However, a variety of mechanisms exist that facilitate establishment of introduced organisms, including escape from constraints of natural predators and/or parasites [12], behavioral flexibility, niche displacement, competitive exclusion, extinctions, and mutualisms [13]. Anthropogenic-induced climate change will likely expand ranges of invasive species as ocean temperatures increase and coastal waters rise [14]. Nonindigenous species can fundamentally modify the structure of an ecosystem, such as through replacement of keystone species or changing the environments' physical features, nutrient cycling, productivity [12], and lead to regime shifts [9].

Invasive species are now considered an integral component of global change [15, 16], and in some cases, are considered as detrimental as anthropogenic atmospheric and oceanic alterations [12]. Invaders are considered most harmful if they disrupt entire ecosystem processes and have wider biotic influences over the structure and function of the environment [15]. For example, *Caulerpa taxifolia*, is a green alga that invaded the Mediterranean Sea which spread to more than 6,000 hectares and significantly reduced diversity in these areas by outcompeting native species [17]. Similarly, *Melaleuca quinquenervia*, is a tree that invaded south Florida which excludes virtually all other native vegetation, provides poor habitat for native animals, uses large quantities of water, and intensifies fire regimes [18]. In addition to environmental damages, invasive species strain economies through loss of potential economic output, costs of combatting the invasions, and costs associated with threats to human health, such as with *Aedes albopictus* in Europe [19]. It is difficult to effectively quantify the magnitude of economic loss associated with invasive species, as these can be in the form of direct or indirect losses [9, 20].

Complete eradication of an established invader is not likely, and control efficacy varies immensely with location [12]. Failing to address issues of biotic invasions can result in severe global consequences, such as altering the world's natural communities by impoverishing and homogenizing the ecosystems that sustain agriculture, forestry, fisheries, and other resources that supply natural services [12]. One of the most threatening invasions to date is the establishment of Indo-Pacific lionfish (*Pterois volitans* [Red lionfish] and *P. miles* [Devil firefish], morphologically indistinguishable species herein referred to as lionfish), which were introduced into the United States through the aquaria trade, off the coast of Florida in the 1980s [21, 22]. This section will review the introduction of lionfish into the Northwestern Atlantic Ocean, Gulf of Mexico (GoM), and Caribbean Sea, the mechanisms which facilitated their drastic rate of expansion, and the impacts associated with the presence of this marine fish invader.

Lionfish were the first non-indigenous marine fish to become established in the Northwestern Atlantic Ocean, Gulf of Mexico, and Caribbean Sea [23, 24], and recently they have been reported in the Mediterranean Sea [25-28] and the South Atlantic Ocean [29]. Genetic analyses have suggested that the invasion in the U.S. began with a few females, as only nine unique haplotypes have been discovered in their invaded range, compared to 37 in their native range, indicating that a founder effect occurred [30, 31]. The Northwestern Atlantic Ocean populations have consisted of all nine haplotypes, while gene flow restrictions have resulted in the Caribbean Sea populations having a subset of four haplotypes, and the GoM having only three of these haplotypes [32]. The GoM populations most closely resembled populations in the Caribbean Sea genetically, suggesting that lionfish from the Caribbean Sea were likely the source of the GoM populations [32]. Additionally, backtracking techniques that were used to investigate dispersal pathways of larval lionfish have suggested that samples that reached the GoM were transported from the Yucatan Peninsula via the Loop Current [33], which further supported the previous genetic findings.

Lionfish are found in much higher densities in their introduced range than in their native range. The first estimates of lionfish densities in the Atlantic Ocean were reported in 2007 [34], which observed 21 lionfish per hectare (LF ha^{-1}) in North Carolina in 2004. Four years later, mean lionfish densities had reached 150 LF ha^{-1}, with some sites exhibiting over 350 LF ha^{-1} [22, 35]. Lionfish appear to be thriving in the warm temperate and subtropical waters of the Northwestern Atlantic Ocean, Caribbean Sea, and GoM, as their densities are an order of magnitude higher than those observed in their native range [36]. Maximum density of lionfish observed in the Pacific Ocean was approximately 23 LF ha^{-1} [37], as compared to max density of over 500 LF ha^{-1} in their invaded range [38]. It is not entirely understood why lionfish have been more successful in their invaded regions; however, lionfish possess several biological characteristics that may support their success and lack physiological barriers (e.g. natural predators, wide salinity and depth tolerance) that could otherwise hinder their invasion.

Adult lionfish show strong site fidelity [39] and have only been observed travelling relatively short distances [40], which suggests that their extensive spatial expansion was likely due to the dispersal of larvae during early life [e.g.33]. In part, the rate of their expansion can be attributed to their high reproductive output [40, 41]. Lionfish become sexually mature by one year of age, with males maturing as early as 100 mm and females at 150 mm total length (TL), respectively [42, 43]. Lionfish exhibit asynchronous spawning in which females can spawn as frequently as every 2-3 days over an 11-month period, which equates to 134 spawns per year in an average sized female (188.6 g) [42, 43]. On average, each spawn can produce approximately 27,000 eggs per female, with reported rates as high as 71,000 eggs per female [43]. Histological examinations found evidence that males may be reproductively active year-round, and although an individual female may not be spawning capable year-round, some females in the population are spawning capable year-round, which results in continuous reproductive output [43]. When spawning occurs, eggs are released in two buoyant sacks that are protected by a chemical deterrent to reduce predation, which reach the surface and are transported upwards of two hundred kilometers by wind-driven currents [33, 40].

In addition to these reproductive capabilities, lionfish have few physiological barriers that would restrict their expansion, which may also contribute to their rapid and extensive spatial coverage.

Lionfish have exhibited a wide range of habitat tolerance that do not appear to be restricted by depth, salinity, or temperature. This invasive fish has been observed in water depths as shallow as 1 m to sea floor depths of 300 m [44, 45]. They have been observed in marine and estuarine habitats, with populations found to be established as far as 5.5 km up river from the ocean [46]. Lionfish have been found in offshore and nearshore coral reefs, inshore seagrass beds and mangroves, as well as human introduced artificial structures [47]. Low temperatures could restrict the lionfish expansion as their critical thermal minimum is 10 °C [48]; however, this temperature has still allowed for their dispersal as far north as New York in the U.S. [49]. The only abiotic factor that may lead to invasion resistance is a high-energy environment such as those with strong wave-exposure and/or high-water velocities [50]. To further contribute to their invasion success, lionfish are subject to few biotic controls that could naturally reduce populations in their invaded range.

There is limited evidence that lionfish are subject to predation by natural predators [51], though recent research suggests predation may limit their occurrence in some regions [52]. Cannibalism of juvenile lionfish has been confirmed in the northern GoM, with the highest incidences occurring in large adults from areas of high densities, indicative of density-dependent regulation [53]. Lionfish appear to evade natural mortality caused from parasitic, viral, or bacterial infections; instead, the fish acts as a generalist host for a limited species of parasites [54, 55]. Recent literature has noted an ulcerative skin disease that seems to be species-specific to lionfish in the Gulf of Mexico and Caribbean Sea [56]. Following the presence of this disease, population declines in lionfish began to occur throughout their invaded region; however, it appears that many of these populations are already recovering [57]. While some regions experienced recent population declines in lionfish, other invaded areas have reported exponential increase in lionfish abundance [e.g. 58], which can be a detriment to native reef species.

Lionfish are opportunistic predators [59] that can lead to substantial declines in the abundance of native reef fishes, including adults of small-bodied species (e.g. wrasse, gobies, damselfishes) and recruits of large-bodied species (e.g. snapper, grouper, grunts) [60]. An individual lionfish can reduce the abundance of small reef fish by nearly 80% in five weeks [61], or upwards of 94% over eight weeks [62]. The severity of predation impacts is not uniform across taxa as small, non-cleaning fish with shallow bodies and a demersal habit are particularly vulnerable [60]. Additionally, lionfish destabilize the population dynamics of native prey species by competing with local predators and altering their use of resources [40].

Interspecific competition between lionfish and snapper species has revealed competitive vulnerability of snapper in small-scale habitat ranges as lionfish exploit resources more effectively and make use of more habitat [63]. Lionfish also exhibit predation rates nearly three times higher than local predators and do not regulate density-dependent mortality, which native predatory fish provide to the food web [62]. Because of this predation, native fish populations are being pushed towards local extirpation in some cases [60]. Given the expansion of lionfish, this may have detrimental effects on already stressed U.S. and Caribbean coral reefs, and local economies and communities of human populations.

Lionfish have cascading impacts that spread across several functional groups of fish and thus have direct and indirect impacts to the invaded environment. For example, reduction of herbivorous fish leads to an increase in algal dominated reefs [64]. This shifts the functional and ecological dynamics of the environment, such that it can no longer operate within its natural regimes. This presents a serious concern when managing coastal and marine resources. Less understood is their impact to local economies and human health; however, research has shown that lionfish are costly to manage because of their low vulnerability to conventional fishing methods [22, 42, 65, 66], and that puncture injuries resulting from contact with the fishes' venomous spines have caused hospitalization in some cases [67, 68]. In this sense, lionfish threaten the environment, economy, and human health; as such, developing a management strategy that sustains their long-term removal is pertinent.

To date, there have been few quantitative analyses on the effectiveness of lionfish removal efforts [69]. The development of a commercial fishery as a long-term strategy to control lionfish has been proposed [70]; however, it has not been quantitatively evaluated. This dissertation aimed to empirically evaluate social, economic, and ecologic parameters that would be needed to develop a sustainable, lionfish fishery by creating parsimonious models that balanced native reef-fish recovery, lionfish population suppression, and economic viability for commercial fishers.

The research question addressed in this study was:

Is a commercial lionfish fishery, that balances ecologic sustainability of local marine systems and economic viability of fishers, achievable as a management strategy?

To answer the research question, this dissertation explored the complex and dynamic interrelationships between the biologic and socio-economic components of marine fisheries in order to empirically evaluate the likelihood of establishing a commercial lionfish fishery in two very different geographic regions, Aruba and Texas. These two locations were chosen to pursue this research as they differed in: 1) invasion chronology (i.e. Aruba was invaded prior to Texas); 2) colonizable habitat availability and structure, in that, Texas has primarily artificial habitat and Aruba has mostly natural; 3) scale with respect to the size of the region and availability of governmental resources; and 4) marine resource governance. Because of these disparities, this study was able to broadly test the hypotheses that:

1. Social acceptance of lionfish as a food resource differ on a Caribbean island and the Texas Gulf Coast;
2. Lionfish abundance differs between regions that offer nearly exclusive natural habitat and those that almost entirely offer artificial habitat;
3. There are regional differences in the beliefs of who should have authority over managing lionfish;

4. There are no differences in removal success of divers between a Caribbean island and the Texas Gulf Coast, and the factors that contribute to those successes are similar;
5. The CPUE needed to support a lionfish fishery differs regionally; and
6. There are differences in the market dynamics (e.g. lionfish wholesale and market price, consistent supply to restaurants) between the two regions that may contribute to the success of a commercial fishery.

Each of the studies in this dissertation can be stand-alone projects, but were designed to occur sequentially, in that, each section built upon the previous, and consequently increased in complexity. In addition, the scale of each study differed, such that, the first project in Aruba (Section 2) acted as a pilot-study that was used to test the original research question of whether social, ecological, and economic data could be assessed holistically and thoroughly enough to offer insight into the capabilities to develop a commercial lionfish fishery. From there, each respective section built upon the previous to assess additional factors, collect and analyze more data, and to address questions that arose from the preceding study.

Social data and consumer preferences are inherently understudied with respect to the harvest of commercially important marine fish species [71]. Collectively, these are important metrics to consider when interpreting the likelihood of introducing a new fish species to the market as public awareness and involvement in management decisions often leads to long-term social acceptance of the proposed solution [72]. It is broadly understood that consumer demand drives targeted fishery harvests [73]. Owing to this, this dissertation prioritized gauging the current social perception of lionfish in the two study regions to determine whether a commercial fishery would be supported. This approach is unique to this dissertation, but arguably should be pursued in future fisheries management practices.

This dissertation is organized in sections that follow a journal format, in that, each could or has been published as an individual article. It began with an introduction that provided a comprehensive review of lionfish literature and addressed the rationale for development of this dissertation (Section 2); analyzed and presented data for Aruba and Texas (Section 3, 4, and 5, respectively) to hypothesize whether each location could support a fishery; described age and growth of lionfish in Aruba and Texas (Section 3) through analyses of sagittal otoliths; and finally evaluated the policy and management implications of a lionfish fishery with recommendations for local, regional, and/or national regulations in the United States (Section 6). Particularly, this dissertation had the following sub-objectives:

1. Develop a simple model and conceptual framework to evaluate various biological, social, and economic components individually and holistically for a commercial lionfish fishery.
2. Determine a lionfish density, i.e. standing stock, for Aruba and Texas to extrapolate a population estimate according to available habitat and structure.

3. Utilize surveys in Aruba and along the Texas Gulf Coast to determine social perceptions and awareness of the ecological and economic threats lionfish pose; gauge understanding of problems associated with lionfish and the level of concern by respondents; examine if a consumer demand for lionfish exists; identify stakeholders needed for lionfish management; and evaluate support and confidence in management regimes to mitigate the stress lionfish pose to the environment and the economy.
4. Review current management strategies for lionfish at local, state, and federal levels for the United States.
5. Provide recommendations for policy changes that may be implemented on a state or national level (e.g. Magnuson-Stevens Act amendment), as well as, define management strategies (e.g. stakeholder engagement, use of scenario planning) that may be effective in controlling the lionfish issue.

The expected outcomes of this dissertation will be valuable for fisheries managers, scientists, and educators as it will provide a general framework for examining the interacting factors necessary to implement a sustainable, commercial fishery for lionfish. Fishers and invasive species are often considered transgressive in reef conservation efforts; however, that could change where the acquiescence of fishers to harvest invasive lionfish provides hope for future fish consumption [74].

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2. EATING THROUGH THE INVASION: A CONCEPTUAL MODEL FOR A COMMERCIAL LIONFISH FISHERY IN ARUBA[1]

2.1 Synopsis

Indo-Pacific lionfish (*Pterois volitans, P.miles*) were the first established marine fish species to have invaded the western Atlantic Coast, Caribbean Sea, and Gulf of Mexico, and undoubtedly have had negative ecological impacts to these regions. Once established, lionfish are nearly impossible to eradicate; however, efforts to suppress populations through organized removal represent a promising mitigation strategy. Long-term management would be more beneficial if it generated income and maintained ecological integrity, such that native reef fish could recover. Such a strategy may be achieved with a commercial lionfish fishery. To assess the feasibility of implementing a commercial fishery, ecological and socio-economic data were integrated, whereby a conceptual model, combining data from existing literature and a field study in Aruba, were used.

In 2014, 116 persons were surveyed in Aruba about their awareness of lionfish and willingness to support a fishery. Eighty-nine percent of surveyed persons had seen lionfish, while 66% were able to identify it. Of 74 persons questioned, 32% had consumed lionfish, while 86% were willing to eat lionfish. In addition, divers collected

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489 lionfish from Aruba within recreational dive limits (<40 m). A total abundance for lionfish was generated to be tested in model simulations by extracting estimates published in scientific literature from other Caribbean regions, then parameterized based on habitat preference/suitability and benthic composition of Southern Caribbean reefs. These estimates were restricted to the area surround Aruba within 40 m water depth, to be within recreational dive limits, as this fishery assumes a diver-centric harvest.

A parsimonious model was used to calculate the theoretical effort needed to achieve an optimum abundance for lionfish (i.e. reduce populations to allow native reef fish recovery) under three different removal scenarios. Based on model estimates, the mean CPUE needed to achieve optimum abundance under the three scenarios was 7.83 kg diver hr^{-1}, assuming 1,920 diver hours per annum between two persons. The mean CPUE computed under each scenario was not significantly different from CPUE computed from lionfish tournament statistics (2.6 kg diver hr^{-1}; $t_{15} = -1.48$, $p = 0.08$), suggesting that a commercial lionfish fishery in Aruba could be achievable. It was evident from this study that establishing a commercial lionfish fishery in Aruba was socially viable and economically plausible, given the figures used for abundance and removal efforts. Future studies should aim to collect site-specific data that would allow for a more robust estimate of theoretical CPUE values. By integrating social, ecological, and economic data, this study can provide a robust recommendation to fisheries managers in Aruba to begin preparation of promoting the use of a commercial lionfish fishery as a mitigation strategy.

2.2 Introduction

Although conservation efforts and sustainable management practices have been implemented in recent years [1], overexploitation of target species remains in the commercial fishing industry [2, 3]. Creative and less impactful solutions are necessary to help mitigate stress on fisheries globally, e.g. commercial harvesting of invasive species. Marine invasive fishes have been shown to dramatically alter socio-ecological systems by changing natural processes, reducing biodiversity, and causing financial hardships [4-6]. Physical removal and commercial utilization of marine invaders have been encouraged and prioritized among resource managers [7]. The adoption of a market-based approach through commercial harvest has been proposed in many instances of marine and aquatic invasions, and has proven successful in some cases, including the invasive rapa whelk (*Rapana venosa*) in the Black Sea and the Duskey spinefoot (*Siganus luridus*) in the Mediterranean Sea [8]. There are potential caveats that exist with the development of commercial market regimes for invasive species (e.g. promotion of new introductions, protection of the invasive species) [9], but the benefits of a removal effort that generates jobs and revenue cannot be ignored.

The introduction of lionfish into the Northwestern Atlantic Ocean is one of the most severe marine fish invasions that has impacted the United States, Caribbean nations, and Central and South America [10]. Lionfish have low vulnerability to conventional fishing methods such as hook and line, and are commonly removed by divers with pole spears or hand nets [11, 12]. However, that removal method is laborious and costly [13, 14]. A mitigation effort that is cost-effective, economically viable, and retains the ecological integrity of the invaded region is preferred.

Creating a commercial fishery for lionfish is an environmentally responsible management approach that can be cost-effective, socially rewarding, and economically viable [15-19]. Commercial harvest of lionfish in the Florida Keys, FL has been successful, which provides a basis for support of engaging in employing the same strategy in other areas [20]. In order to determine the feasibility of implementing a commercial fishery for lionfish, it is critical to first determine if support and local demand exists in the community, about which information can be obtained using surveys, as well as gather information about the status of the population.

Small Caribbean island states offer an ideal location to study the creation of a commercial lionfish fishery, as they often rely on small-scale fisheries to support the dietary needs of their local populations [21]. This study devised a holistic approach using social, economic, and ecological data to determine the feasibility of establishing a commercial lionfish fishery in Aruba. First, social data collected from fishers, divers, restaurant owners, government officials, tourists, and locals were qualitatively and quantitatively evaluated to determine if support existed among a variety of stakeholders that would warrant the desire to commercially harvest lionfish. Once it was determined that a fishery was socially viable, ecological data were assessed using a parsimonious model to calculate the theoretical effort needed to achieve an optimum abundance for lionfish (i.e. reduce populations to allow native reef fish recovery). Finally, market dynamics were assessed to determine if a commercial lionfish fisher could be economically supported. By integrating social, ecologic, and economic data, a more robust recommendation could be provided to fisheries managers in Aruba on the viability of using a commercial lionfish fishery as a mitigation strategy.

2.3 Methods

2.3.1 Study area

Aruba is part of the Leeward Netherland Antilles island chain that also includes Bonaire and Curacao (Figure 2.1), that has an approximate land area of 180 km^2, and a population of over 105,000 persons [22]. Aruba was visited at two different times during the study year: once from May to August in 2014 to conduct the necessary social surveys and to gather economic information, and in November the same year to host the first organized lionfish tournament to collect ecological data. The lionfish tournament was a two-day event (14^{th} -15^{th}) that resulted in eight registered dive teams, ranging in size from two to five divers, removing lionfish throughout the region within water depths that did not exceed recreational dive limits (40 m). Each team was required to submit lionfish catches over a two-day period, with no limit on the number of submissions. Upon submission of catch, lionfish total length (TL in cm), wet weight (g), the region divers hunted (Figure 2.1), maximum diving depth, number of divers, and the total dive hours were recorded.

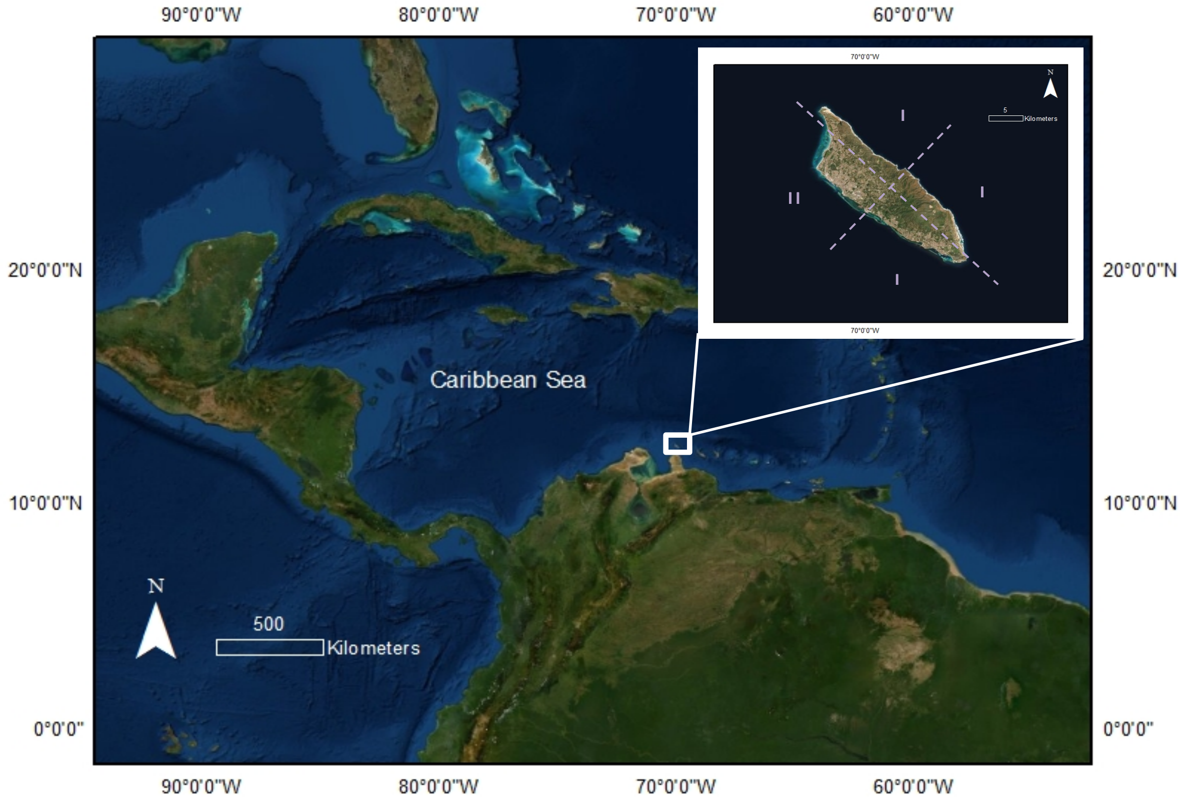

Figure 2.1 Map showing sampling sites on leeward island of Aruba, Netherlands Antilles. The inset map was used during the 14 – 15 November 2014 lionfish tournament to divide the study area into four different quadrants. Divers selected quadrant I-IV based on their dive location at each submission of lionfish catch.

Monetary awards were provided by the Department of Agriculture, Husbandry, and Fisheries Aruba for the largest lionfish, smallest lionfish, and greatest cumulative weight caught by team (i.e. total weight of lionfish removed). These incentives were used to motivate participants to remove a greater number of lionfish, reduce the likelihood of size-selectivity of larger lionfish during removals, and to gather a representative sample of the different size classes in Aruba.

2.3.2 Social survey design

Social data were collected with in-person interviews of people classified into six different stakeholder groups (divers, fishers, government officials, locals, restaurant owners, and tourists) to gauge awareness of lionfish in Aruba and overall willingness to support a commercial fishery [23]. The surveys were non-probability, convenience surveys, in that, it was not possible to generate a sampling frame and individuals were selected based on their availability to this investigation. This sampling style is useful for collecting pilot data, but may not be representative of the target population. As this project was designed as a pilot study, a non-probability, convenience survey was appropriate. Surveys received pre-approval by Texas A&M University's Internal Review Board for Human Subjects Research and all of those surveyed provided informed consent to participate (IRB2014-0355D). Survey questions were closed-ended and open-ended in design, to offer quantitative and qualitative analyses of the responses. The surveys were administered at varying times (0700-1900) and locations (inland and coastline) around Aruba over the study period.

Each participant was identified to one of the stakeholder groups by the following definitions: fishers – any person whom captures and sells fish recreationally or commercially; divers – dive shop owners and employees of dive shops whose livelihood relied upon this profession; restaurant owners – any person whom owned or managed a local restaurant; government official – any person who worked for the government; local – any person who were not included in one of the previous groups but lived in Aruba; tourists – any non-native person visiting Aruba. Basic demographic data were collected:

ages categorized 20-40 (n = 57), 41-60 (n = 50), and >61 (n = 9), and gender (male = 73, female = 43).

Stakeholders were asked a series of questions tailored to their specific knowledge and experiences to better understand their role in a fishery, identify their familiarity with and perceptions of lionfish, as well as willingness to eat the fish (Appendix A). The groups were divided into two broad categories: consumers, who were asked if they would eat lionfishes (divers, locals, tourists), and industry, who were asked if they would support a lionfish fishery in some capacity (fishers, restaurant owners, government officials).

All participants were shown a photograph of a lionfish and asked whether they had seen the fish and could identify it by name to determine a level of basic familiarity. If participants indicated they had seen the fish before, they were given a list of options to choose from to indicate where they had seen it (e.g. television, newspaper, menu/seafood market, ocean). Participants that said they had seen it while in the ocean were asked to select whether they had seen it in the water diving, snorkeling, or swimming.

Consumers were questioned on their participation in water related activities (e.g. diving, snorkeling, swimming, boating), while divers were asked more specific questions about how many times per week they dove and who they cater to most regularly during dive charters (i.e. tourists, locals, both). Additionally, divers were asked about their experience with lionfish with regards to business impacts and read a list of options to choose from (e.g. loss of money, increased revenue, dive locations; Appendix A). Divers were also asked about their participation in the removal of lionfish recreationally or through organized tournaments and/or competitions with focus on how often they remove lionfish, how many they typically remove, and what becomes of the fish post-mortem.

Participants were inquired as to whether they tried lionfish before, if it had been recommended to them in a local restaurant, if they would eat it again or recommend it to friends and family, and if they would eat it if it were served elsewhere (Appendix A).

A scripted description of the fish was read to consumers:

> *"Lionfish is a good, white tender meat fish with a taste and texture between a snapper and a grouper. It is not restricted on preparation or seasoning, as it is good fried, grilled, steamed, as sushi or ceviche, and served whole or filleted."*

Consumers were then asked if they would eat lionfish based on the above description. Finally, consumers were asked if they would eat lionfish if it were eco-friendly.

Industry participants were first asked questions that were used to determine their current level of involvement with lionfish management. It is important to note that government official questions were all open-ended as to not bias responses to study goals. Fishers were asked about their harvest preferences, what they did with fish after capture, and if different fish were harvested seasonally. Government officials were asked if they considered lionfish to be a problem for the island, if/how the fish should/could be removed from Aruban waters, and if there were any regulations in place for lionfish. Restaurant owners were asked the type of cuisine served, where they purchased seafood (if served in the restaurant), and if they served lionfish. Restaurants that indicated they were serving lionfish were then asked more detailed questions about where they purchased the fish, why they served it, how it was prepared, customer reactions, how it was advertised, and whether or not consumers were willing to try it.

At the end of industry surveys, questions were tailored to determine if support existed to establish a commercial lionfish fishery in Aruba. Fishers were asked if they had caught lionfish before, if they would be willing to harvest and sell lionfish, and if they had been impacted by the fish (e.g. loss of income, increased harvest). Government officials were asked if they would help in tournaments (i.e. promotion of event, funding, etc.), if they thought lionfish could be used to benefit Aruba, and if they would promote or implement regulations. Restaurant owners were asked about their willingness to serve lionfish in their restaurants, to purchase lionfish from local fishers, if they would recommend that other restaurants serve the fish, and if they would support lionfish tournaments.

Survey responses from consumers and industry were qualitatively and quantitatively assessed to determine the level of social support of creating a lionfish fishery in Aruba. Qualitative assessments were based on percent distribution of responses to the survey questions, while quantitative information was evaluated with statistical modelling.

2.3.2.1 Quantitative assessment with statistical analyses

The objective of the statistical model was to identify important factors that contributed to an individual's support for a lionfish fishery in Aruba. Data consisted of dichotomous responses that were interpreted as “does support a lionfish fishery” (1) or “does not support a lionfish fishery” (0). Ordinary least squares (OLS) procedures require that error terms (∈) be normally distributed with constant variance. Dichotomous dependent variables are not normally distributed and do not have constant variance, therefore, the use of OLS results in inefficient parameter estimates [24]. Logistic regression models (logit model) use a nonlinear cumulative logistic probability function to transform predictor variables that facilitate the analysis of the effects of changes in the values of the predictor variable on the probability estimates, which is not possible with the OLS. A logit model is more appropriate to use for dichotomous dependent variables [24].

Logistic regression models predict the probability of a dichotomous (“Yes/No”) outcome variable, Y_i, as a function of one or more predictor variables X_{ij} by:

$$\ell n\left(\frac{P_i}{1-P_i}\right) = \sum_j \beta_j X_{ij},$$

where the parameters β_j describe the relationship between X and Y and are generally estimated by maximum likelihood techniques [24]. When using the logit approach, the probability of observing a “yes” on a subject i may be estimated using the logistic function:

$$P_{i,Logit} = e^{\{\sum_j \hat{\beta}_j X_{ij}\}}/(1 + e^{\{\sum_j \hat{\beta}_j X_{ij}\}}).$$

Survey responses were evaluated to determine whether or not a participant supported a lionfish fishery, as the dependent variable in the logistics model. For example, divers were asked if they were willing to participate in a lionfish tournament or derby (Yes/No). If a diver responded yes, it was interpreted that they would support a lionfish fishery. If a diver responded no, it was interpreted that they would not support a fishery. Tourists and locals were asked if they were willing to eat lionfish if served at a restaurant. If the response was yes, this was regarded as support for a lionfish fishery, while a no response was regarded as does not support a lionfish fishery.

The participant's familiarity of lionfish was determined by showing a photograph of a lionfish and asking whether the individual had seen the fish before and if they could identify it by name. The variable "know_LF" was coded 3 if participants had seen lionfish before (yes), while a "no" response was coded 2. If interviewees indicated that they knew the fish, they were asked if they could provide the name. If participants provided the correct name, lionfish, the variable "identify" was coded 1 and if they could not provide the correct name or did not respond, the variable was coded 2.

For questions that did not have a binary answer option, responses were categorized as binary choices to be run in the model. For example, all persons that indicated they had seen lionfish before, were asked where they had seen the fish and given a list of options to choose from, whereby more than one option could be selected. Options for selection were: news, scientific journal, personal research/interest, diving/snorkeling/swimming, fishing, documentary, menu/seafood market, other. Other responses were open-ended and results included: divers, pier, fishers, and aquaria. The selections for this response were divided among activities associated with the water and those they were not. The variable "see" was coded 1 if participants had seen lionfish with activities associated with water, and coded with 0 for those who had seen lionfish in activities that were not associated with water (e.g. news, seafood market).

A logistic model was fitted to the data to determine the likelihood of an individual to support a lionfish fishery based on their stakeholder group, gender, age, their familiarity of lionfish, and where they had seen lionfish.

$$\ell n(\frac{LF_{fishery}}{1-LF_{fishery}}) = \beta_0 + \beta_1 group + \beta_2 gender + \beta_3 age + \beta_4 know_{LF} + \beta_5 identify_{LF} + \beta_6 see_{LF} + \varepsilon$$

Table 2.1 provides a description of the sample characteristics of persons interviewed in the survey.

Table 2.1 Description of the survey sample characteristics of persons interviewed in Aruba based on stakeholder classification, gender, and age.

Stakeholder Classification	Gender		Age (years)		
	Male	**Female**	**20-40**	**40-60**	**>60**
Fishermen	21	0	10	5	6
Divers	13	2	7	8	-
Restaurant Owners	5	3	6	2	-
Government Officials	8	5	2	10	1
Locals	16	20	20	15	1
Tourists	10	13	12	10	1

Because β is no longer easily interpreted in a logit model, the coefficients must be transformed in order to calculate the predicted probability of the likelihood to support a lionfish fishery based on the explanatory variables. The marginal effects of age, gender, and group were computed to measure the change in Y in response to an incremental change in one of the explanatory variables, while keeping all other predictors at their means.

2.3.3 Optimal abundance for lionfish in Aruba

This model used an optimal abundance, that was modified from Zabel et al.'s [25] ecologically sustainable yield, which aims to prioritize fishery harvests in terms of the impacts to the ecosystem, rather than a single fish species. It is well understood that lionfish have deleterious impacts to the environment, therefore, this fishery would establish harvests based on an ecological optimum sustainable yield (OSY), as opposed to the traditional maximum sustainable yield. The OSY for this study was defined as the lionfish yield that an ecosystem can sustain without having undesirable impacts. As lionfish have been recorded to decimate local native fish populations [12, 26, 27], a yield must be established that allows for a lionfish population that can economically sustain a fishery, but is ecologically responsible and reduces or eliminates the pressure to reef communities.

Reducing lionfish densities 75-95% on targeted reefs in the Bahamas resulted in 50-70% recovery of native reef fish densities [28]. This model simulated three removal scenarios, whereby 75% (minimum), 85% (median), and 95% (maximum) of the lionfish abundance were removed to determine optimal abundance of lionfish for Aruba. It has been documented in the literature that yields are likely to be site-specific for lionfish [13, 28], but, for the purpose of model simulations, the 75-95% estimates were used to assess the optimal abundance.

2.3.4 Estimating lionfish abundance

A fishing area was defined for this study which required water depths that were within recreational dive limits (< 40 m). A bathymetric shapefile of Aruba was downloaded from the Dutch Caribbean Biodiversity Database [29]. The area of each depth contour polygon was calculated in ArcMap; areas for all < 40 m depth polygons surround Aruba were summed to obtain the total area, herein referred to as fishing grounds.

Lionfish are known to exhibit habitat preferences that impact their distribution [30]. In Aruba, the fishing grounds are comprised of a variety of habitats that include mangroves, coral reefs, seagrasses, and sand. Limited data were available that characterized the benthic community surrounding Aruba, with only two surveys from Global Reef Record. In order to generate a representative estimate for habitat coverage, benthic data for several countries in the Southern Caribbean were obtained (Table 2.3). For sites that reported multiple surveys, the mean values for each benthic category were used. It was assumed that these Caribbean island states would have similar bottom topography as Aruba. The benthic categories that were simulated to estimate lionfish abundance were hard coral, soft coral, algae, sponge, and sand (Table 2.3).

Table 2.2 Benthic community composition of Southern Caribbean island reefs.

Location	**Hard coral**	**Soft coral**	**Algae**	**Sponge**	**Sand**	**Source**
Aruba	7	5	54	1	28	[31]
Bonaire	16	9	53	1	11	[31]
Curaçao	13	7	60	2	17	[31]
St. Vincent	4	4	69	3	12	[31]
Barbados	20	1	41	13	na	[32]
Grenada	15	3	59	5	na	[33]
St. Lucia	17	2	31	19	26	[34]

All of the values extracted from the literature are provided in Table A-1, Appendix A. Mean percent cover were rounded to the nearest whole number for model simulations. For each category, the minimum and maximum values were used as bounds to be simulated in the model to estimate lionfish abundance.

Uniformly distributed, random values for percent distribution of habitat cover were generated for hard coral, soft coral, algae, sponge, and sand over the fishing grounds. Random values were bound within the minimum and maximum of the mean values reported in Table 2.2, such that the distribution of habitat was not over-estimated for any of the five categories. For example, 500 simulations of habitat distribution were generated with random values of hard coral bound between 4% and 20% percent cover over the 73.3 km^2, such that coral comprised 2.9-14.6 km^2 of the fishing grounds. An "other" category was generated to ensure 100% of the fishing grounds by subtracting the cumulative percent habitat cover from one.

No baseline estimates for lionfish density (individuals $hectare^{-1}$) have been published for Aruba. Density estimates from existing literature, coupled with the benthic descriptions from Table 2.2, were used to simulate lionfish abundance in Aruba. Mean lionfish densities reported in Elise et al. [35] for Venezuela, Bonaire, and the Bahamas were used as estimates for density distribution among the different habitat categories (Table 2.2). It was assumed that lionfish density was heterogenous around the island, dependent on the habitat available for colonization. Lionfish exhibit a behavioral preference for structure, therefore, it was assumed that benthic coverage which provided some form of natural structure would host a higher density of lionfish [30]. As such, percent cover of sand and sponge were estimated to harbor the lowest densities, soft coral and algae the median densities, and hard coral the maximum densities.

Uniformly distributed, random values for lionfish density were generated for each scenario. Random values were bound within the minimum and maximum mean density estimates for each scenario reported in Table 2.3, so that the distribution of lionfish across the different habitats was not over-estimated. The total fishing area (73.3 km^2) was converted to hectares (i.e. 7,330 ha) in order to calculate a lionfish abundance based on the densities in Table 2.3.

Table 2.3 The minimum, maximum, and median values of mean lionfish densities (individuals hectare^{-1}) reported in Elise et al. [35] for Venezuela (Scenario 1), Bonaire (Scenario 2), and the Bahamas (Scenario 3).

	Scenario 1 (ind. ha^{-1})	**Scenario 2 (ind. ha^{-1})**	**Scenario 3 (ind. ha^{-1})**
Maximum	121	228	520
Median	70.5	41	393
Minimum	26	9	300

Total abundance was computed for each of the scenarios by multiplying lionfish density with total habitat coverage, and summing these values across all habitats.

$$A = \sum_{HC} \sum_{SC} \sum_{AL} \sum_{SP} \sum_{SA} D_l H_n$$

where A is abundance, HC is hard coral, SC is soft coral, AL is algae, SP is sponge, SA is sand, D_l is the density of lionfish, while H_n is total area (ha) of habitat coverage, where n represents all habitat types. Based on scenario 1 values from Table 2, sand and sponge cover would be expected to host lionfish densities of less than or equal to 26 ind. ha^{-1}, soft coral and algae densities of 26.1-70.5 ind. ha^{-1}, hard coral 70.5-121 ind. ha^{-1}, and the “other” category was randomly assigned a density value that was bound within 26-121 ind ha^{-1}. By doing this, 500 simulations of lionfish abundance were generated for the fishing grounds around Aruba.

2.3.5 Model to compute removal effort

A simple model was generated to compute the effort (*e*), reported as CPUE (LF diver hr^{-1}), needed to achieve the optimal lionfish abundance were computed:

$$e = \frac{(L - L^*)}{diver\ hours}.$$

where L^* is the optimal abundance of lionfish, *e* is the effort needed for removals to achieve L^*, L is the abundance of lionfish prior to removals, and diver hours, which is calculated by multiplying the total number of divers with total bottom time. To estimate CPUE, a bottom time on one-hour was used. Assuming dives lasted one-hour $diver^{-1}$, 4 dives day^{-1}, 5 days $week^{-1}$, and 48 work weeks, a diver could expect to dive a minimum of 960 hours per annum. It was assumed there were two divers per dive when computing theoretical CPUE for the model.

Scenarios were generated for the model, that operated in the range of removal estimates (75-95%) reported in Green et al. [28]. In order to determine the effort needed to achieve optimal lionfish abundance, given the current lionfish abundance estimates that were generated for Aruba.

2.3.6 Testing the model: lionfish tournament

Data gathered from dive teams during the 2014 lionfish tournament were used to calculate a CPUE for each diver and for each region (Fig 1):

$$CPUE = \frac{n}{diver\ hours}$$

where n is the total number of lionfish collected during a dive, and diver hours were the total number of hours spent diving (i.e. bottom time x number of divers). Analysis of variance (ANOVA) test was used to determine if CPUE was significantly different between each quadrant. A Tukey post-hoc test was used to identify specific differences in the CPUE among regions quadrants if ANOVA results indicated significant differences were present. CPUE values from the tournament were compared to the estimates from the model using a two-sample t-test to determine if the current effort of divers in Aruba could meet the demands needed to sustain a commercial lionfish fishery.

As all lionfish were handled post-mortem for this study, an Animal Use Protocol (AUP) was not required, as determined by Texas A&M University's Animal Welfare Assurance Program Institutional Animal Care and Use Committee. The locations visited during this study did not require any specific permissions, nor were any endangered or protected species involved.

2.3.7 Regression analysis of tournament statistics

To determine the significant factors that contributed to the removal of lionfish during the tournament in 2014, an OLS regression was performed. As the assumption of heteroscedastic error terms was violated in the initial regression, the model was adjusted to be run with robust standard errors to address this problem. The dependent variable in the model was the total weight (kg) of lionfish captured, as this provided the greatest predictive power (i.e. adjusted R-squared value), with independent variables being quadrant (region), depth [36], the number of divers (divers_n), and the dive team. A correlation of the independent variables was performed to identify collinearity among terms. An OLS with robust standard errors was fitted to the data to determine what, if any, factors significantly contributed to the removal of lionfish in Aruba in 2014.

$$Total_{W_{kg}} = \beta_0 + \beta_1 region + \beta_2 depth_{ft} + \beta_3 divers_n + \beta_4 team + \varepsilon$$

All statistical analyses and model computations were carried out in Stata IC/15.1 Mac version.

2.4 Results

2.4.1 Qualitative assessment survey results

Approximately 89% (n = 103) of the participants had seen lionfish, while 66% (n = 76) of individuals were able to identify it correctly. This shows that the majority of persons interviewed were aware of lionfish, but did not gauge their understanding of the negative impacts or their feeling towards lionfish. Thirty-two percent (n = 24) had eaten lionfish, 87% (n = 13) of divers, 28% (n = 10) of locals, and 4% (n = 1) of tourists, respectively (Figure 2.2). It is clear from these results that there was a higher incidence of lionfish consumption with respect to local Arubans (locals, divers), as compared to the lower incidence amongst tourists. Among the divers, locals, and tourists, 86% (n = 64) were willing to try lionfish, which broke down as: 93% (n = 14) of divers, 92% (n = 33) of locals, and 74% (n = 17) of tourists, that included individuals who had eaten lionfish and those who had not. In total, ten participants (1 diver, 3 locals, 6 tourists) identified they would not eat lionfish (Figure 2.2). Overall, this shows pervasive support for consuming lionfish in Aruba, amongst local groups and tourists.

Some interviewees were not asked about their willingness to consume (i.e. government officials, restaurant owners, and fishers), rather they were asked about whether or not they would support efforts in removing lionfish from Aruban waters. Support for lionfish removal was categorized as a tournament/derby or a fishery. Sixty-two percent (n = 11) of fishers were willing to participate in a fishery and 87% (n = 13) of divers were willing to participate in a tournament. This indicated that there was general support for participating in commercial removal amongst the two stakeholder groups that would likely harvest lionfish in a fishery if employed. Government officials, fishers, and divers were asked whether or not they would support or participate in a lionfish tournament, respectively. Of these respondents, 66% (n = 29) indicated that they would support tournament efforts (Figure 2.2). Out of eight restaurants, 50% (n = 4) served lionfish on their menus, with 75% (n = 3) willing to serve lionfish that were not already doing so. Eighty-eight percent (n = 7) of the restaurants supported fishers by purchasing locally caught seafood, of which, 50% (n = 4) were willing to continue if they began selling lionfish. Sixty-three percent (n = 5) of restaurant owners were willing to support lionfish tournaments.

Fishers were inquired on perceived impacts by lionfish, of which fourteen individuals identified that they were not impacted by lionfish (67%); five responded that they had been impacted (24%); and two individuals did not respond (10%). Fishers that indicated they had been impacted by lionfish provided that the fish had caused a reduction in target-fish capture (n = 1), fewer target fish available (n = 3), negative aesthetic change in the marine environment (n = 1), and aggression/avoidance behavior towards divers (n = 1). These results imply that lionfish have far-reaching impacts, not only to the local reef fish populations, but also have socio-economic consequences that could prove to be just as, if not more, impactful than the ecological damages.

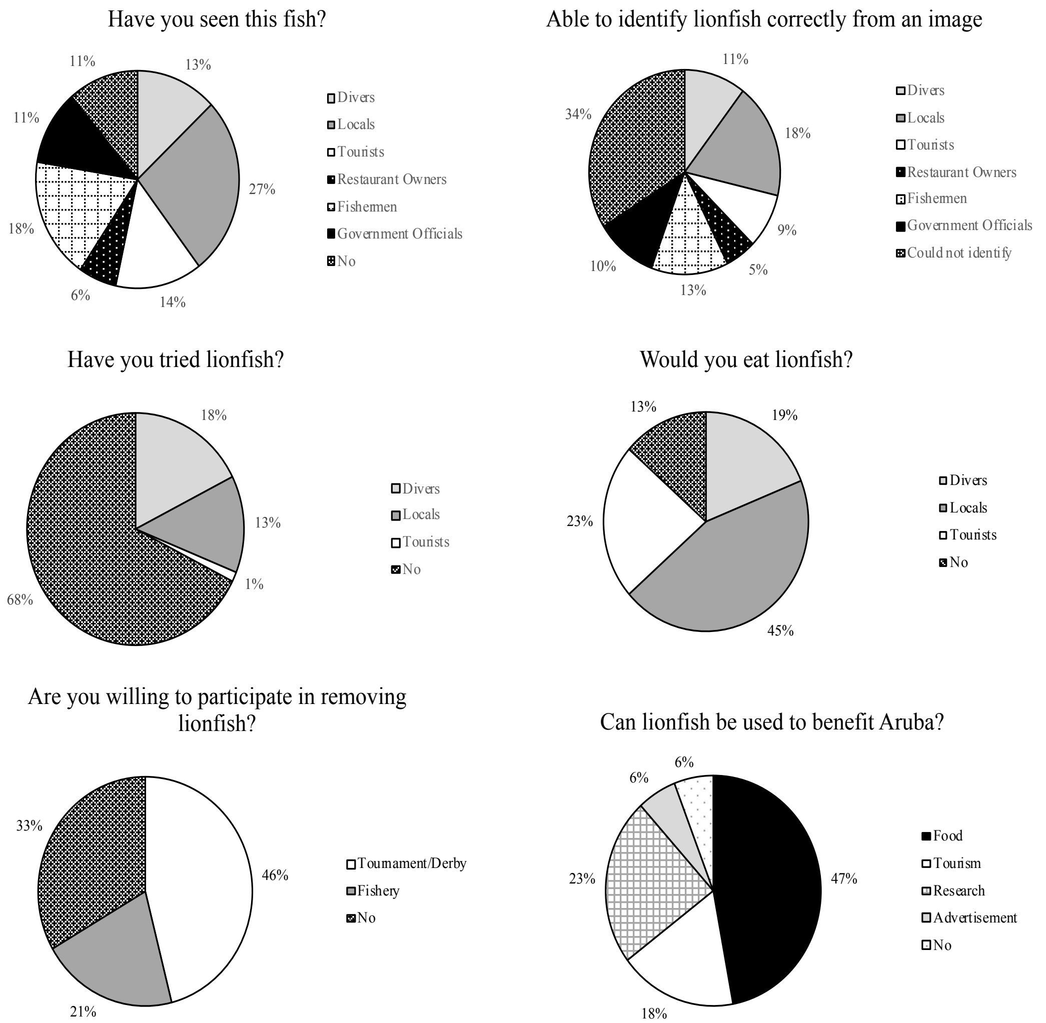

Figure 2.2 Percent distribution of answers related to questions regarding awareness of and willingness to support harvest/consumption of lionfish in Aruba.

Government officials were asked an opened-ended question if they considered lionfish to be a problem for the island, of which 100% responded yes. They were also asked how or if lionfish could be beneficial for Aruba. Responses included food source (47%), tourist attraction (18%), research (24%), advertisement (6%), or none (6%). A few of the officials replied with multiple options, therefore, there may be overlap in responses (Figure 2.2). Overall, results from the qualitative analysis suggested overwhelming support for a lionfish fishery in Aruba from a diverse group of stakeholders.

2.4.2 Logistic regression for quantitative analysis

Additional analyses were computed to determine the likelihood of an individual to support a lionfish fishery on Aruba based on their stakeholder group, gender, age, their familiarity of lionfish, and where they had seen lionfish using a logistic regression. The full results of the logit regression model are reported in Table A-2, Appendix A.

In the results of the analysis, stakeholder groups were tested as dummy variables to compare effects among the participants. Fishers and restaurant owners were less likely to support a lionfish fishery than divers, but this was not statistically significant. Tourists were more likely than divers to support a lionfish fishery, but this was not statistically significant. Locals were more likely to support a lionfish fishery than divers, which was not statistically significant. Results shown for males suggested, that on average, women are less likely to support a lionfish fishery than men, but this was not statistically significant. Age groups were compared to the youngest age range (20-40); on average, support for a fishery decreases as an individuals' age increases. This was marginally significant at 10% significance level for the age group 3 (> 60 years old). Participants were more likely to support a lionfish fishery if they knew lionfish, could identify it by name, and had seen it in or near the water; however, these were not statistically significant.

Marginal effects were computed for age and stakeholder group, as these were significant terms in the logit regression, to determine if individual factors within each of these demographics were statistically significant and to determine the predicted probability of the likelihood that an individual would support a lionfish fishery (Table 2.5).

Table 2.4 Results from the marginal effects for stakeholder group, age, and gender.

VARIABLE	MARGIN (STANDARD ERROR)
Divers	0.593 (0.125)*
Fishers	0.418 (0.112)*
Locals	0.912 (0.048)*
Restaurants	0.295 (0.137)*
Tourists	0.837 (0.065)*
Age 1 (20–40)	0.814 (0.048)*
Age 2 (40–60)	0.618 (0.071)*
Age 3 (>60)	0.529 (0.162)*

Statistically significant terms are indicated with an asterisk (*). All of the independent terms are statistically significant with respect to their predictive power in determining if a characteristic would contribute to an individuals' likelihood to support a lionfish fishery. Local Arubans and younger adults were the most likely to support a lionfish fishery. Marginal effects are reported at their 95% confidence intervals and standard errors were computed using the delta method. All statistical analyses were completed using Stata/IC 15.1 Mac version.

The results of the marginal effects calculations suggested that locals and younger adults were the most likely groups to support a lionfish fishery as compared to the other groups in their respective categories. The margins value in Table 2.5 can be interpreted as percentages: divers were on average 59% likely to support a lionfish fishery; adults between the ages 40-60 were on average 62% likely to support a lionfish fishery. Alternatively, these results could also be interpreted by comparing the groups against each other in their respective categories by subtracting their marginal values. For example, locals were approximately 63% more likely to support a lionfish fishery than restaurant owners: 92%-29 % = 63%. Figure 2.3 plots the marginal effects presented in Table 2.4 for each of the groups within their respective categories.

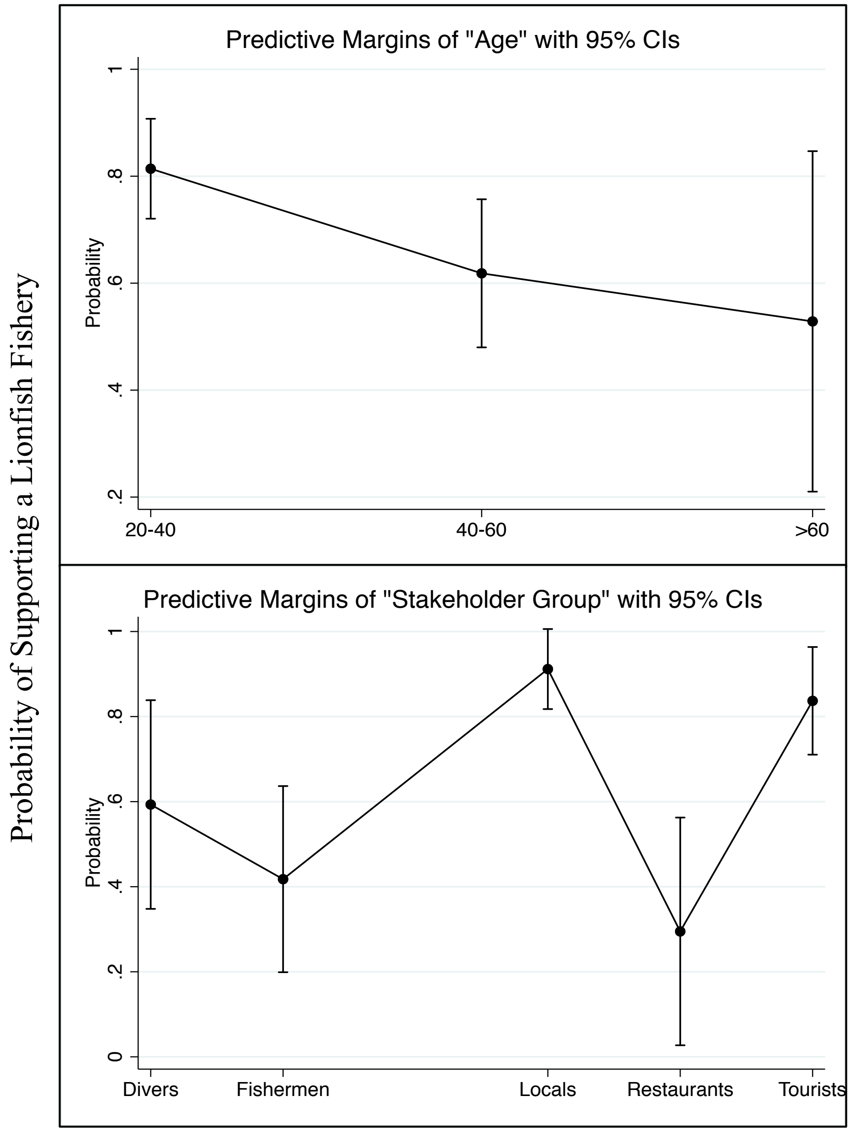

Figure 2.3 Results from the marginal effect calculations for group and age. The predictive probability was bound between 0 and 1, with 1 being a greater likelihood to support a lionfish fishery.

Results of the model suggested social support for a lionfish fishery in Aruba existed. Owing to this, additional models were pursued to determine if ecologic and economic data indicated support.

2.4.3 Lionfish abundance

The fishing grounds covered a total area of 73.3 km^2 (7,330 ha) based on GIS bathymetry data. Lionfish abundance estimates for Aruba, under each of the three scenarios (Table 2.3), were presented in Table 2.5. Mean density estimates were calculated by dividing total lionfish abundance by the total fishing grounds. The predicted densities for scenario 1 and 2 were considered realistic as these estimates were lower than lionfish density reports for fished areas (30 ind ha^{-1}) and significantly lower than unfished areas (66 ind ha^{-1}) in the neighboring island of Bonaire [37]. Although mean density estimates for scenario 3 were considerably higher than scenario 1 and 2, it appears these values are also consistent with mean density values from unfished areas in Cuaraçao (127 ind ha^{-1}) [37], suggesting that the estimates for each of the three scenarios were realistic predictions of mean lionfish densities in Aruba (Table 2.5).

Table 2.5 Summary statistics of predicted lionfish abundance (LF) and density (ind ha^{-1}) estimates for Aruba under the three scenarios presented in Table 2.3.4.

Scenario	Minimum	Maximum	Mean (± SD)
1	23,935 LF (3.27 ind ha^{-1})	338,024 (46.1 ind ha^{-1})	137,309 (± 73,905) (18.7 ind ha^{-1})
2	15,001 (2.0 ind ha^{-1})	330,521 (45.1 ind ha^{-1})	115,375 (± 67,895) (15.7 ind ha^{-1})
3	311,378 (42.5 ind ha^{-1})	2,070,518 (282.5 ind ha^{-1})	870,644 (± 487,071) (118.8 ind ha^{-1})

Results are presented with lionfish abundance on top and density below in parentheses. Densities were computed by dividing lionfish abundance by the total available fishing grounds (7,330 ha). A total of 500 simulations were performed; the table presents the minimum, maximum, and mean (± standard deviation) values.

An optimal abundance estimate was calculated for each scenario in Table 2.5

using the removal estimates mentioned above (i.e. 75%, 85%, and 95%), which generated nine total scenarios with 500 simulations (Table 2.6). Of these nine groupings, the lowest mean L^* for each abundance scenario was used for further calculations to determine the removal effort necessary to obtain L^*. Under each grouping, scenarios using removal 1 estimates generated the lowest mean abundance.

Table 2.6 Optimal abundance estimates for lionfish in Aruba under the three different lionfish abundance scenarios and three removal scenarios.

Scenario	Minimum L*	Maximum L*	Mean (± SD) L*
Abundance1*Removal1 (1.1)	5,984	84,506	34,327 (± 18,476)
Abundance2*Removal1 (1.2)	3,750	82,630	28,844 (± 16,974)
Abundance3*Removal1 (1.3)	77,845	517,630	217,661 (±121,768)
Abundance1*Removal2 (2.1)	3,590	50,704	20,596 (± 11,086)
Abundance2*Removal2 (2.2)	2,250	49,578	17,306 (± 10,184)
Abundance3*Removal2 (2.3)	46,707	310,578	130,597 (± 73,061)
Abundance1*Removal3 (3.1)	1,197	16,901	6,865 (± 3,695)
Abundance2*Removal3 (3.2)	750	16,526	5,769 (± 3,395)
Abundance3*Removal3 (3.3)	15,569	103,526	43,532 (± 24,354)

The groupings are identified by the abundance scenario*removal scenario, for a total of nine groupings for model simulations. Minimum, maximum, and mean values were reported for each of the groupings.

2.4.4 Removal effort for a commercial fishery

Effort (*e*), reported as CPUE, needed to achieve the optimal lionfish abundance scenarios in Table 2.6, were computed. CPUE was highly variable, ranging from 0.10-

72.2 kg diver hr^{-1} (Table 2.7).

Table 2.7 Diver hours and catch per unit effort (CPUE) estimates for each scenario in Table 2.6.

Scenario	Diver hours	CPUE (Min - Max)	CPUE (Mean ± SD)
1.1	1,920	0.8-11.8	4.8 (± 2.6)
1.2	1,920	0.5-11.5	4.0 (± 2.4)
1.3	1,920	10.8-72.2	30.4 (± 17.0)
2.1	1,920	0.5-7.1	2.9 (± 1.5)
2.2	1,920	0.3-6.9	2.4 (± 1.4)
2.3	1,920	6.5-43.3	18.2 (± 10.2)
3.1	1,920	0.2-2.4	1.0 (± 0.5)
3.2	1,920	0.1-2.3	0.8 (± 0.5)
3.3	1,920	2.2-14.4	6.1 (± 3.4)

CPUE values are reported as kg diver hr^{-1}. It was assumed that two divers would dive a total of 1,920 hours per year. Lionfish harvest was converted to weight assuming the mean weight of lionfish collected in Aruba (267.8 g).

2.4.5 Testing the model: lionfish tournament

In 2014, 489 lionfish were removed in the November tournament. The lionfish ranged from 86-435 mm TL, with mean length of 245 mm, and ranged in weight from 6-1,373 g, with a mean of 267.8 g (Figure 2.4).

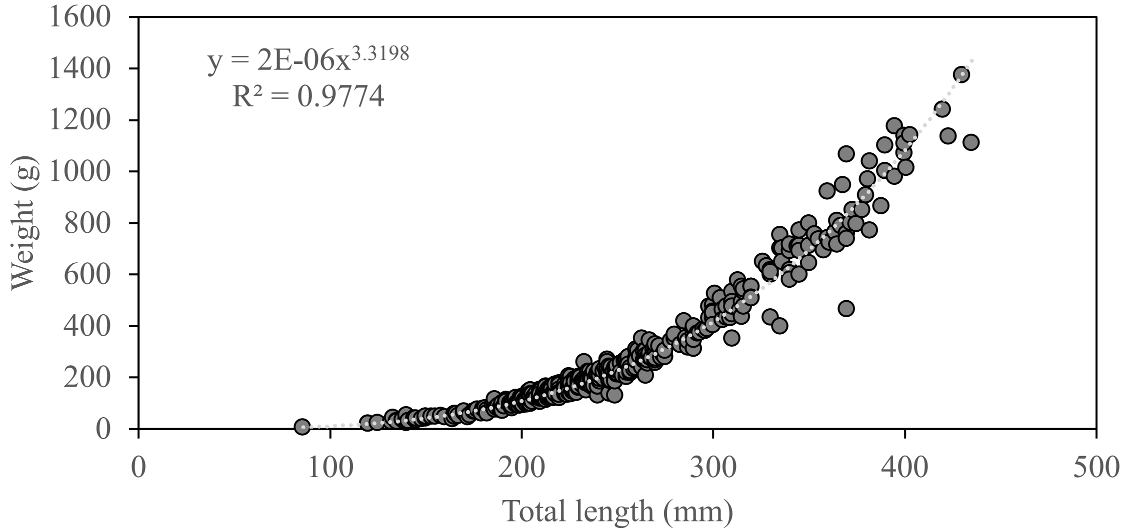

Figure 2.4 Total length (mm) and weight (g) measurements for lionfish removed during the 2014 Aruba tournament.

For the eight dive teams in the 2014 tournament, the number of divers, time spent diving, total weight captured, total number of lionfish collected, and quadrant fished were recorded (Table 2.8). The teams were able and encouraged to submit catch more than once across the two-day tournament. As such, the teams submitted lionfish that were removed from different quadrants, had altered the number of divers used during removals, and reported different diver hours at each submission (Table 2.8). Owing to this, CPUE was calculated for each submission and then averaged for the team. Mean CPUE for the tournament overall was 2.6 kg diver hr^{-1}.

Table 2.8 Lionfish tournament results for each submission of the eight dive teams in Aruba, November 2014.

Dive team	Quadrant	Dive hours	Number of divers	Number of lionfish captured (n)	CPUE (kg diver hr^{-1})	Mean CPUE (kg hr^{-1} $diver^{-1}$)
1	IV	1.17	2	12.4	5.3	4.0
		2	3	15.7	2.6	
2	I	0.67	2	1.9	1.5	1.6
	II	0.58		1.3	1.1	
	IV	1.42		6.3	2.2	
3	II	0.72	2	12.4	8.7	5.7
	IV	0.58		3.2	2.8	
4	I	2.53	5	25.3	2.0	4.5
	III	1	2	13.9	7.0	
5	I	1.67	3	8.3	1.7	1.4
	III	0.88	2	2.1	1.2	
6	I	2	3	4.4	0.7	0.5
		1.25	4	1.6	0.3	
7	III	1.38	3	4.4	1.1	1.1
8	III	2.25	3	12.1	1.8	2.2
		0.75		5.8	2.6	

CPUE values are reported as kg diver hr^{-1}.

Additionally, mean CPUE for each quadrant were 0.9, 1.4, 5.4, and 1.0 kg diver hr^{-1} for quadrant I, II, III, and IV, respectively. The number of dives completed in each quadrant were five, three, five, and four in quadrants I, II, III, and IV, respectively. ANOVA analysis indicated significant differences in CPUE among quadrants ($F_{3, 528}$ = 78.09, $p < 0.000$). Tukey-post hoc test results revealed that CPUE in quadrant I ($p < 0.000$) and IV ($p < 0.05$) differed from all other quadrants (Table A-3, Appendix A), with significantly lower CPUE values than all other regions. When compared to each other, quadrant IV had significantly higher CPUE than quadrant I (Table A-3, Appendix

A).

Mean CPUE values generated under the different lionfish abundance scenarios (Table 2.7) were similar to the mean CPUE values computed for divers in the 2014 tournament, in many instances. Results of the paired t-test revealed no significant differences in the mean CPUE values between the removal scenarios (Table 2.7) and the mean CPUE values for the 2014 tournament (Table 2.8; $t_{15} = -1.48$, $p = 0.08$). Given these results, it is likely that divers could meet the CPUE requirements under any of the three removal scenarios (i.e. 75-95%).

2.4.6 Regression analyses tournament statistics

Correlation of the independent variables indicated that there was no collinearity among terms, such that all could be retained for the OLS. Results of the OLS model are presented in Table 2.9. The number of divers (Divers_n) and team were categorical variables, as such, the results of the categories that remain in the model are compared to the category that is missing. For example, the number of divers ranged from 2-5 per dive, because the category for two divers is missing from the OLS results, the coefficients of the remaining categories are compared to this. Based on this, the total weight captured of lionfish during the tournament increased with the number of divers, which was significant ($p < 0.000$) in all cases.

The quadrant in which lionfish were collected was a significant factor in all cases, whereby total weight captured was lower in II, III, and IV compared to quadrant I. Results of the OLS suggest that the lowest total weight captured occurred in quadrant IV (Table 2.9). Water depth also had a significant effect, in that, the total capture of lionfish increased with increasing water depth. There were also significant effects with respect to the team captures of lionfish – all of the teams (2-8) captured significantly fewer lionfish than team 1. Team 7 captured the fewest lionfish, while teams 5 and 8 and teams 3 and 4, captured a similar amount of lionfish, respectively (Table 2.9). Full regression results can be found in Appendix A (Table A-5).

Table 2.9. Results of the ordinary least squares (OLS) regression analysis to determine significant factors that contributed to the removal success of divers in the 2014 Aruba lionfish tournament.

Total weight captured (kg)	**Regression Coef.**	**P>|t|**
Quadrant		
II	-10.19213	0.000*
III	-5.120238	0.000*
IV	-22.78666	0.000*
Depth	0.4360476	0.000*
Divers_n		
3	3.704048	0.000*
4	5.189524	0.000*
5	5.797716	0.000*
Team		
2	-2.711322	0.000*
3	-7.879154	0.000*
4	-7.900513	0.000*
5	-22.77485	0.000*
6	-13.57042	0.000*
7	-34.67904	0.000*
8	-23.95953	0.000*
_cons	1.205941	0.061

The dependent variable is total weight captured (kg), with independent variables: quadrant hunted (see Figure 2.1), depth, number of divers (Divers_n), and the team (adjusted R^2 = 0.9778). As the number of divers and team were categorical variables, results are presented such that the results of the categories that remain in the model are compared to the missing category. Statistically significant values are indicated with an asterisk*.

2.4.7 Economic feasibility of lionfish fishers

Lionfish sell as gutted, whole fish for U.S. \$11.00 kg^{-1} to restaurants and individuals in Aruba. This was not size dependent, in that small and large lionfish were sold at the same rate. Based on divers in the 2014 tournament, mean CPUE was 3.1 kg diver hr^{-1}. Assuming the same estimates for annual diver hours in the theoretical model (i.e. 1,920 diver hours between two divers), two divers could feasibly remove approximately 5,914 kg of lionfish per year. At U.S. \$11.00 kg^{-1}, this would generate \$65,054. Annual expenditures for fully rigged commercial fisher vessels in the northern Caribbean average U.S. \$11,500 [38]. Typical gross salaries of residents in Aruba average approximately U.S. \$24,000 [39]. Based on these parsimonious salary and expenditure estimates, the two commercial lionfish fishers could be supported.

2.5 Discussion

Aruba served as a proof-of-concept study for the first lionfish fishery model in an attempt to provide a quantifiable solution to a transnational issue. Instilling a successful fishery will be a long-term commitment that will require sustained monitoring efforts to ensure that impacts are reduced and reef functionality is recovered. Based on this initial conceptual model, it was determined that Aruba could sustain lionfish fishers, based on the social support, harvest effort, and current market dynamics. There were no significant differences between the theoretical CPUE and CPUE from divers that participated in the 2014 tournament, suggesting that the effort needed to sustain a fishery could be achievable in Aruba. This study was the first attempt at combining biologic and socio-economic data to determine the applicability of a lionfish fishery in the Caribbean.

As such, it was recommended that Aruba propose the opportunity to interested divers, conduct a limited field trial to evaluate its success, and then move forward to formulate regulations.

Survey questions for this research were designed as a pilot study to identify important stakeholders and gather relevant information to determine the social viability of instilling a commercial lionfish fishery in Aruba. Results from the logit regression and computation of the marginal effects supported the conclusions of the qualitative assessment [23]. Approximately 78% (n = 90) of the participants surveyed supported a lionfish fishery in some capacity. For example, 92% of locals (n = 33) supported a lionfish fishery by their willingness to consume lionfish, while approximately half of fishers (n = 11) supported a lionfish fishery by their willingness to support a lionfish tournament. The results from these analyses do suggest some interesting perceptions that would require additional analysis to determine the underlying causes.

Restaurant owners were the least likely of any of the stakeholder groups to support a lionfish fishery (Figure 2.2). Owing to the fact that restaurant owners must be willing to serve lionfish in order to promote a market for a fishery, it would be beneficial if they were more supportive of its establishment. The inability of fishers or divers to provide a consistent supply of lionfish has been noted as an issue by the restaurant industry [23, 40] and may contribute to a restaurant owners unwillingness to support a fishery. The survey did not specifically target the factors that contributed to a restaurant owner's choice to serve lionfish and was beyond the interpretation of this model. However, restaurant owners anecdotally commented that the inconsistencies in supply of lionfish and price per kg requested by divers deterred their confidence to include lionfish on their menus. Additionally, other restaurant owners offered that they felt they were assuming all of the risk to offer a lionfish dish, with the understanding that a consistent supply and cost could not be ensured, as they assumed patrons would be upset if their requests for lionfish dishes could not be met. It would be advantageous for future surveys to identify these factors to help with directing efforts to change choice behavior.

The likelihood to support a lionfish fishery decreased with an increase in age on Aruba (Figure 2.2). There is insufficient evidence to support that a consumers willingness to try new foods is correlated with age [41, 42]. It may be coincidental that the results of the marginal effects indicate a negative linear relationship with respect to increasing age or it may be reflective of the perceptions of older adults in Aruba and their reluctance to support a new industry. Additional information would be required to conclude that this willingness, or lack thereof, was correlated with age and to identify what factors contributed to that correlation.

During the interviews, critical observations related to fishers and divers were made that are advantageous for future survey work and/or when considering a region for a lionfish fishery: 1) Distinguish between fishers and recreational or commercial divers, primarily driven by the demands of the profession and the need to consistently supply lionfish; 2) identify appropriate stakeholders to streamline the processes of creating and regulating a new fishery; and 3) address who will have the authority to oversee management of lionfish. Although support from local fishers existed, it is unlikely that these individuals would discontinue their current targeted-fisheries to strictly supply lionfish. Recreational divers are associated with dive charters that primarily entertain tourists. These divers do opportunistically remove lionfish; however, are also not likely to quit their profession to solely hunt lionfish. For the fishery proposed, a commercial diver whose distinct purpose and income is obtained from harvested lionfish is more appropriate. As spearfishing was banned in Aruba in 2001, and re-instated only for the removal of lionfish, it is not likely this profession could be supported with other species; however, this can vary by region. If future surveys intend to assess choice factors of willingness to participate in a lionfish fishery, researchers should screen divers and fishers to target individuals who are willing and able to commercially remove lionfish only, to better understand the characteristics that influence these decisions.

Visitor volume will impact a restaurant's ability to serve lionfish. Lionfish have 18 venomous spines that can puncture an individual during preparation and would require care and diligence when handling to avoid a sting injury; this additional preparation effort could increase their wholesale purchase price. It is unlikely that large restaurants that accommodate high customer volume would be able to serve lionfish, as it would not be time or cost effective. Higher-end restaurants with smaller customer-bases should be targeted to market a lionfish fishery as they can afford to charge a premium price for their seafood dishes. It is evident that maintaining a consistent supply and wholesale cost for lionfish is an underlying issue in establishing a fishery [40]. To address this issue, a central processing location could be established that streamlines time and efforts, upholds health code standards, and provides an avenue to sell and purchase lionfish at a consistent rate. This would address the concerns expressed from restaurant owners and provide necessary structure for the establishment of the fishery.

Future surveys should tailor questions that ask persons about their willingness to participate in a lionfish-centric fishery, rather than their willingness to participate in a lionfish tournament or derby. It is important to notify divers that an occupation centered around a lionfish fishery would entail long-term commitment to harvesting lionfish throughout the year, rather than solely participating in a singular, lionfish removal event. This survey targeted the stakeholder groups separately with tailored questions; however, future studies should also seek the use of focus groups with a panel of dedicated stakeholder respondents that could develop a more systematic method in addressing lionfish management within a commercial fishery. Finally, questions should contain more quantifiable information that pertains to marketability of lionfish, such as respondents' annual wages, the price they are willing to pay for lionfish, and a scaled response of their support and/or confidence in the government to manage a commercial lionfish fishery. Caveats exist that could hinder the productivity of the commercial fishery (e.g. [9]) and would also need to be evaluated prior to pursuing this management strategy.

The construction of the surveys for this study were limited in scope, sample size, and predictive power of given responses. This was designed to be a pilot study to determine whether social, ecological, and economic data could holistically be assessed with respect to commercial harvest of an invasive species. Because the surveys were non-probability, convenience surveys and the sample size was small, it is difficult to say with confidence whether the results reflect population-level characteristics that can be interpreted as they stand. It is not clear whether a representative sample of each group was collected, as population-level characteristics were not assessed prior to pursuing the survey. Although these limitations exist and should be addressed in future surveys, we are confident that they were adequate and served the intended purpose for this study.

The removal model assumed that harvest area was within recreational diving limits; however, greater lionfish densities are found beyond these depths and have been noted to spawn more frequently [43]. To date, it is not understood if lionfish transition from mesophotic habitats (30-150 m) to shallow reef systems, though this could result in greater abundances or act as a form of recruitment for stocks within recreational dive limits [44]. Additional research into the behavior of mesophotic lionfish are needed to determine their potential role in a commercial fishery. It must also be stressed that recent initiatives in lionfish trap development could act as a significant contributor to lionfish harvest in the advent of successful field trials. This removal strategy has the potential to mitigate impacts of lionfish beyond recreational dive limits [45] and could act as a secondary gear source for a commercial fishery [46]. It would be beneficial to simulate a lionfish fishery coupling diver removals and lionfish-specific traps to determine the effectiveness of multiple gear types, if this is available to individual regions.

Lionfish become marketable in Aruba at 150 mm TL and nearly 95% (n = 465) of the fish removed in the 2014 tournament were of marketable size, which suggested that the lionfish population in Aruba was likely comprised of enough marketable sized fish for the commercial fishery to be economically viable. However, length-at-age data could provide critical information about the rate of growth, which could be used to estimate how quickly lionfish reach a marketable size. Because lionfish are marketable at 150 mm TL, the commercial fishery in Aruba would include juveniles [14], which may be more effective at combatting the environmental impacts of lionfish [14] and reduce the pressure to create a size-selective market. Future models could incorporate important social and market parameters that would better address the economic feasibility of this management strategy.

I acknowledge that the model presented in this study had several limitations that should be addressed in future models. Predictions generated for lionfish abundance and optimal abundance were theoretical, as no data were available to compute these parameters. Lionfish abundance and density computations for scenario 1 and 2 (Table 2.6) were comparable to density estimates from neighboring countries reported in the literature [35, 37, 47], and was assumed that they could be an accurate representation of the anticipated lionfish population in Aruba. Future models should collect site-specific data that targets lionfish density, as well as, prey fish density, such that an optimal lionfish abundance can be calculated using methods similar to Green et al. [28].

Recruitment was ignored for this model as the objective was to determine the removal effort needed to obtain an optimal density at the time of data collection. Lionfish have extremely high reproductive potential, as a single female lionfish is capable of sexual reproduction year-round, can release eggs every 2-3 days, and produces an average of 26,904 eggs per spawn [48]. These data inputs could be computed following similar methods of Mykoniatis and Ready [49], and would be advantageous in future models to determine the longevity of lionfish removals necessary to sustain a commercial fishery. Additionally, it would be worthwhile to compute a carrying capacity for lionfish in specific regions based on a simulated-model-age-structure comparable to that described in Chavez [50].

To maximize the ecologic and economic benefits of a commercial lionfish fishery, there are additional nuances that should be considered. Lionfish have shown higher abundances in culled areas than at non-culled locations [51], suggesting that frequent, insistent culling at repeated sites could render a higher catch rate with less effort. Some regions have reported catch stabilization or decrease in culled sites [52]; therefore, divers must explore alternative locations to maximize removal success. Growth rates have been found to be density dependent, with lionfish growing more slowly in higher densities. No evidence has suggested that lionfish experience density-dependent loss which suggests that manual removals may be the only control mechanism available [53]. These behavioral and life history characteristics could be monitored with the advent of commercial harvesting to determine if they hold true with local lionfish populations.

Quadrants I and IV were statistically different in terms of mean CPUE. Quadrant I is located on the northern shore of Aruba (Figure 2.1) which is characterized by strong underwater currents, high wind-driven surface currents, steep facing cliffs, deep water, and expansive sand flats with scattered boulders and patch reefs that can render dense populations of large lionfish. This area has much more challenging environmental conditions that requires more experienced divers to safely navigate the conditions, while managing the necessary gear to remove lionfish. Dives in this area are often spent swimming against the current which reduces success of lionfish removal. In addition, this quadrant has limited spatial coverage of highly ideal habitat. Quadrant IV is on the southern shore of Aruba (Figure 2.1) and is protected from high winds, offering less challenging diving conditions. Popular recreational dive sites are located in this region and it is frequently used to accommodate divers. This quadrant boasts a wide spatial distribution of highly suitable habitat, such as Malmoc Reef, which provides favorable structure for lionfish, that likely contributed to the higher CPUE for this area. The variability in environmental conditions and suitable habitat likely explains the significant difference in CPUE between quadrants I and IV.

When calculating CPUE in future studies, it would be advantageous to record experience level of divers based on their frequency and duration of targeted removals. Intuitively one would assume CPUE would increase with experience; however, this value is also influenced by environmental parameters, lionfish abundance, and depth. Incorporating this information would aid in identifying preferential candidates to become commercial lionfish divers. However, consideration must be given to the diving conditions, and experience level should be used in conjunction with the other parameters presented in this study, rather than becoming an exclusive entity.

Implementing a commercial fishery for lionfish that targets a specific suppression of local populations can be ecologically and economically effective [28]. Although this model targeted removals ranging from 75-95% to obtain an optimal abundance estimate, locations would benefit from identifying site-specific thresholds of lionfish that result in the greatest recovery of endemic reef species [28]. That level of investigation was beyond the scope of this conceptual model; however, it may offer a more realistic target density for a lionfish fishery in subsequent studies.

It is important to note that this model is not suggesting that the optimal abundance estimates provided here are appropriate for every invaded location, or that this density is sufficient to reduce impacts to native prey fish in Aruba. Determining species and functional level impacts to native fish was beyond the scope of this study, but it is critical to monitor with the implementation of the commercial fishery. Lionfish with densities greater than those presented in Table 2.6 have been observed in their invaded range without having noticeable impacts to native prey fish assemblages [35], but this varies by location, invasion chronology, and the environments susceptibility to stressors. As this study served as a proof of concept, it is critical that the empirical data presented in this model be investigated in Aruba to provide more discriminative parameters.

A lionfish-centric fishery is much different than an organized tournament or derby and would need to be managed more closely than singular tournament events. If a region planned to implement both management strategies, the tournament landings would need to be evaluated within the framework of the fishery, so that annual quotas can still be met to ensure economic viability of lionfish-specific fishers. This is not aimed to discourage the use of tournaments as a management strategy, or deny their effectiveness in combatting the invasion; rather, that this strategy may be implemented in congruence with a commercial lionfish fishery and should be evaluated within the same regulatory framework.

2.6 Conclusion

Marine resource managers in the Caribbean often work with budget, equipment, and personnel limitations, which greatly reduces their ability to sustain effective long-term management solutions. Understanding the effort needed to maximize long-term environmental goals to reduce the effects of pressures from lionfish are greatly beneficial to local managers. Removal of lionfish through targeted efforts alone will not likely render the necessary reduction needed to manage local populations in a way that limits impacts to native prey species, such that biodiversity, ecosystem function, and local-scale fisheries are protected [13]. A high exploitation rate fishery may produce sustainable and measurable results, but may not be a practical mitigation strategy for all invaded regions [13, 37, 54] as this is highly dependent on complex socio-ecological dynamics. Future studies should aim to link socio-economic systems with biology to understand the dynamic interactions between humans and the marine environment to holistically evaluate how these can influence commercial fishery harvests.

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3. COMPARISON OF AGE, SIZE, AND GROWTH STRUCTURE OF LIONFISH IN THE SOUTHERN CARIBBEAN AND NORTHWESTERN GULF OF MEXICO

3.1 Synopsis

Indo-Pacific lionfish (*Pterois volitans, P.miles* complex) were first introduced off the coast of Florida in the 1980s and have become one of the most severe marine fish invaders in the Northwestern Atlantic Ocean, Gulf of Mexico, and Caribbean Sea. Age-specific life history parameters are required for use in models that can be used to determine removal rates needed to effectively manage lionfish densities. This study validated annual increment formation in sagittal otoliths to assess the age and growth of lionfish collected in Aruba in 2014 (n = 44) and the northwestern Gulf of Mexico (NWGoM) in the Flower Garden Banks National Marine Sanctuary (FGBNMS) in 2018 (n = 100). Additionally, Fulton's condition factor and asymptotic maximum lengths (L_∞) were calculated for each of the populations to compare the favorability of environmental conditions and respective growth characteristics. Results suggested that populations were significantly different between the two regions, with lionfish from Aruba exhibiting a greater L_∞, growth rate, and greater condition values than lionfish from the NWGoM. It is unclear if these differences were attributable to variability in species composition, or if they in fact, show that lionfish in Aruba have more favorable environmental conditions which resulted faster growth.

3.2 Introduction

Indo-Pacific lionfish (*Pterois volitans/miles* herein referred to as lionfish) are a nonindigenous marine fish that were introduced in the 1980s along the western Atlantic coast in the U.S., most likely by release from aquaria [1]. Their distribution has since expanded along the Eastern seaboard of the United States, into the Caribbean Sea, and throughout the Gulf of Mexico [2]. More recently, lionfish have been reported to have invaded the Mediterranean Sea [3] and South Atlantic [4]. These fish have the potential to alter marine communities by consuming herbivorous fishes responsible for maintaining algae production, that could contribute to regime-shifts in coral reef habitats [5-8]. It is important to gather baseline ecological data about lionfish populations to inform management of the best actions to control the invasive species.

Age/size composition and age-specific life history traits (growth, mortality) of marine fishes are essential inputs in population models used to determine removal rates needed for effective management based on age- and size- structure population dynamics. [9, 10]. These data become particularly important when a marine fish invades a new region, as this can provide necessary insight for fisheries managers to assess the effects nonindigenous fish have on native species, and to develop strategies to mitigate stress to the environment. Changes in size and age structure of fishes are common indicators of overfishing [11, 12], but in the case of invasive species, may be used to determine the success of management strategies [13].

Lionfish age and growth parameters may differ among regions that were invaded at different times [14] and it has been suggested that lionfish growth may differ in the southern regions of their invaded range [6, 15]. It is expected that lionfish in the northern Gulf of Mexico would be much younger than other invaded regions because they became established later [2]. Research has not compared age, growth, and condition of lionfish between such spatially and temporally separated populations, as those between the Southern Caribbean and northwestern Gulf of Mexico (NWGoM). This study aimed to determine if differences were evident in relationships between age/size and age structure composition, and if condition factors varied among the different ecosystems of Aruba, south Caribbean, and Flower Garden Banks National Marine Sanctuary, NWGoM.

3.3 Methods

Lionfish were collected from Aruba and U.S. Gulf of Mexico by divers via SCUBA in depths ranging from 6–30 m. Lionfish in Aruba (n = 489) were removed following techniques described in the methods of Section 2. A subset of otoliths (n = 63) were retained for analysis in this study. In the NWGoM, lionfish were collected from East Flower Garden Bank (EFGB) and West Flower Garden Bank (WFGB) in the U.S. Gulf of Mexico following techniques described in the methods of Section 4 (Figure 3.1). Two lionfish research expeditions were conducted on 26–28 June and 27–30 August 2018 in the NWGoM, which removed 364 and 776 fish, respectively. Of these, a total of 122 otoliths were retained from EFGB (n = 65) and WFGB (n = 57) to be used for this analysis.

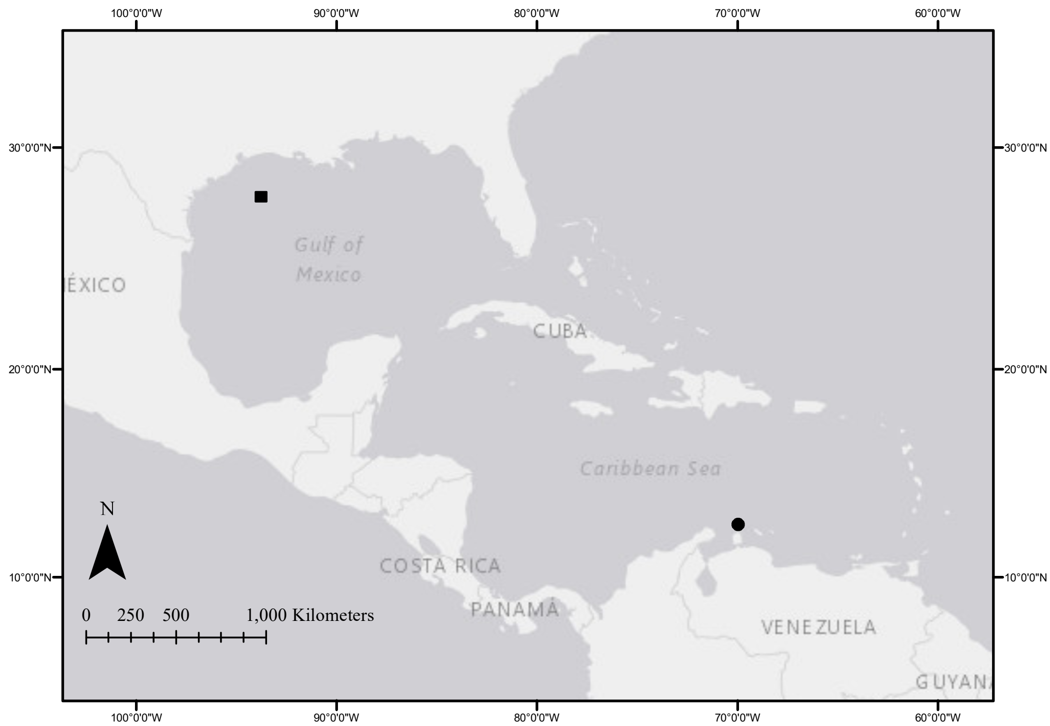

Figure 3.1 Map showing sampling sites on leeward islands of Aruba, Netherlands Antilles and U.S. Gulf of Mexico. The circle indicates Aruba, while the square shows the U.S. Gulf of Mexico.

Total length (TL) and total weight (TW) were recorded in the field for all lionfish collected in 2014 (Aruba) and 2018 (NWGoM). Lionfish were sexed in the NOAA lab following descriptions from Green et al. [16] to compare age and sex data. No lionfish collected in Aruba were sexed.

Sagittal otolith pairs were extracted by cutting vertically between the head spines and the first dorsal spine to the isthmus of the gill opening to remove the head. Cuts were made along the posterior side of the cranial cavity down through the spine to allow access to the sagittae [16]. Using a pair of fine-tipped forceps, otoliths were removed from the cranial cavity, rinsed with fresh water, dried, and stored in uniquely labelled vials.

Single otoliths were mounted in 22 x 22 x 20 mm embedding molds by filling the molds with a small layer of West System 105 resin and 206 hardener mixture that was left to dry for 24 hours (h). After the resin was dry, otoliths were placed dorsal-ventrally in the center of the mold, and then filled to the top of the embedding molds with the resin mixture. When possible, the left otolith was used for aging. These were allowed to dry for a minimum of 24 h. After drying, the resin blocks were removed from the embedding molds, and a straight line was drawn across the block to indicate the ideal location of the section to be aged.

Otoliths were sectioned along the transverse plane using a Buehler IsoMet saw with a diamond wafering blade to expose the primordium and growth increments (i.e., annuli). Sections were mounted onto glass slides using Crystal Bond and allowed to dry for 24 h. After drying, sections were grinded and polished to the vertical mid-sagittal plane with a graded series of Buehler silicon carbid paper (600, 800, and 1200 grit) and Buehler micropolish alumina 0.3 μm. The sections were finished with Buehler microcloth to smooth the surface of each section and assure the best visibility of annuli. Otoliths are composed of a number of concentric shells with differing radii that can appear as extremely opaque or completely hyaline (transparent) bands [10]. The opaque bands are formed during the period of slowest growth, while the hyaline bands are laid during the period of fastest growth [10]. The lamination of the opaque and hyaline bands can be counted to determine age in years.

Annuli were viewed under a Leica compound microscope at 4.5x magnification, and the sections were enumerated using the Leica LAZ EZ image analysis software. Otoliths were examined by two independent readers to determine age. If a discrepancy in age occurred between paired age estimates of an individual lionfish, otolith sections were aged collaboratively by both readers. If an agreement could not be made, the otolith was discarded from further analysis. Daily increments were not read.

Age and length data from each region were used to model growth by estimating parameters for the von Bertalanffy growth equation [17]:

$$L_t = L_\infty(1 - e^{-K[t-t_0]}),$$

where L_t is the length at age (t), L_∞ is the asymptotic maximum length, *K* is the Brody growth coefficient or rate of growth toward L_∞, and t_0 is the theoretical age at which a fish would be 0 mm in length. In addition to this, condition factor was determined for each of the fish following Fulton's condition factor, *K*:

$$K = 100\frac{W}{L^3},$$

where *W* is whole body wet weight in grams, L is length in cm, and the factor 100 is used to bring *K* close to unity [18].

The age/size structure, age composition, growth parameters, and condition factors were compared between the two study locations with statistical analyses using Stata/IC 15.1 Mac version. Analysis of variance (ANOVA) was used to contrast TL between sex in the NWGoM, as well as location between the two banks (EFGB, WFGB). If no significant differences were found by bank or sex, all data were pooled for the NWGoM to be compared to lionfish sampled in Aruba. If there were significant differences, a Tukey post-hoc test was used to determine the specific differences within the NWGoM groups with respect to sex (male, female, immature) and bank (EFGB, WFGB). A sum of squares reduction test was carried out to determine if there were differences in age and condition between Aruba and FGBNMS, because of the non-linear nature of the von Bertalanffy growth curve.

3.4 Results

3.4.1 Aruba

The TL-TW relationships for lionfish aged in Aruba (n = 44) are presented in Figure 3.2.

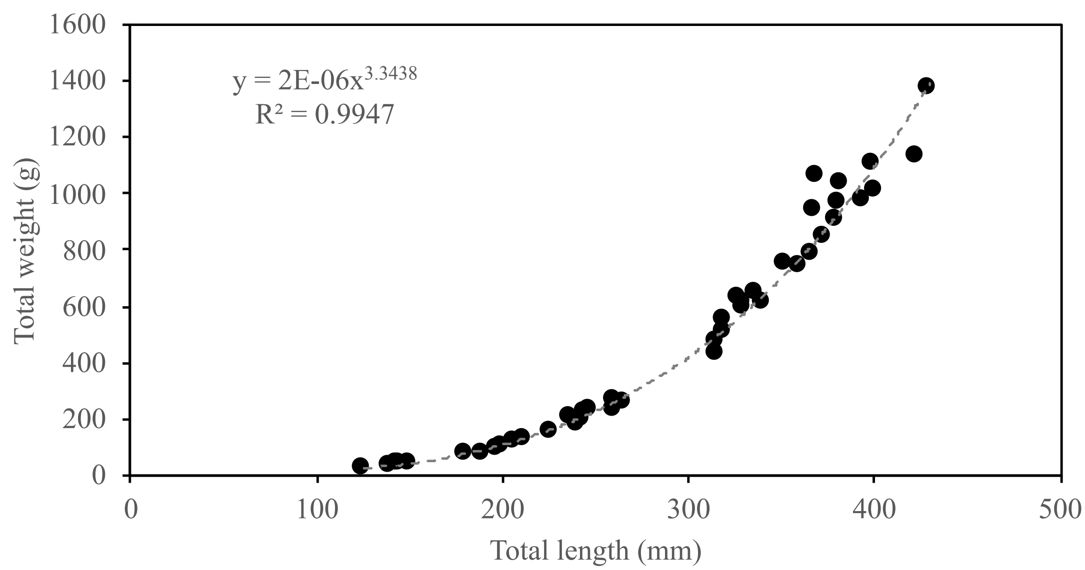

Figure 3.2 Total length-total weight relationship for lionfish from Aruba (n=44).

A total of 63 pairs of otoliths were removed from lionfish ranging in size between 125 – 430 mm. Of those, 16 otoliths were discarded due to over-polishing of the sections or because the core was missed during the sectioning process. Of the remaining 47 samples, age agreement was reached collaboratively on 44 otoliths (93.6%). Lionfish ages ranged from 0 to 6 years (Figure 3.3), with 31.8% of aged lionfish being 2 years old (see examples Figure 3.4). In total, 86.4% of lionfish aged from Aruba were less than three years old.

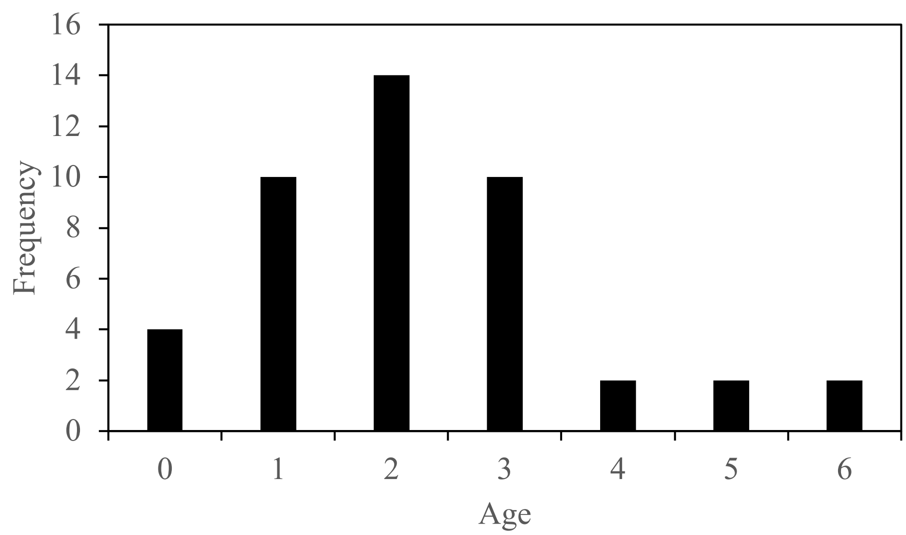

Figure 3.3 Age frequency distribution of lionfish in Aruba

The K values in Fulton's condition factor ranged from 1.096 – 2.105 (1.516 ± 0.2168).

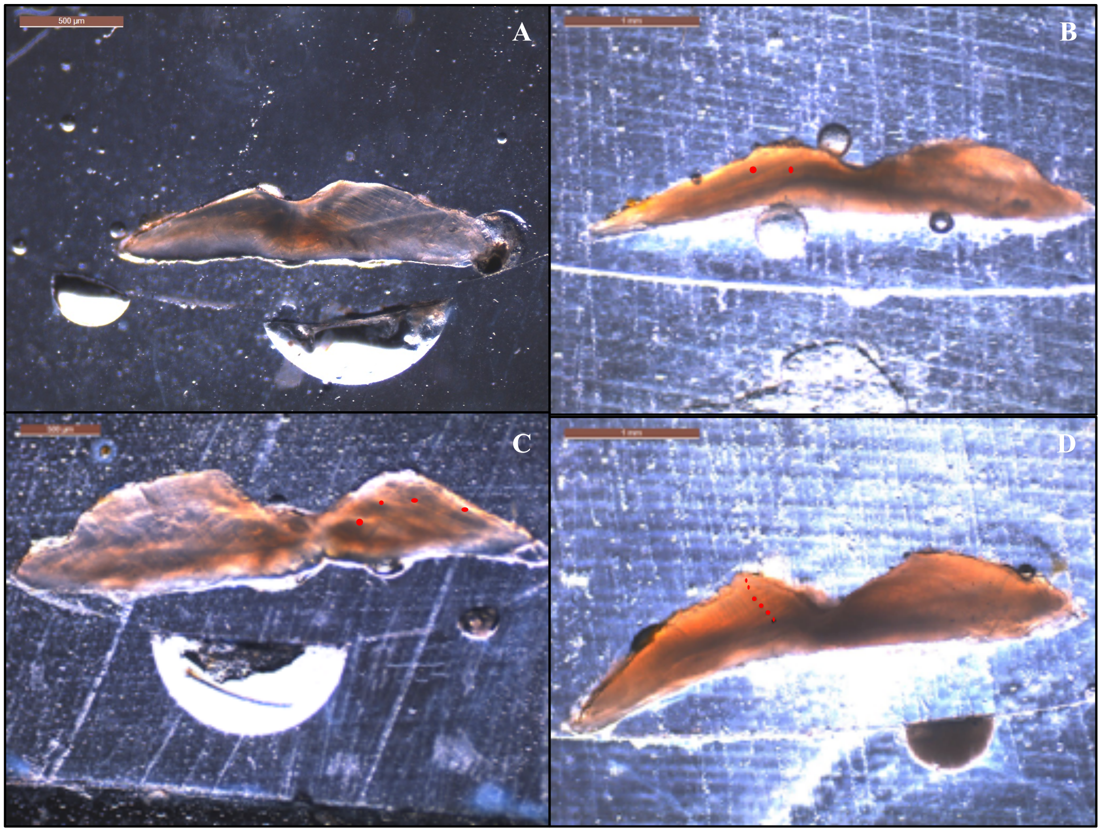

Figure 3.4 Annotated images of sectioned otoliths shown for different age classes from lionfish collected in Aruba. Red dots represent annuli. Percentages represent age distribution within the respective class for lionfish in Aruba. A. Age 0 (9.0%), B. Age 2 (31.8%), C. Age 4 (4.5%), D. Age 6 (4.5%).

3.4.2 U.S. Gulf of Mexico

There were no significant differences in TL between banks (ANOVA: $F_{2, 98} = 2.57$, $p = 0.434$); however, there were significant differences in TL between sexes (ANOVA: $F_{2,97} = 6.46$, $p = 0.045$). The data were pooled for both banks, but sexes were handled separately to generate a von Bertalanffy growth curve (VBGC). The TL-TW relationship for lionfish aged from the NWGoM (n = 100) are presented in Figure 3.5. Of these lionfish, 65 were male, 33 were female, and 2 were too small to identify their sex.

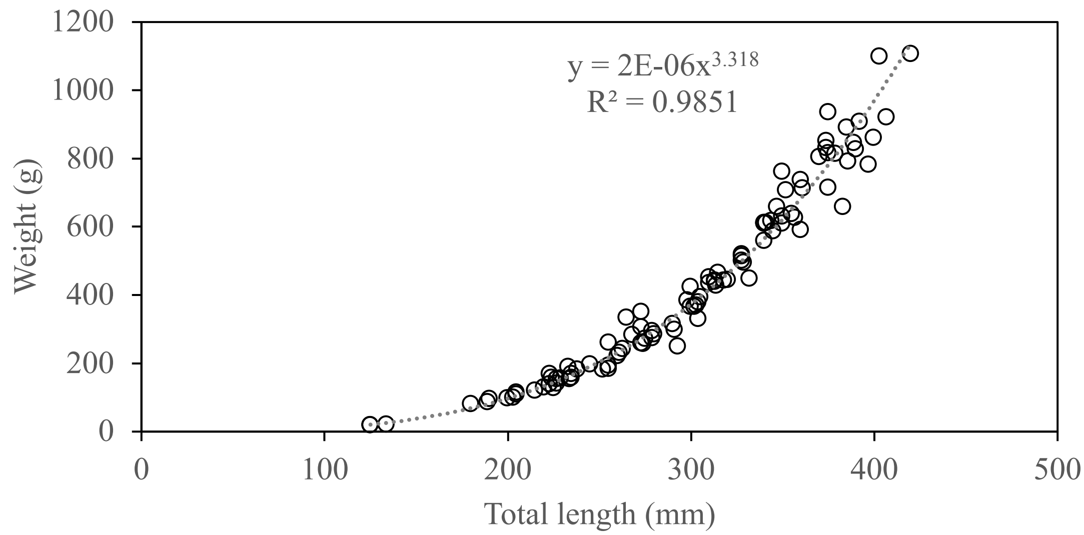

Figure 3.5 Total length-total weight relationship for aged lionfish from East and West Bank in Flower Garden Banks National Marine Sanctuary.

Otolith pairs were removed from 122 lionfish (EFGB = 65, WFGB = 57), ranging in size from 125 – 444 mm TL. Of those, 12 were discarded due to poor cuts or over-polished sections. Of the remaining 110 samples, age agreement was reached collaboratively on 100 otoliths (91%). Lionfish ages ranged from 0-10 years (Figure 3.6), with 37% of those sampled being ≥ 5 years of age (see examples Figure 3.7).

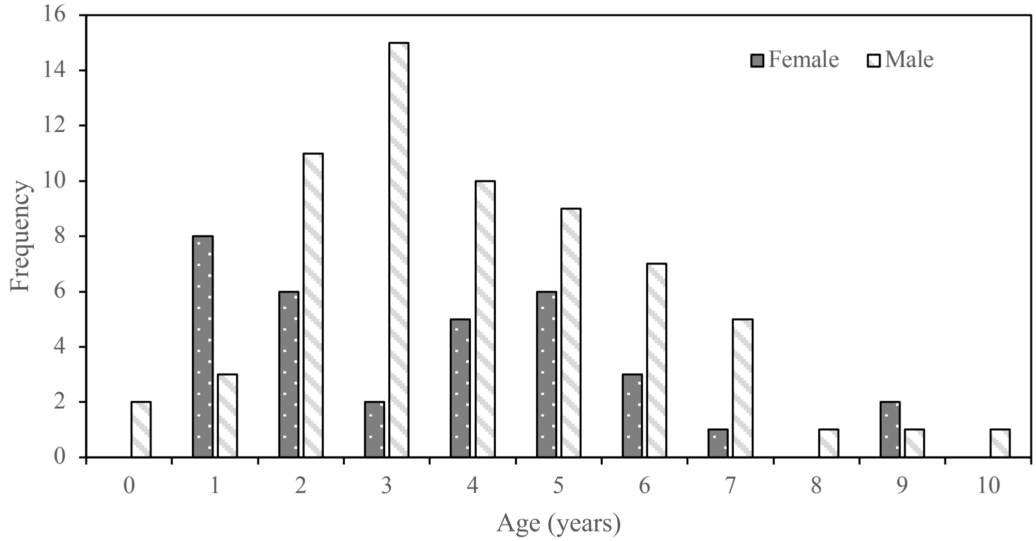

Figure 3.6 Age frequency distribution of lionfish by sex in the U.S. Gulf of Mexico.

Although significant differences in TL existed between male and female lionfish in the NWGoM, the age-structure was identical. Of lionfish collected from the NWGoM, 33 were female, while 65 were male. Following age-determination, 36% of each females were ≥ 5 years of age, while 37% of males fell within these ages. The remaining 64% of females were < 5 years of age, while 63% of males were younger than 5.

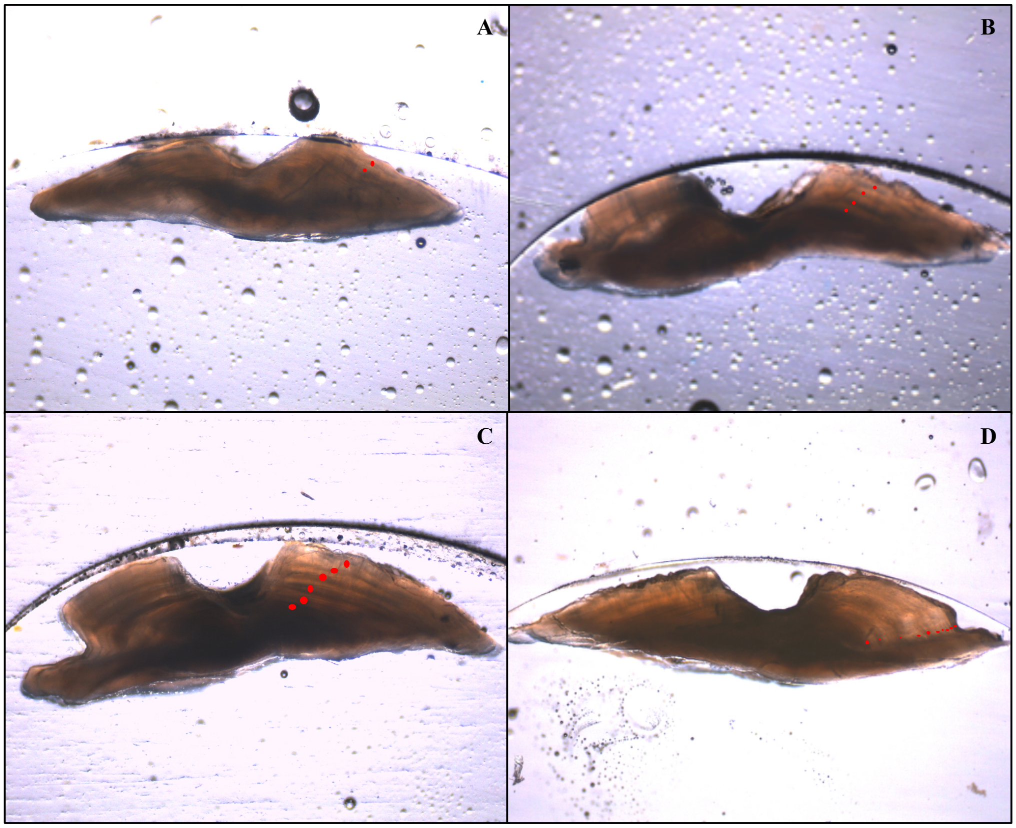

Figure 3.7 Annotated images of sectioned otoliths shown for different age classes from lionfish collected in the U.S. Gulf of Mexico. Red dot represents annuli. Percentages represent age distribution within the respective class for lionfish. A. Age 2 (18%), B. Age 4 (15%), C. Age 6 (10%), D. Age 10 (1%).

Comparisons revealed that males achieve a greater mean TL (320.8 mm ± 72.7) than females (273.8 mm ± 51.4) which was statistically significant ($p<0.001$), and though minimal, lionfish at WFGB achieve a greater TL (317.3 mm ± 10.3) as compared to EFGB (292.2 ± 64.9), but this was not significant. The K values in Fulton's condition factor ranged from 0.8 – 1.7 (1.3 ± 0.2) for females, 0.7 – 2.0 (1.3 ± 0.2) for males, and 0.7 – 2.0 (1.3 ± 0.2) for the NWGoM lionfish overall.

3.4.3 Comparison of growth and condition of lionfish in Aruba and the U.S. GoM

Von Bertalanffy growth curves were generated for lionfish in Aruba and the NWGoM (Figure 3.8). Additionally, because there were significant differences in TL between sex in the NWGoM, a VBGC was generated for each sex separately (Figure 3.9). There were significant differences in growth curves ($F_{1,142} = 20.91$, $p < 0.001$) and condition ($F_{2,141} = 23.25$, $p < 0.001$) between the two locations.

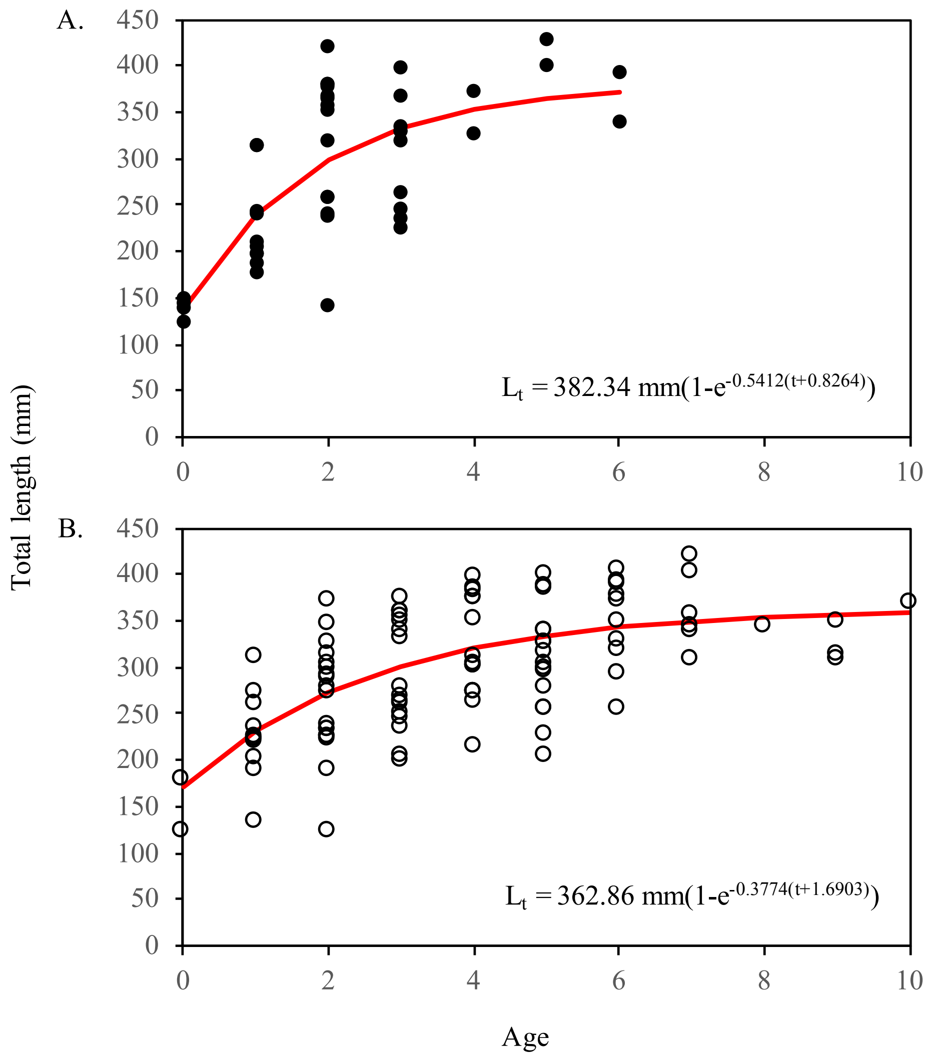

Figure 3.8 Von Bertalanffy growth curves and associated equations for Aruba (A) and U.S. Gulf of Mexico (B).

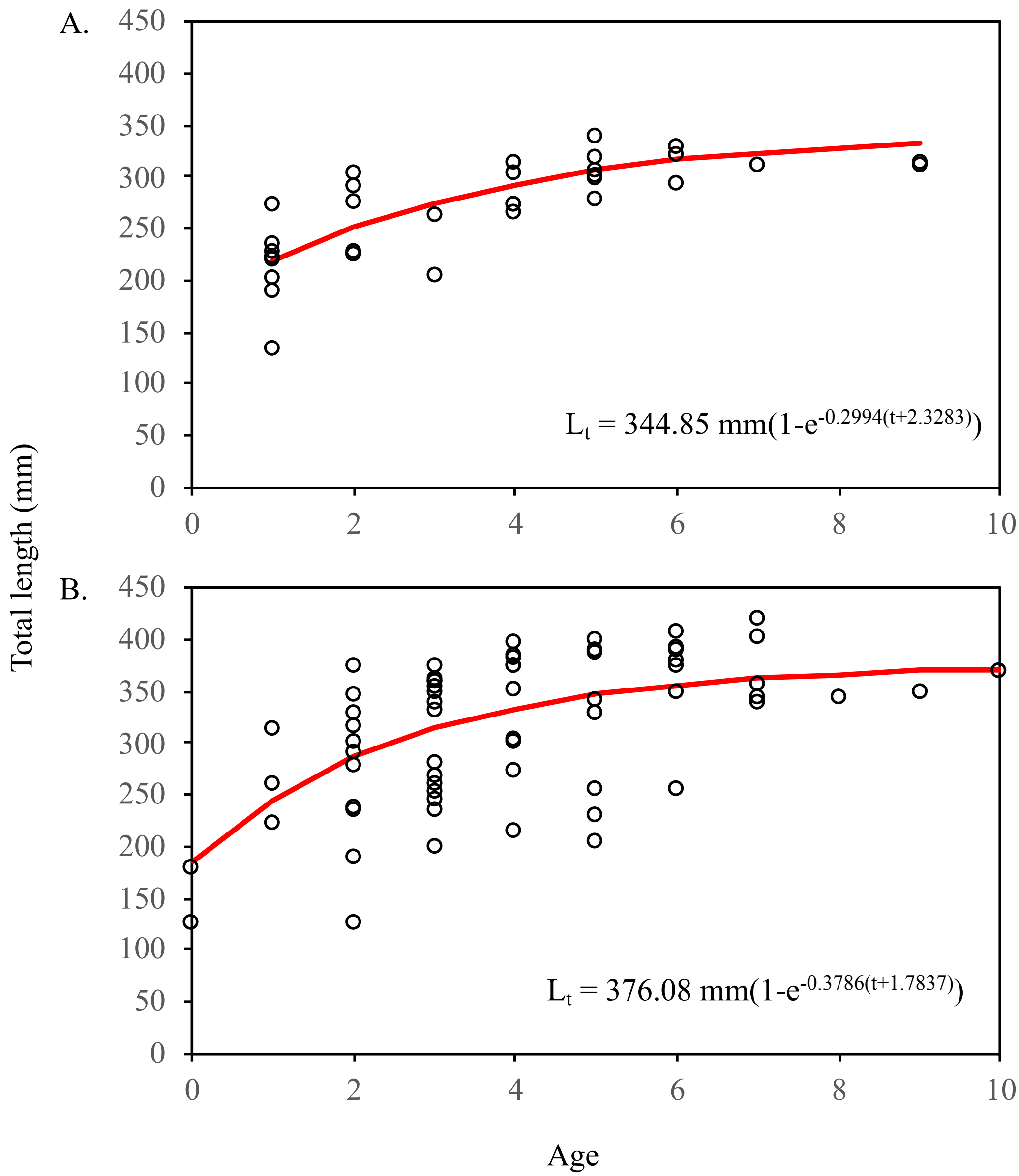

Figure 3.9 Von Bertalanffy growth curves and associated equations for female (A) and male (B) lionfish from the U.S. Gulf of Mexico.

Lionfish in the NWGoM obtained older ages, but lower condition, than those in Aruba (Table 3.1). Lionfish in Aruba had higher growth rates (K), asymptotic maximum length (L_∞), and reached a greater length-at-age than those in the NWGoM (Table 3.1).

This was true for the pooled U.S. Gulf of Mexico data, and those separated by sex. In the NWGoM, male lionfish had higher growth rates (K), asymptotic maximum length (L_∞), and reached a greater length-at-age than females (Table 3.1). The scaling factor, t_0, is a modelling artifact that is used to adjust the model for the initial size of the fish by defining the age at which the organism would be of zero length if it's growth were constant over-time [19, 20]. Results from the VBGC suggested that lionfish in the NWGoM would obtain age 0 at a smaller TL than lionfish Aruba, and that females would obtain age 0 at a smaller TL than males in the NWGoM (Tabble 3.4.1).

Table 3.1 Von Bertalanffy growth curve parameter estimates, ages, and Fulton's condition factor values for lionfish in Aruba and U.S. Gulf of Mexico.

Parameter	Aruba	NWGoM (pooled)	NWGoM (female)	NWGoM (male)
Age Min-Max (Mean ± SD)	0-6 (2.2 ± 1.5)	0-10 (3.9 ± 2.1)	1-9 (3.6 ± 2.3)	0-10 (3.9 ± 2.1)
L_∞ (mm TL)	382.3	362.9	344.9	376.1
K	0.5413	0.3774	0.2994	0.3786
t_0	-0.8264	-1.6903	-2.3283	-1.7837
Condition Min-Max (Mean ± SD)	1.096-2.104 (1.516 ± 0.216)	0.873-1.794 (1.377 ± 0.173)	0.817-1.725 (1.267 ± 0.161)	0.716-2.043 (1.320 ± 0.227)

Minimum, maximum, and mean values (± standard deviation) are reported for lionfish ages and values of the Fulton's condition factor.

Estimates for von Bertalanffy growth parameters from this study were compared to previous studies (Table 3.2). Overall, lionfish from the NWGoM achieved relatively low L_∞ when compared to other regions, and more specifically, when compared to other regions in the northern Gulf of Mexico. This held true for lionfish age and growth parameters that were pooled for the NWGoM study site, and those separated by sex. Lionfish in Aruba achieved comparatively high L_∞, and experience one of the highest growth rates (K) recorded. Alternatively, NWGoM lionfish from this study grow comparatively slower than those in other regions. To date, the oldest record of lionfish collected from the invaded region came from the NWGoM (Table 3.2).

Table 3.2 Comparison of age and growth parameters and maximum age reported for lionfish from their invaded regions.

Location	L_∞	K	t_0	Max Age	Source
Aruba	382.3	0.5412	-0.8264	6	This study
NWGoM (pooled)	362.8	0.3774	-1.6903	10	This study
NWGoM (female)	344.8	0.2994	-2.3283	9	This study
NWGoM (male)	376.1	0.3786	-1.7837	10	This study
Gulf of Mexico	400.2	0.56	-0.21	4.5	[21]
Gulf of Mexico	381.3	0.302	-0.519	7.7	[22]
Little Cayman	349	0.42	-1.01	5	[23]
North Carolina	425	0.47	-0.5	8	[6]
Yucatan, Mexico	420	0.88	-0.107	-	[24]
Bermuda	381	0.77	-0.42	9	[25]

3.5 Discussion

The current study revealed significant differences in lionfish age and condition between two invaded regions. Otolith-based age and growth estimates are important to understand and document for fish in order to measure the potential changes that may occur within the population due to implemented management [26]. Graham and Fanning [27] evaluated lionfish management plans of eight countries in the Caribbean, whereby all but one country scored remarkably low, with respect to prevention measures, suggesting that no prevention mechanisms were being addressed at the time of the study. Additionally, plans ranged in addressing lionfish research needs, with the majority of the countries explicitly identifying the need for research, but lacking specific links to goals or action items [27]. For the countries that did specify research needs, monitoring lionfish distribution and control activities were among the most pressing. Unfortunately, age and growth was not a prioritization for research in these regions, likely due to constraints in financial and technical capacities [27]. Johnston et al. [28] specifically identifies age and growth to be a research prioritization for management of lionfish in the NWGoM, of which, this study provides an initial assessment. Updating age and growth parameters for lionfish in their invaded region [29] will be necessary to ensure current research and findings are being used in future research.

Age/size and age-structure composition are one of the most influential life history characteristics that control the productivity of fish populations [26]. These parameters can be used to develop age-structured population models specific to invaded regions that are helpful to evaluate potential efforts needed for targeted removals. Barbour et al. [6] computed an age-structured population model for lionfish in North Carolina, suggesting an annual exploitation of 35-65% was necessary to cause recruitment overfishing. Conversely, an age-structured population model computed for lionfish in Little Cayman revealed a lower rate, needing only 15-35% annual exploitation to induce recruitment overfishing [23]. This shows there is not a “one size fits all” scenario for lionfish removal, as such, directed research at a local and regional level should be prioritized before determining the best management practices.

Documenting age, growth, and age-structure relationship metrics are important to monitor potential changes in the population due to implementation of management.

Age determination was successful in this study for both regions, with 93.6% and 91% comparative agreement between readers for samples from Aruba and NWGoM, respectively. Percent agreement between readers upon initial aging was lower, with 48% and 57% for samples from Aruba and NWGoM, respectively. The comparative agreement is higher than other studies from similar regions, with 60.1% [22] and 87.8% [21] from the northern GoM, and 42% in the Caribbean [23]; though initial percent agreement is comparable. Age determination was more difficult to assess for lionfish from Aruba, than those from the NWGoM, though this is not explicitly evident in the age agreement percentages. The concentric increments found in otoliths are marked by any major change in the environment, such as temperature or food availability. Fish that live in more uniform environments consequently have less conspicuous annuli and generally lack distinct bands laid during seasonal changes [10]. Sea surface temperatures (SST) in Aruba remain relatively stable throughout the year, varying at maximum 5.1°C [30]. While SST in the NWGoM varies by 8.2 °C throughout the year [31].

Lionfish ages ranged 0 to 6 years old (yo) in Aruba and 0 to 10 yo in FGBNMS. Although the 10 yo lionfish collected in the NWGoM is the oldest on record for the invaded range to date, this remains significantly younger than the maximum reported age of lionfish in captivity [32]. It is unclear whether lionfish can achieve 30 years of age outside of captivity; however, it is more likely to occur in marine protected areas or sanctuaries that do not actively control local populations, or in mesophotic zones where lionfish are beyond the depth limits of divers. The back-calculated ages for lionfish from this study confirm the presence of lionfish in Aruba and the NWGoM in 2008. This delay in detection is expected, as invasive species are not often observed immediately after introduction. Rather a lag associated with their population growth and spatial expansion results in a gap between arrival and initial detection [33].

Age distribution of marine fish is an important metric in evaluating the overall health of the population [12]. An established population will typically exhibit a well-balanced age structure with numerous larger, older individuals [34]. In Aruba, 63.6% of lionfish were ≤ 2 yo, suggesting their population may have still been stabilizing at the time of the study. Age classes in the NWGoM presented a more uniform distribution, with 31% of individuals being ≤ 2 yo, 58% ranging from 3-6 yo, and 11% ranging from 7-10 yo.

Lionfish in Aruba appeared to grow faster, reach a larger size, and be in better condition than those sampled from the NWGoM. This may be explained by the density dependence in growth and condition of lionfish [22]. Anecdotally, lionfish were observed in much lower densities in Aruba than at both banks in the NWGoM. This is likely due to the variability in habitat type and availability among the different locations. The NWGoM, specifically East and West Flower Garden Banks, are marked by high, continuous coral cover that offers an unparalleled refuge from external stressors such as predation, competition, and habitat availability. Additionally, East and West Flower Garden Banks experience extremely high fish biomass [31], offering an abundance of food available for lionfish consumption. Conversely, Aruba is marked by small patch reefs, large sea grass beds, and extensive sand patches. Lionfish were observed in all of these habitats, but it was evident that competition for resources would be much higher, given the limitations of the environment. Reef fish abundance has significantly declined in the Caribbean over the past half-century [35]. This lower food and habitat availability may result in faster growth and better condition of lionfish in Aruba, as they compete for these resources.

Lionfish have exhibited variable growth rate and other life history characteristics in the northern Gulf of Mexico [36]. The growth rate of lionfish is different among invaded regions, with the fastest growth reported in the southern Gulf of Mexico; however, this may be an artifact of their methodology as growth parameters were not confirmed with otoliths [24]. The growth rate of lionfish from Aruba is comparable to those reported from one northern GoM study [21], while the growth rate of lionfish in the NWGoM study site were comparable to that reported from artificial and natural reefs from a different northern GoM study [22]. It is not clear if this differentiation between the Aruba and NWGoM lionfish is due to speciation, in that, both species of lionfish (*P. volitans*, *P. miles*) have been confirmed in the Caribbean Sea, while only one species (*P. volitans*) has been confirmed in the Gulf of Mexico [37]. Genetic analyses were not completed for this study, but if included in future research, may afford the ability to determine if differences reported in age/size and growth demographics are species-specific

Subsequent studies, with a larger sample size and multiple sampling times and years, would be advantageous and may provide more insight than presented here.

Age/size and growth structure measures of lionfish have not been comprehensively reported for all of their invaded ranges. This study provides vital life history metrics that can aid in sound management decisions, and also provides the first statistical comparison of lionfish age and growth in such spatially separated regions.

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4. TEXAS STAKEHOLDER PERCEPTIONS OF CONTROLLING LIONFISH WITH CONSUMPTION

4.1 Synopsis

Marine fish invasions are a global issue that have accelerated in magnitude in recent years, of which can be detrimental to conservation efforts, local economies, or human health. Indo-Pacific lionfish (*Pterois* complex) are the first marine fish invasion to become established in the Western Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. Controlling lionfish with a commercial fishery has been proposed as a management strategy, though has not been readily investigated. In order to understand the likelihood of establishing a fishery, societal perceptions of the fish must be understood and investigated. Lionfish invaded the northwestern Gulf of Mexico, off the coast of Texas, in 2010 and their populations have since grown exponentially. In 2017, Texas Gulf Coast county residents (n = 420) were surveyed on their perceptions of the threats' lionfish pose, their willingness to consume and purchase the fish, and their support and confidence for managers to suppress the population. An ordered logistic regression model estimated the likelihood of an individual's willingness to pay for lionfish given their awareness of lionfish as a threat, level of concern for the fish, and level of support/confidence for management agencies governing the issue. Surveys revealed that 56.7% of the Texas Gulf Coast county residents were willing to purchase lionfish, and that 45.2% thought a commercial lionfish fishery would be good for the economy and environment. This report elucidated the significance of incorporating

social data into traditional biologically studies to gather an understanding of the community level characteristics that contribute to their acceptance of consuming an invasive marine fish.

4.2 Introduction

A biotic invasion occurs when a nonindigenous organism is introduced into a new location where the population proliferates, spreads, and persists [1]. Ecological consequences of biotic invasions can vary in scope and magnitude, while management focused on population suppression is almost always exceptionally costly [2]. Biotic invasions in the marine environment can be more challenging because of the high environmental connectivity between water bodies, in that, it is more difficult to manage a population as the spatial range and dispersion capacity increases [3].

Indo-Pacific lionfish (*Pterois volitans/miles* complex) have become the first successful marine fish invader in the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea [4, 5], attributed to several life history and behavioural traits that are believed to facilitate their continued expansion and population growth [6]. Lionfish were first reported in the northwestern Gulf of Mexico (NWGoM), off the coast of Texas, in 2010 [7] and are well known for having severe negative impacts to native reef communities [4, 8-13]. A suite of management strategies has been proposed to suppress lionfish populations; however, thus far are unsuccessful in achieving long-term recovery of native systems. This study focused on commercial harvest of lionfish, as the approach is likely to be cost-effective, socially rewarding, and ecologically sustainable if maintained.

Physical removal and commercial utilization of marine invaders has been encouraged and highly prioritized among resource managers [3], especially with respect to marine and aquatic invasions [14]. There are a number of positive aspects associated with gastronomic use of invasive marine species; however, formidable barriers exist within people's consumptive habits [15], owing to their inherent conservatism in food preferences and cuisine, with a general tendency to dislike new foods [16, 17]. A deeper knowledge of seafood markets and consumption preferences of a human population can be investigated through the use of surveys [18, 19], in order to determine their willingness to accept the introduction of a new marine invasive fish species into the market [20]. Therefore, prior to implementing a fishery, it is important to first gauge if the support and local demand exists within the community that would drive the harvests, about which information can be obtained using surveys [20].

A previous study investigated the willingness of consumers to accept consumption of Asian carp (*Hypophthalmichthys* spp.), another invasive fish species in the United States [21], which found that an individuals' willingness to eat the fish increased with their level of knowledge about the teleost. They reported that the majority of their sample population was willing to consume Asian carp [21]. In addition, Giakoumi et al. [3] found that fisheries managers highly prioritized commercial utilization and physical removal of marine invasive fish species, including lionfish. The greatest prioritization was expressed in public education and outreach efforts that would inform the public about the risks associated with an invasive marine species and their respective exploitation [3]. This type of public education is crucial for securing long-term social acceptance of management approaches for marine invasive species [22] and should be a priority within the framework of developing a commercial fishery for lionfish. Commercial utilization of lionfish could be an attainable management approach for Texas coastal communities, but prior to implementing this strategy, analyses should be undertaken to ensure social acceptance and understanding.

This study targeted residents of Texas Gulf Coast counties (n = 420) in 2017 in an attempt to understand what characteristics influence people's willingness to buy lionfish in Texas. Previous studies have shown that patrons in Florida were willing to pay more for lionfish when informed about their negative impact to the environment [23]. Fewer studies have addressed the social factors that influence an individual's willingness to support management, or willingness to pay towards, controlling an invasive species [24, 25]. The research presented here is unique in that it attempts to understand the social factors that contribute to an individual's willingness to pay for lionfish, using data gathered about their support/confidence in governing bodies to manage lionfish, their knowledge of lionfish, previous exposure to education and outreach efforts, and willingness to support management of the invasive species. We expect that a Texas Gulf Coast county resident would be more willing to pay for lionfish if they supported control, had confidence that the fish can be successfully managed, were knowledgeable about lionfish, and were concerned for the environment because of the detriment lionfish cause to native reef communities.

4.3 Methods

4.3.1 Social survey design

An original survey was developed and launched to Texas Gulf Coast county residents in July 2017. The survey was administered online through a panel of respondents recruited by Qualtrics, that were quota-based to match population demographics obtained from the 2016 U.S. Census Bureau of Statistics. The panel matched quotas for age, sex, and race for each of the designated counties (Table 4.1). The use of quotas to match the respondent pool to population characteristics created a representative sample that allowed for generalizations and applied statistical tests to examine individual level factors associated with willingness to buy lionfish.

Table 4.1 Characteristics of the sample

Individual level Characteristics	Distribution in Population	Frequency	Percent
Age			
18-24 years	13.0%	55	13.1%
25-39 years	39.6%	166	39.5%
40-64 years	32.3%	136	32.4%
65+ years	15.0%	63	15%
Race			
White	34.3%	155	36.9%
Hispanic/Latino	43.2%	170	40.5%
African-American	15.6%	66	15.7%
Asian	5.3%	22	5.2%
Other	1.7%	7	1.7%
Gender			
Female	50.8%	213	50.7%
Male	49.2%	207	49.3%

A total of 420 respondents completed the survey, and because the sample and population parameters were closely matched, a survey weight to adjust the sample population parameters was not needed. Eligibility criteria for survey respondents included being 18 years of age and residing in one of the following Texas coastal counties: Aransas, Brazoria, Calhoun, Cameron, Chambers, Galveston, Harris, Jackson, Jefferson, Kenedy, Kleberg, Liberty, Matagorda, Nueces, Orange, Refugio, San Patricio, Victoria, and Willacy (Figure 4.1).

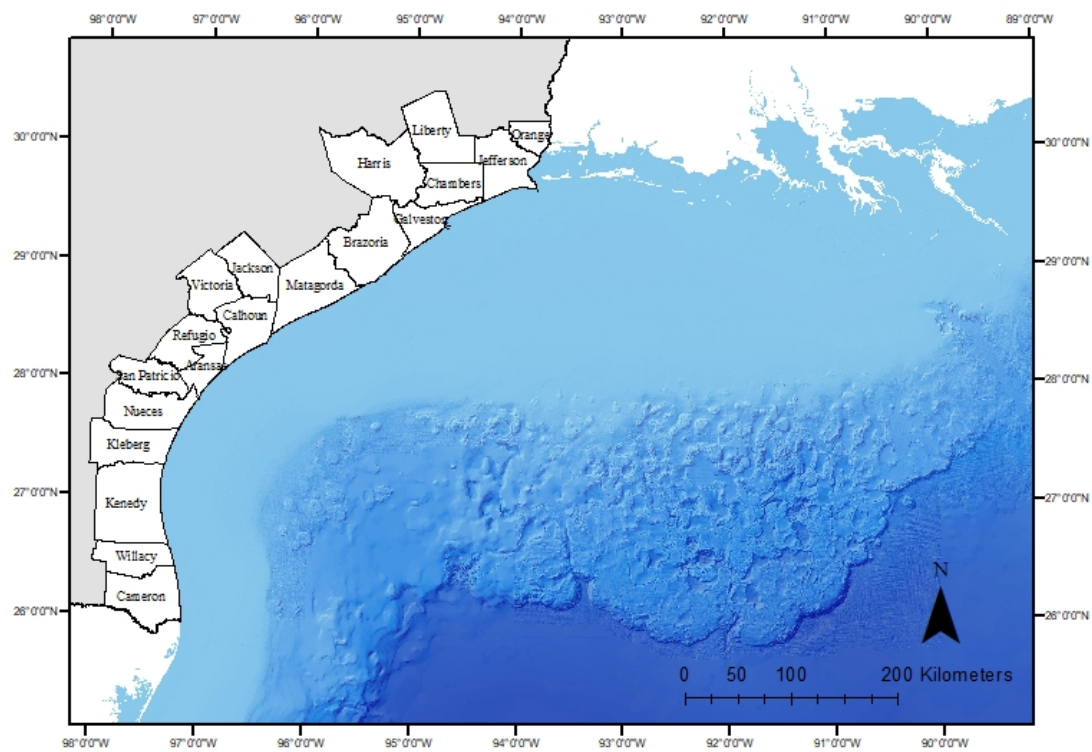


Figure 4.1 Map of sampling sites in Texas Gulf Coast counties as designated by the National Oceanic and Atmospheric Administration's coastal zone management program. Continental slope bathymetric data were provided from USGS [41]; Texas county data were retrieved from TxDOT [42].

The survey-instrument used in this study was non-probability and quota-based, whereby respondents were selected using a stratified sampling technique to specify the number of individuals within each group, matched to population parameters (Table 4.1). An 18-item survey was generated with novel items to capture previously unmeasured perceptions about the willingness to buy lionfish. Specifically, questions were designed to assess: 1) level of concern for lionfish impacts, 2) level of support for control efforts, 3) identify priority areas for management effort, 4) perception on who has or should have responsibilities for management of the fish, 5) willingness to support a lionfish fishery, and 6) exposure to lionfish education and outreach efforts (Appendix B). This study provides the most comprehensive evaluation of social factors that impact an individual's willingness to buy lionfish and is the first to investigate this willingness in Texas and at such a large spatial scale.

4.3.2 Variable preparation

To examine what factors influenced an individuals' willingness to purchase lionfish in a seafood market or at a restaurant, *willingness to buy lionfish* was used as the dependent variable (*buy_lf*). To measure this, a survey question was asked: "How willing would you be to order lionfish at a restaurant or purchase fillets in a seafood market?" Response options included: not willing (coded 1), somewhat willing (coded 2), very willing (coded 3), and undecided. The response undecided was omitted from regression analyses and evaluated separately.

The survey provided seven measures to interpret perceptions of lionfish as explanatory variables for willingness to purchase the fish. These included questions related to lionfish ecology, management and control, education and outreach efforts, exposure to science, relationship with the environment, a connectedness to nature scale, and ideology (Appendix B). Respondents were asked – "What would you say is your level of knowledge of lionfish?", by which individuals selected a numerical value between 0 and 10, where 0 was "no knowledge" and 10 "expert knowledge". This identification to level of knowledge was left up to the individuals so that they could respond to the question based on how much they felt they knew about lionfish. The variable "*know*" was coded to identify respondents with limited knowledge (0-1, coded 0), some knowledge (3-5, coded 1), knowledgeable (6-8, coded 2), and expert knowledge (9-10, coded 3).

Respondents were provided an informational excerpt that preceded two sets of questions regarding their concerns for impacts to the environment and the economy:

> *"An invasive species is any kind of living organism, such as a plant or animal, that is not native to an area and whose presence causes harm. The harm can be to the environment, the economy, native plants and animals, or even human health. Lionfish are a marine invasive fish species that has become established in the Atlantic, Gulf of Mexico, and Caribbean regions. The fish pose impacts to coastal environments and communities."*

Following this, individuals were asked to indicate their level of concern as: not concerned (1), somewhat concerned (2), neutral (3), concerned (4), or very concerned (5) for impacts to recreational fisheries, commercial fisheries, coral reefs, native fish populations, coastal economies, tourism and recreation, SCUBA diving operations, and offshore energy production. Each of these variables were then separated into two categories: concern for the environment (i.e. coral reefs, native fish populations, dive operations) and concern for the economy (recreational and commercial fisheries, coastal economies, tourism, and energy production). These categories were indexed to generate means of the two independent variables: concern for environment (*con_env*) and concern for economy (*con_econ*), comprised of the mean value of each of the response variables within each category.

The survey asked "Would you support control efforts aimed at reducing the impacts of lionfish in the Gulf of Mexico" (*supp_cont*), whereby respondents could select yes (coded 1) or no (coded 2). Additionally, they were asked a question about who they felt should be responsible for controlling the lionfish populations (*control*), in which they could select federal or state government fishery managers (coded 1), recreational water-sport operators (coded 2), recreational volunteers (coded 3), all of these (coded 4), or not enough knowledge to say (coded 5). Respondents were asked if they supported collaboration between researchers, fishermen, and managers to develop a strategy to control lionfish (*supp_coll*), whereby they could select not enough knowledge to say (coded 1), no (coded 2), or yes (coded 3). Finally, respondents were asked about whether they were confident that researchers, fishermen, and managers could develop a management strategy to effectively control lionfish (*conf_man*), where they could select not enough knowledge to say (coded 1), no (coded 2), or yes (coded 3).

The survey contained questions specific to a lionfish fishery whereby respondents were asked – "Do you think establishing a lionfish fishery would be good for the economy and the environment?" (*fish_good*). Options for responses included: it would be good for the economy and the environment (coded 1), it would not be good for the economy or the environment (coded 2), it would only be good for the economy (coded 3), it would only be good for the environment (coded 4), or not enough knowledge to say (coded 5). Respondents were asked if they had ever eaten lionfish (*eat_lf*), where they could respond no (coded 1) or yes (coded 2).

Finally, a different management strategy was proposed for lionfish control, where the respondents were provided an informational excerpt:

> *"Lionfish are imported from the Indo-Pacific for the aquarium industry. Scientists believe lionfish were introduced into the Gulf of Mexico by release from aquaria".*

The question asked – "Do you think that banning the importation of lionfish from the Indo-Pacific could help with control efforts in the Gulf of Mexico?" (*ban_lf*), which respondents could select yes banning lionfish will be very helpful or yes banning lionfish will be somewhat helpful (coded 1), no banning lionfish will not be helpful (coded 2), and not enough knowledge to say (coded 3).

Respondents were asked if they had ever attended an educational program, activity, or presentation to learn about lionfish (*educ_lf*), in which they could respond no (coded 1) or yes (coded 2). Additionally, they were asked if they belong to any environmental or conservation groups, whereby they could respond no (coded 1) or yes (coded 2).

The connectedness to nature scale (CNS) was used to measure an individuals' level of feeling emotionally connected to the natural world as a parameter for determining their willingness to buy lionfish. Mayer et al. [26] concluded that the CNS is a reliable and valid scale, whereby an individual's feeling connected to nature leads to their concern for nature and value of their ecological behavior. The statements used to evaluate CNS were compiled from Mayer et al. [26], specifically statements 2, 5-8, and 14 from Appendix A, and Dutcher et al. [27], specifically statements 2 and 4 from CNS and 2 and 4-5 from the environmental concern scale in Table 5. Composite scores (*cns*) were obtained by calculating the mean of the 11 items in the scale. Each of the items was scored using a 5-point Likert scale of agreement with options of: neither agree or disagree (coded 1), somewhat agree (coded 2), somewhat disagree (coded 3), strongly agree (coded 4), and strongly disagree (coded 5). It was assumed that an individual feeling more connected to nature or having a higher level of concern for the environment would be more willing to buy lionfish, to reduce the negative impacts to the environment. Previous research has shown that patrons having a high level of connectivity with nature retained a positive relationship to environmental concern and behavior [27].

4.3.3 Quantitative assessment with ordered logistic regression analysis

Given the coding of the dependent variable, y, an ordered logistic regression was estimated to determine the significant factors that influenced the likelihood of a resident in Texas coastal counties to purchase lionfish in a restaurant or seafood market. An ordered logistic (ologit) regression model is an ordinal regression model that is designed to determine how well a dependent variable response can be predicted by responses to independent variables. This regression model is used when the dependent variable is on an ordinal scale, which allows for a rank order (1, 2, 3 …, n), by which data can be sorted; however, it does not allow for the relative degree of difference between them [28, 29]. The model only applies to data that meet the proportional odds assumption, in that the number added to each of the logarithms to get to the next response is the same in every case, to form an arithmetic sequence. To arrive at the ologit, for K possible outcomes, the proportions of members of the population that would respond with not willing (1), somewhat willing (2), and very willing (3), can be represented by K_1, K_2, and K_3, respectively. The logarithms of the odds of answering in a particular way is estimated by:

$$not\ willing = \log\left(\frac{K_1}{K_2+K_3}\right),$$

$$somewhat\ willing\ or\ very\ willing = \log\left(\frac{K_1+K_2}{K_3}\right).$$

The ologit model for this analysis was:

$$Likelihood\ to\ buy\ lionfish\ (buy_{lf}) = \beta_0 + \beta_1(age) + \beta_2(sex) + \beta_3(race/ethnicity) + \beta_4(polid) + \beta_5(eat\_lf) + \beta_6(con\_env) + \beta_7(con\_econ) + \beta_8(know) + \beta_9(supp\_cont) + \beta_{10}(conf\_man) + \beta_{11}(supp\_coll) + \beta_{12}(fish\_good) + \beta_{13}(ban\_lf) + \beta_{14}(educ\_lf) + \beta_{15}(env\_group) + \beta_{16}(cns) + \beta_{17}(control) + \beta_{18}(county)$$

Observations with the dependent variable outcome “undecided” (n = 53) were omitted from the regression analysis and instead analyzed separately using cross-tab examinations (chi^2 statistics) of the independent variables. The “undecided” category was omitted from the analysis because it did not provide a response that was indicative of willingness to buy lionfish, and thus, was not appropriate for the model. See Table B-1, Appendix B for descriptive statistics of all variables included in the analyses.

4.3.4 Survey demographics

Quotas for each coastal county were defined based on population characteristics obtained from the U.S. Census Bureau of Statistics. All of the quotas requested from Qualtrics were met, thus, the data did not have to be weighted for analyses. The number of responses from each coastal county are shown in Figure 4.2, with the greatest number of responses from Harris County (n = 256), and fewest from Calhoun, Kenedy, and Refugio counties (n = 1), respectively.

The model controls for respondents *age* (coded: 1 = 18-24 years; 2 = 25-39 years; 3 = 40-64 years; 4 = 65+ years), *sex* (coded: 1 = female; 2 = male), and *race/ethnicity* (coded: 0 = white; 1 = minority race). Characteristics of the sample population were presented in Table 4.1. There were seven respondents that identified their race as other, of which, four responded with Black, and one with multiracial, Pacific Islander, and Southern Cheyenne, respectively. The four “other” responses that indicated their race was Black were included into the African American race category for analyses.

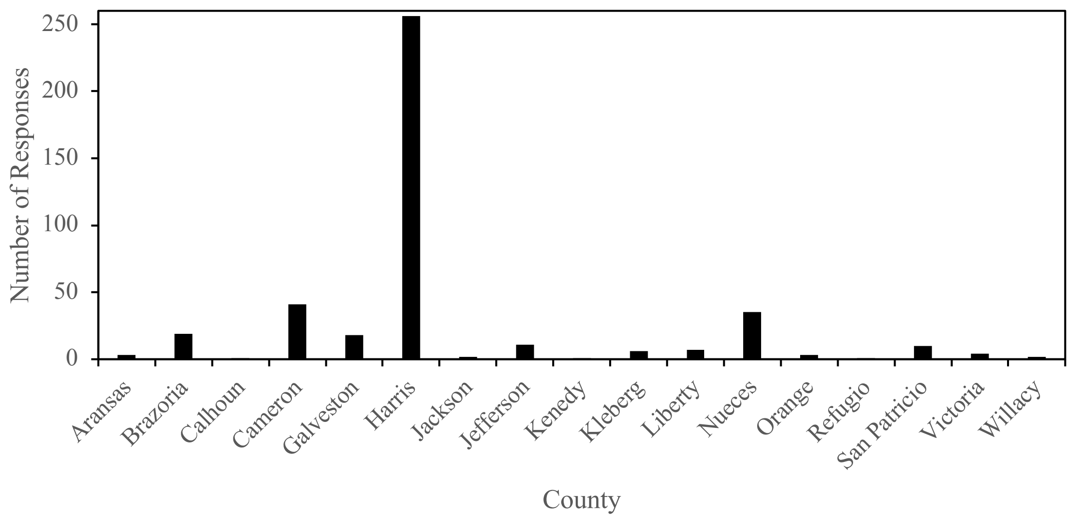


Figure 4.2 Number of responses from the 19 NOAA designated Gulf coast counties in Texas. The number of responses are proportional to population parameters as defined based on data obtained from the U.S. Census Bureau of Statistics.

The model also controls for political ideology (*polid*), restricting the responses to Liberal, Middle, and Conservative. Responses to the political ideology question ranged on a 7-point scale from "extremely liberal" to "extremely conservative". Three political ideology categories were created: Liberal – those who identified as "extremely liberal", "liberal", "slightly liberal"; Middle – those who said they were "middle"; and Conservative – those who selected "slightly conservative", "conservative", "extremely conservative". The model controls for political ideology because Conservatives are often tied to the Republican party, and typically less supportive of environmental programs but broadly more supportive of free market policies, while liberals tend to be more supportive of the environment but less supportive of free market mechanisms. Ideology, then, is important to explore to account for underlying environmental and economic attitudes that may influence willingness to buy lionfish.

4.4 Results

Table 4.2 describes the distribution of responses to the survey questions for willingness to buy lionfish, and other parameters tested in the model. Overall, 32.9% and 23.8% of Texas Gulf Coast residents were somewhat willing or very willing to purchase lionfish in a restaurant or at a seafood market, respectively. Fewer people were not willing to purchase the fish, at 30.7%, and 12.6% were undecided. Interestingly, only 8.1% of participants had previously consumed the fish. Given that only 8.3% had attended an educational program about lionfish, it is not surprising that 51.2% of participants had limited knowledge, while 7.1% claimed to have expert knowledge of lionfish. The majority (88.6%) of residents supported control efforts aimed at reducing the impacts of lionfish in the NWGoM. When asked about who they felt should be responsible for the control efforts, 44.8% responded government entities, while 40% selected collaboration among governments, recreational operators, and volunteers. Finally, 45.2% of participants said that a commercial lionfish fishery would be good for the economy and the environment, 10.7% responded that it would only be good for the environment, while 6% selected that it would not be good for either entity. An ordered logistic regression model was used to identify underlying factors that may have contributed to an individual's willingness to buy lionfish.

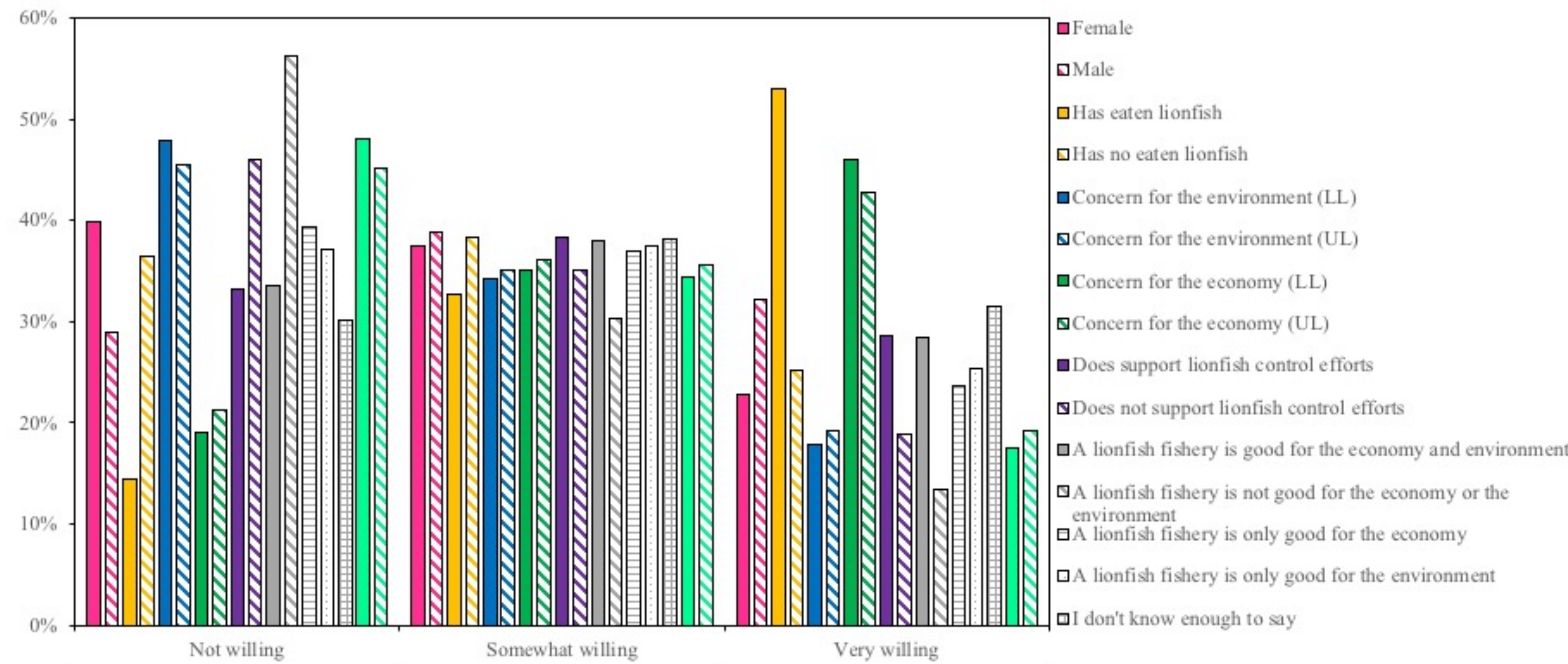
Table 4.2 Descriptive characteristics of responses to survey questions.

Variable	Frequency	Percentage
Willingness to buy lionfish		
Not willing	129	30.7%
Somewhat willing	138	32.9%
Very willing	100	23.8%
Undecided	53	12.6%
Eaten lionfish		
Yes	34	8.1%
No	386	91.9%
Attended educational program about lionfish		
Yes	35	8.3%
No	385	91.7%
Level of previous knowledge about lionfish		
Limited knowledge	215	51.2%
Some knowledge	101	24.1%
Knowledgeable	74	17.6%
Expert knowledge	30	7.1%
Support control efforts to suppress lionfish populations		
Yes	372	88.6%
No	48	11.4%
Entities responsible for managing and controlling lionfish		
Government (state/federal)	188	44.8%
Recreational operators	11	2.6%
Volunteers	3	0.7%
All of the above	168	40%
I don't know enough to say	50	11.9%
Commercial lionfish fishery benefit to society		
Only good for economy	25	5.9%
Only good for the environment	45	10.7%
Good for both	190	45.2%
Not good for either	25	5.9%
I don't know enough to say	135	32.1%

4.4.1 Ordered logistics regression analysis results

The initial ologit model resulted in questionable standard errors, therefore, the independent variables were tested for collinearity using correlations and variance inflation factor (VIF) statistics. VIF scores of 2.5 or greater are generally indicative of considerable collinearity [30]; therefore, variables that had VIF ≥ 2.5 were omitted from the ologit model. Owing to this, age and county were dropped, which resulted in a reliable model ($p < 0.001$). Results of the full regression are provided in Appendix B (Table B-2).

How willing are Texas Gulf Coast county residents to purchase lionfish, either by ordering the fish at a restaurant or buying fillets in a seafood market? There are some generalized findings from the regression analysis that are worth noting. On average, males were more willing to purchase lionfish than females. The likelihood to purchase lionfish significantly increased if an individual had previously consumed lionfish. An individual's willingness to purchase lionfish decreased with their concern for the environment, while their willingness increased with their concern for the economy. People were significantly less willing to purchase lionfish if they did not believe that a commercial lionfish fishery would benefit the economy or environment. And finally, an individual's feeling connected to nature decreased their willingness to consume lionfish. Given that ologit coefficients are difficult to interpret directly, the marginal effects of significant factors are presented in Figure 4.4.5.



	Not willing	Somewhat willing	Very willing
Female	39.81%	37.42%	22.78%
Male	29.00%	38.81%	32.19%
Has eaten lionfish	14.45%	32.63%	52.92%
Has no eaten lionfish	36.39%	38.38%	25.22%
Concern for the environment (LL)	47.90%	34.28%	17.82%
Concern for the environment (UL)	45.58%	35.16%	19.27%
Concern for the economy (LL)	18.99%	35.02%	46.00%
Concern for the economy (UL)	21.24%	36.05%	42.71%
Does support lionfish control efforts	33.16%	38.31%	28.53%
Does not support lionfish control efforts	46.08%	35.08%	18.83%
A lionfish fishery is good for the economy and environment	33.49%	38.05%	28.46%
A lionfish fishery is not good for the economy or the environment	56.31%	30.27%	13.42%
A lionfish fishery is only good for the economy	39.36%	36.99%	23.65%
A lionfish fishery is only good for the environment	37.17%	37.48%	25.34%
I don't know enough to say	30.20%	38.23%	31.57%
Connectedness to Nature Scale (LL)	48.11%	34.42%	17.48%
Connectedness to Nature Scale (UL)	45.22%	35.54%	19.24%

Figure 4.3 Factors influencing willingness to buy lionfish among Texas Gulf Coast country residents. Marginal effects were computed using the delta method. Marginal effects for concern for the environment, concern for the economy, and CNS were computed with respect to the lower limit (LL) and upper limit (UL) of their 95% confidence intervals. All marginal effects for dependent variables were statistically significant.

Pairwise comparisons of marginal effects were run for variables that were statistically significant to determine the magnitude of the effect and whether or not these differences were significant. A male is 10.8% ($p = 0.017$) less likely than a female to not be willing to purchase lionfish, whereas a male is 9.4% ($p = 0.019$) more likely than a female to be very willing to purchase lionfish. Additionally, a chi-squared test between gender and the individuals' previous consumption of lionfish indicated there was a significant relationship between these two variables ($X^2_{(2)} = 4.229$, $p = 0.04$), but that the strength of the association was relatively weak (Cramer's V = 0.1073). Twice as many men had tried lionfish in the sample population, as compared to women, though this number was still relatively low (males = 22; females = 11). Males were 1.4% more likely than females to be somewhat willing to purchase lionfish, but this was not significant.

An individual that had consumed lionfish was 27.7% ($p = 0.013$) more likely than someone that had not consumed lionfish to be very willing to purchase the fish, while they would be 21.9% ($p < 0.001$) less likely to not be willing to purchase the fish. An individual that feels a lionfish fishery is not good for the economy or the environment is 15.0% ($p = 0.004$) less likely to be very willing to purchase lionfish than an individual that feels a fishery would be good for the economy and the environment. Individuals who feel a fishery is only good for the economy or only good for the environment are 4.8% and 3.1% less likely to be very willing to purchase lionfish, respectively, than one who feels the fishery could benefit both the environment and economy. All results of the pairwise comparisons are reported in Table B-3-5, Appendix B.

Paired t-test indicated that participants concern for the environment, with respect to potential damages from lionfish, were greater than their concern for the economy ($p < 0.001$). A t-test was used to compared the indexed mean of individuals' responses to the environmental concern scale and connectedness to nature scale, to determine whether the idea that connectivity with nature resulted in a positive relationship with environmental concern. The comparison revealed that individuals' showed a greater concern for the environment, rather than showing an overall feeling of being connected to nature ($p = 0.006$), which slightly contradicts previous research [27]. It was assumed that a respondent would be more willing to buy lionfish if they reported a high level of connectivity with nature or a high level of concern for the environment, because of the negative impacts' lionfish have on invaded ecosystems.

The dependent variable category "undecided" resulted in 53 responses from the sample population (Table 4.2). The majority of individuals that selected "undecided" were middle-aged (25-39 years old; 41.5%), Hispanic/Latino (37.7%), and female (52.8%) that identified their ideology as middle (54.7%), and supported control efforts to suppress lionfish populations (81.1%).

Table 4.3 Descriptive characteristics of the dependent variable "undecided" response category

Variable	Frequency	Percentage
Age		
18-24 years	5	9.4%
25-39 years	22	41.5%
40-64 years	18	33.9%
65+ years	8	15.1%
Race		
White	14	26.4%
Hispanic/Latino	20	37.7%
African American	11	20.8%
Asian	6	11.3%
Other	2	3.8%
Gender		
Female	28	52.8%
Male	25	47.2%
Political ideology		
Liberal	13	24.5%
Middle	29	54.7%
Conservative	11	20.8%
Support control efforts to suppress lionfish populations		
Yes	43	81.1%
No	10	18.9%

Chi-squared statistics were used to investigate the relationship between independent variables with respect to the "undecided" category of the dependent variable to determine if there were any significant factors that contributed to this response. Gender, age, previous consumption of lionfish, race, political ideology, support for lionfish control, concern for the environment, and concern for the economy were all investigated. Descriptive statistics of these variables are provided in Table 4.3. There was no significant relationship between gender and any of the other variables.

Interestingly, this is contradictory to the results of the chi-squared test that compared gender and consumption of lionfish in the previous analysis (see above).

There was a significant relationship between previous consumption of lionfish and concern for the environment ($X^2_{(15)}$, $p < 0.001$), and the association between these two variables was strong (Cramer's V = 1.000). There was no significant relationship between previous consumption of lionfish and any of the other variables. The relationship between age and political ideology was marginally significant ($X^2_{(6)}$, $p = 0.078$). From ages 25-64, most individuals identified their political affiliation as "middle". The youngest (18-24) and oldest (65+) individuals were split nearly evenly between liberal (n = 2) and conservative (n = 3), respectively. There were no significant relationships between age and any of the other categories. There was a significant relationship between concern for the economy and concern for the environment ($X^2_{(165)}$, $p < 0.001$), and there was a particularly strong association between the two variables (Cramer's V = 0.7213). This significant relationship may be due to multicollinearity, as results of the Pearson correlation revealed the terms were highly collinear (Table B-6, Appendix B). No significant relationships existed between any of the other variables (i.e. race, political ideology, and support for lionfish control).

4.5 Discussion

Given that very few of the individuals from Texas had previously consumed lionfish (n = 34), it is noteworthy that more than half of respondents were willing to purchase the fish in a restaurant or seafood market in some capacity (n = 238). The pairwise comparisons of marginal effects indicated that there was statistically significant differences in being very willing or not willing to purchase lionfish between males and females, whether an individual had eaten lionfish or not, and an individual's feeling towards a lionfish fishery's benefit to the environment or the economy. An individual was more likely to be very willing to purchase lionfish if they had previously consumed it. Witkin et al. [31] showed that New England consumers were willing to pay more for an underutilized fish if they had previously purchased it. Given the results of our analysis, it is likely that this is also true for a consumer's willingness to purchase an invasive species that is new to the market. A community's ability to increase consumer's exposure to a new fish (e.g. lionfish, invasive species) in restaurants, seafood markets, or through organizations that promote its consumption, could be successful in establishing social support for the development of a commercial fishery [31]. As such, marketing campaigns should target efforts in promoting the consumption of lionfish in local seafood restaurants in Texas to increase consumer exposure to it being introduced as a new fishery.

The results of the pairwise comparisons indicated that men were more likely than women to be very willing to purchase lionfish. As lionfish would be a new species to the market, food neophobia could play an important role in an individual's willingness to consume the fish. The effect of gender on food neophobia remains unclear [32] and contradictory, where some studies indicate that men are more neophobic than women [33, 34], while others show no signficant differences between genders [35, 36]. This present study adds to that contradiction; nevertheless, I did not explicitly ask if individuals had a fear of trying new foods. If an individual had not eaten lionfish before, and were also not willing to eat it, it was assumed that this could be an indicator of food neophobia. Additional analyses would need to be pursued to determine the underlying factors that may contribute to this aversion.

There are recommendations to increase the awareness of consumers' food choices to show that they represent significant environmental decisions. Recently, the Food and Agriculture Organization (FAO) focused on eco-labelled fish products to increase sustainable seafood production and environmental protection [37]. Lionfish is often marketed as an eco-friendly fish alternative in areas where the fish is consistently sold (e.g. Florida Keys). In the survey developed for the present study, I did not ask about an individuals willingness to buy or eat lionfish if labelled as an eco-friendly fish. Perez-Ramirez et al. [38] found that coastal residents in northwestern Mexico favored eco-labelled fish as a sustainable seafood option, even knowing that it is often costlier than common alternatives. Informing consumers about the ecologic benefits of eating invasive fish species, such as lionfish, could result in their prioritization of ordering and demanding ecologically-favorable seafood options. It would be beneficial for future surveys to measure a consumer's willingness to pay for lionfish if labelled as an eco-friendly option, and whether or not this is impacted by the price. This information could provide essential insight into the market development of a commercial lionfish fishery.

A limitation of this study is the quota-based survey used, as this sampling technique relies on a non-probability sampling frame. Quota-based sampling aims to match a panel of respondents that match population parameters, thereby increasing the representativeness of the sample, but it does not allow for calculating marginal errors that provide measurable precision. Thus, this introduces unknown sampling biases into the sampling estimates [39]. This sample bias can be reduced through the use of survey weights to adjust the sample population to fit population parameters [40]. This was not necessary for this study as the sample population closley followed the population parameters of the quota (see Table 4.1).

The lionfish survey distributed to Texas Gulf Coast residents was relativley comprehensive in design, but there is still much to learn about the factors that contribute to a persons *behavior* in their choice to purchase or consume lionfish. As mentioned above, there were several other components that could have been assessed in the survey; however, this survey acted as a novel pilot study to identify knowledge gaps that could be addressed with additional questionnaires. Alternatively, the survey methodology can be re-structured to provide more information about how to change consumptive behavior. For example, a panel dataset could be configured, whereby the same individuals are asked a series of questions over-time following exposure to scientific information, education and outreach efforts, and lionfish consumption. This would better address the need to develop effective marketing shemes to result in the greatest social support. Focus groups can also be used among stakeholders to determine their underlying apprehensions and management perspectives, to allow for a more comprehensive strategy to be developed.

Overall, social data showed pertinent support for commercial utilization of lionfish in Texas Gulf Coast counties, irrespective of the relatively low exposure to the risk the fish imposes to the environment or previous consumption. This is very promising for the development of a lionfish fishery as a management option on the Texas coast. Subsequent analyses, as mentioned above, would likely improve fisheries managers and scientists understanding of the social implications of this strategy, and it is recommended to pursue those avenues prior to implementing a fishery. Because of the pervasive social support in Texas, the ecologic and economic feasibility of attaining a lionfish fishery were also investigated.

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5. CURBING THE LIONFISH INVASION WITH CONSUMPTION: USING A COMMERCIAL FISHERY TO MANAGE TEXAS ECOSYSTEMS

5.1 Synopsis

Indo-Pacific lionfish (*Pterois volitans/miles* complex) invaded the Gulf of Mexico in 2009 and their population has since grown exponentially in some areas. There are few systematic removal strategies to manage the population, so it is evident that a long-term, sustainable tactic is merited. This study devised a framework to determine the likelihood of establishing a commercial lionfish fishery through development of a conceptual model parameterized with ecologic and economic data collected off the Texas coast. Two hypothetical lionfish fishery models were developed that aimed to balance native ecosystem vitality and economic viability, whereby Model 1 focused primarily on costs relative to distance from shore, while Model 2 merged costs and ecological data. The validity of these two hypothetical models were compared to data collected during lionfish research cruises to Flower Garden Banks National Marine Sanctuary (FGBNMS) 2015-2018 using two-sample t-tests.

Mean lionfish density was 80.0 and 72.9 individuals per hectare (ind ha^{-1}) at West Flower Garden and East Flower Garden Banks in 2018, respectively. The average density of lionfish on artificial structures ranged from 25.0-30.6 ind ha^{-1}. Model 1 predicted a catch per unit effort (CPUE) that ranged from 4.2-166.6 kg diver hr^{-1}, while Model 2 estimated a CPUE of 0.3-4.6 kg diver hr^{-1} at an optimum sustainable yield (i.e. yield to be ecologically sustainable) of 50%, and 0.3-5.3 kg diver hr^{-1} at an optimum

sustainable yield of 75%. Catch statistics from lionfish research cruises ranged on average from 2.0-5.7 kg diver hr^{-1}, respectively. Two-sample t-tests indicated Model 2 and tournament data were not significantly different from each other. Given the habitat available for lionfish to colonize and the CPUE values computed in Model 2, the results of this study revealed that a lionfish fishery was likely to be one of the few options available for long-term suppression of lionfish populations in Texas.

5.2 Introduction

The introduction of nonindigenous organisms is a global problem that has accelerated in magnitude in recent years [1]. Marine invasions, in particular, have increased substantially with globalization, through human-mediated dispersals [2, 3]. An invasive species is considered most harmful if they damage human health and community wealth, shift the structure and function of an ecosystem, or lower biological diversity [4, 5]. The establishment of Indo-Pacific lionfish (*Pterois volitans/miles*, herein referred to as lionfish) has been labelled as a threat to global biodiversity by Sutherland et al. [6]. Lionfish have proliferated due to a wide range of physiological adaptations [7-10], that mediated their persistent expansion from the Western Atlantic Ocean to the Caribbean Sea, Gulf of Mexico [11], and more recently South America [12]. These invasive fish decimate native reef fish populations [13-16] and have shown competitive advantages over native predators that occupy similar ecological niches [17, 18]. The breadth of their ecological impact is arguably one of the most severe of any invasive marine fish species. Less understood is their impact to local economies and human health; however, research has shown that lionfish are costly to manage because of their low vulnerability to conventional fishing methods [19-22], and that puncture injuries resulting from contact with the fishes' venomous spines have caused hospitalization in some cases [23, 24]. In this sense, lionfish threaten the environment, economy, and human health; as such, developing a management strategy that sustains their long-term removal is pertinent.

Commercial harvest of lionfish for human consumption has been proposed as a potential mitigation strategy [25-27]; however, few studies have empirically evaluated this approach (see Section 2). To be effective in this management tool, it is imperative that commercial utilization for consumption be evaluated from a social (see Section 4), ecologic, and economic perspective. Too often, one or more of these components is ignored in fisheries biology, but recent research has shown that the integration of these sub-systems is an effective approach for holistically assessing the potential impact to the interaction of the human-environmental unit [28]. Ecologically relevant information can be obtained by assessing distribution patterns, population and life history characteristics, and establishing a current stock status [29, 30]. Data such as removal efficiency, catch per unit effort (CPUE), fuel and vessel costs, market price of lionfish, and percent fillet yield can provide insight into the economic feasibility of a commercial fishery [28]. The importance of amalgamating these components to develop a systematic approach to assessing the commercial harvest of a marine invasive fish species cannot be ignored, and was thus pursued in this study.

Social data revealed support for the consumption of lionfish and management with a commercial fishery (see Section 4), therefore, ecologic and economic data were evaluated to assess the feasibility of establishing a commercial fishery for lionfish off the coast of Texas. The northwestern Gulf of Mexico (NWGoM, area in the northern GOM off the continental shelf of Texas and Louisiana) is marked by well-established coral reefs and banks that encompass biologically important features [31] and oil and gas platforms that sustain the coasts' petroleum industry. The Flower Garden Banks National Marine Sanctuary (FGBNMS) represents the northernmost coral reef system in the GoM and was designated a nationally recognized sanctuary by the Office of National Marine Sanctuaries (ONMS), within the National Oceanic and Atmospheric Administration (NOAA), in 1992 [32]. This marine sanctuary is located approximately 75-100 miles (113-161 km) offshore from Texas and Louisiana, and is comprised of three reef systems : East Flower Garden Bank (EFGB), West Flower Garden Bank (WFGB), and Stetson Bank.

Lionfish were first sighted at FGBNMS in 2010, and since then, their population has grown exponentially [33]. This study assessed the use of a commercial fishery for lionfish as a mitigation strategy for the NWGoM with data collected during annual research cruises that targeted removal of lionfish from FGBNMS (2015 – 2018). In this section, two different fishery models were developed, which were hypothetical in nature. The validity of the two theoretical models were tested by comparing their results to catch statistics data collected during lionfish research cruises to FGBNMS. By comparing the CPUE computed for the two models and catch statistics data, I was able to determine whether a commercial lionfish fishery in the NWGoM was an achievable management strategy, as well as identify the threshold for which a lionfish fishery was no longer viable given our model constraints.

5.3 Methods

5.3.1 Study area

East Flower Garden Bank (EFGB) and West Flower Garden Bank (WFGB) are characterized as prominent geological features located near the edge of the continental shelf created by the uplift of underlying salt domes ([32]; Figure 5.1). The boundaries of EFGB encompass approximately 66 km^2, while WFGB is comprised of approximately 77 km^2. EFGB and WFGB are marked by well-developed hard coral species (e.g. boulder coral, starlet coral, fire coral) that cover 1 km^2 and 0.4 km^2, respectively [32], in water depths ranging from 16-40 m [34]. Stetson bank (STET) resides at the northern limit of coral community ranges along the continental shelf, and is an uplifted claystone feature associated with the underlying salt domes (Figure 5.1). STET supports a much different benthic community than East and West Bank, marked by tropical marine sponges, low densities of hard corals, and silted hard-bottom features [35].

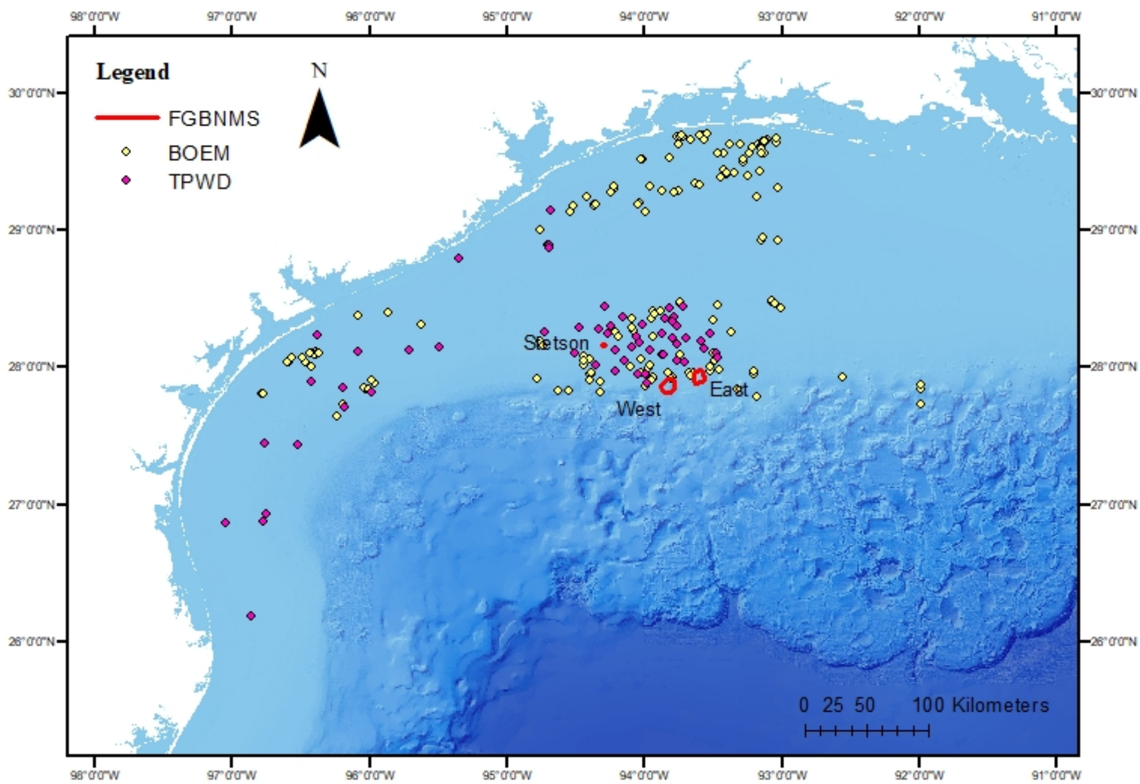

Figure 5.1 Map of the Flower Garden Banks National Marine Sanctuary and oil and gas platforms in the northern Gulf of Mexico in reference to Galveston, TX. Platform coordinates were obtained from BOEM's online data portal [66]; artificial reef data came from TPWD's online database [67]; topographic benthic coverage data was provided by USGS [68]; and FGBNMS polygon shapefile was provided by FGBNMS [69].

Lionfish cruises were performed at FGBNMS in 2015, 2016, and 2018 to both survey and remove invasive lionfish. A single, multi-day cruise was conducted in 2015 (31 August – 3 September, 2015) and 2016 (29 August – 1 September, 2016), while two cruises occurred in 2018 (26-28 June, 2018; 27-30 August, 2018). Volunteer removal divers (n = 22) and scientific divers (n = 8) dove at buoyed sites within EFGB, WFGB, and STET (Table C-1, Appendix C). Once the vessel was moored to the buoys, a total of four dives (2 scientific, 2 removal) occurred at each of the locations. The first and fourth dives were completed by the scientific divers, while dives two and three were done by the removal divers, following the methods described in section 5.3.2. In addition to the natural structures found in the NWGoM, the region is also marked by artificial structures that can act as habitat for lionfish.

Approximately 3,500 oil and gas production structures reside in the northern GOM, with over 3,200 still active [36] and installed in water depths ranging from 3-3,048 m. The Bureau of Ocean Energy Management (BOEM) oversees the responsible development of these platforms and pipelines, and works congruently with industry, state, and federal agencies to manage the installation and deconstruction of the infrastructure [36]. Once an oil and gas structure is decommissioned, it can be repurposed as an artificial reef, which is then managed by the Texas Parks and Wildlife Department (TPWD) [37]. TPWD currently maintains 91 artificial reefs that are comprised of fabricated materials, oil and gas structures, natural rock, and vessels (https://tpwd.texas.gov/gis/ris/artificialreefs/). Natural and artificial structures were investigated in this analysis (Figure 5.1).

5.3.2 Scientific and removal dives

Spearfishing is an illegal activity in FGBNMS, therefore, each year a research permit was obtained to remove lionfish for this study (Table 5.1). Each research cruise (n = 4) was comprised of two dive teams, with two rotations of dive operations: science personnel were responsible for setting up the study site and conducting underwater visual fish census surveys, while the removal divers' primary objective was to remove any lionfish sited within the study area. Prior to the removal dives, the science team deployed 100 m measuring tapes at the base of each buoyed dive site. The measuring tapes were attached to mooring u-bolts that were secured to the substrate, and run in each of the cardinal directions (N, S, E, W). Each two-person buddy team conducted fish surveys along the measuring tapes.

Table 5.1 Research permit numbers for each of the lionfish invitational cruises

Year	Permit number
2015	FGBNMS-2015-001
2016	FGBNMS-2016-006
2018	FGBNMS-2018-002

Two cruises occurred in 2018 that operated under the same permit number.

5.3.2.1 Pre-removal fish surveys

Each science dive team selected a cardinal direction to place their transect tape and conduct their fish surveys before entering the water. Along each transect line, each buddy team conducted two surveys, one that targeted lionfish and predators (herein referred to as lionfish survey), while the other targeted native prey fish and cryptic reef species (herein referred to as prey fish survey). The lionfish survey was conducted as a 50 m x 20 m transect, whereby the diver swam in a sinusoidal pattern hovering above the transect tape, surveying under ledges and over coral heads to collect data on lionfish and native competitor (e.g. grouper, eel) sizes, behaviors, and locations (see protocol and data sheet in Appendix C). Congruently, a prey fish survey was conducted by the other diver as a 25 m x 4 m belt transect to identify native reef fish and sizes (see protocol and data sheet in Appendix C). For each buddy pair, the first diver began the prey fish survey at the 75 m mark on the meter tape, while the second diver waited five minutes before starting the lionfish survey.

5.3.2.2 Lionfish removal dives

Following the science team dive, the 22 removal divers (total of 11, two-person buddy teams) conducted two consecutive removal dives on site that were separated by a two-hour surface interval. Each team was assigned a quadrant (Figure 5.2), that had a 100 m radius, in which the divers searched for and removed lionfish using Hawaiian sling pole spears. Divers also recorded data that included: the location that lionfish were removed, an estimated total length (cm), the number of attempts made to spear the lionfish, and if lionfish were successfully removed (see protocol and data sheet in Appendix C). Removal divers stayed within their assigned area and did not go below 30 m water depth because of the depth restriction guidelines of the FGBNMS permit. The data recorded during these dives allowed for calculation of a CPUE (kg diver hour^{-1}) and removal efficiency for each diver.

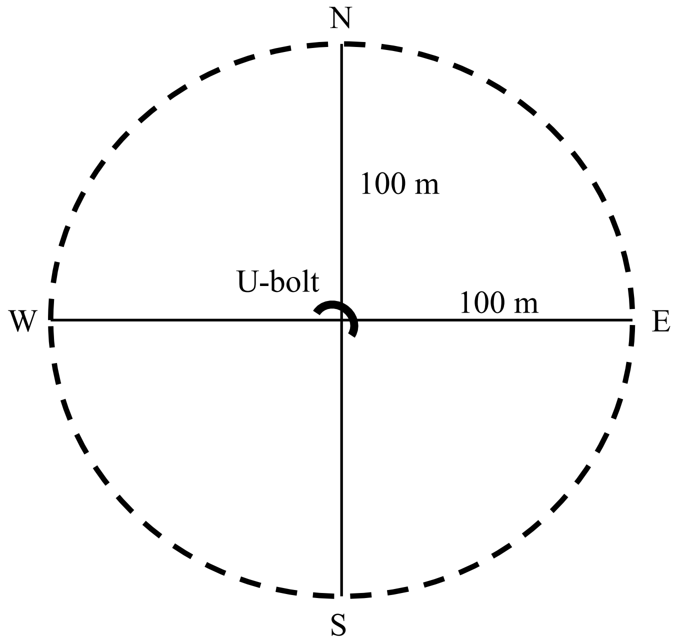

Figure 5.2 Schematic of the area set up at each study site with a transect tape attached to a mooring buoy u-bolt on the substrate that were laid out in all four cardinal directions. Science divers conducted fish surveys along each of the transect tape lines, while removal divers were assigned a quadrant (e.g. NW) to extract lionfish with pole spears and record data.

5.3.2.3 Post-removal fish surveys

Following the second removal dive, the science team conducted a second assessment to gather data on size, behavior, and location of any remaining lionfish within the transect areas, as well as characteristics of other native predator and prey fish at the site. Surveys began at the 25 m mark on the meter tape and once surveys were completed, the team picked up the survey lines to be returned to the vessel.

5.3.3 Characteristics of the lionfish sampled from natural reefs

Lionfish total length (TL) was measured in situ onboard the *M/V Fling* following each removal dive in all three years of collection (2015, 2016, 2018). Lionfish were retained onboard the vessel in uniquely labelled bags that contained information about the removal team, date removed, bank and buoy, and the dive number for that day (i.e. dive 1, dive 4) in a small freezer. Once returned to port, the lionfish were transported to the NOAA Galveston Lab to analyze additional metrics at a later date.

Lionfish were thawed overnight in the NOAA Galveston Lab prior to making the additional measurements. Once thawed, lionfish TL and standard length (SL) were measured to the nearest tenth of a centimeter, followed by their total weight (TW) to the nearest gram. Each lionfish was then dissected to determine sex following the protocols and gonad staging key provided in Green et al. [38]. Sagittal otoliths were removed from a subset of lionfish from the 2018 cruises (June n = 51; August n = 71), following the methods described in Section 3.

All of the lionfish removed in 2015 (n = 317) and 2016 (n = 394) were retained for metric measurements in the NOAA Galveston Lab. Lionfish removed during the June 2018 (n = 398) and August 2018 (n = 776) cruises exceeded the vessels freezer storage capacity, therefore, a portion of the samples had to be discarded prior to returning to port (June n = 268; August n = 570). Owing to this, only 130 and 206 fish were retained from the June and August trip, respectively, for metric measurements. Weights for the discarded fish had to be calculated using an allometric weight-length-relationship (WLR). The WLR was calculated based on:

$$W = aL^b,$$

where W = whole body wet weight in grams (g), L = length in centimeters [39], and a and b are parameters [40]. Coefficient a and b were estimated by a linear regression of logarithms:

$$logW = Loga + blogL,$$

with parameters defined above, whereby a is the intercept and b is the regression coefficient (slope). Length and weight measurements from the lionfish retained during the cruises were utilized to calculate parameter estimates (a, b) in order to determine weights for lionfish discarded. Analysis of variance (ANOVA) was used to determine if there were differences in the TL of lionfish removed for each cruise; if significant differences were detected, a WLR was calculated for each cruise, rather than pooling all of the data together.

5.3.4 Calculating lionfish densities for natural reefs

Density calculations were completed for each buoyed site per bank. Data were entered onboard following each survey by the divers that completed the transects (i.e. lionfish and prey surveys) each year. Once in port, data underwent quality assurance quality control (QA/QC) by a second party, to ensure consistency between data recorded in the field and data entered into the database. All data underwent QA/QC prior to completing any analyses.

Data were sorted to calculate density of lionfish by buoy for each of the banks for each sampling year based on data recorded during the lionfish (50 m x 20 m) and prey fish surveys (25 m x 4 m). The total area surveyed was computed by multiplying the transect length and transect width. The number of lionfish recorded during a survey in each of the cardinal directions were summed to provide the number of lionfish per area, which was used to determine the cumulative density of lionfish per buoyed study site, for each sampling method. The cumulative density for lionfish at each bank was computed by adding all of the densities from each buoyed site together. For example, in 2015, at three East Bank buoys, divers recorded 10, 3, and 3 lionfish over the 4000 m^2 at each buoy, respectively; which cumulatively would result in 16 lionfish per 12,000 m^2 or 13.3 lionfish per hectare (LF ha^{-1}). Densities were compared between each survey method using paired t-tests to determine if the results were significantly different.

5.3.5 Calculating lionfish densities for artificial habitat structures

Lionfish observation data are available from eleven of TPWD's artificial reefs, which include: High Island A (HIA)-298, HIA-271, the Texas Clipper, Brazos-A (BA)-28, HIA-532, HIA-447, HIA-497, HIA-515, HIA-555, HIA-270, and the Kraken, from 2014-2018. TPWD provided lionfish observation data for all monitored reefs except the Kraken. During the August 2018 lionfish cruise to FGBNMS, divers conducted a single dive at the Kraken, which provided the lionfish observations for this analysis. TPWD's monitored reefs only comprise 4% of the artificial substrate that is available for lionfish to colonize off the coast of Texas. Observation data from TPWD and the 2018 research cruise were used to artificially extrapolate a density estimate for lionfish on all available artificial habitat in the NWGoM.

Oil and gas platform data were downloaded from BOEM (https://www.data.boem.gov/Platform/PlatformStructures/Default.aspx), which were reduced to include only fixed structures that were still in place, had material reachable within recreational diving limits (40 m), and were leased off the Texas coast (Table C-2, Appendix C). These structures included fixed leg platforms (FIXED) and compliant towers (CT). Oil and gas structures off of Texas reside in the Western Planning Area that is zoned into fourteen different gas block areas: High Island, West Cameron, Sabine Pass, Galveston, Brazos, Matagorda Island, Mustang Island, Padre Island, Port Isabel, Corpus Christi, East Breaks, Alaminos Canyon, Garden Banks, and Keathley Canyon (Figure 5.3). Estimates for lionfish densities on artificial structures were restricted to these gas block areas.

Figure 5.3 Map of the Bureau of Ocean and Energy Management's Western Planning Area in the northern Gulf of Mexico. Reprinted from ONT, https://www.oceannews.com/news/energy/western-gulf-of-mexico-lease-sale-goes-live-on-the-internet, 2016 [70].

Structural dimensions were assumed to be the same for all structure types, which were used to calculate the total "footprint" area. Detailed dimensions of BOEM oil and gas platforms are proprietary information while a lease remains active, thus could not be obtained for this analysis. Detailed specs for each structure were not necessary for computation of total surface area. Rather, it was assumed that the surface area of the "footprint" of the oil and gas platforms were similar to a pyramid with a square base and top. Therefore, the area of each oil and gas structure was calculated by:

$$A_1 = \left[\left(\frac{a+b}{2}\right)h\right] * 4$$

$$A_2 = aw_1$$

$$A_3 = bw_2$$

$$A_S = A_1 + A_2 + A_3$$

where *a* is the length (i.e. longest side) of the top, *b* is the length of the bottom, *h* is water depth, w_1 is the width (i.e. shortest side) of the top, and w_2 is the width of the bottom, and A_S is total surface area of the "footprint". In all cases, $A_3 > A_2$, such that, the base of the oil and gas platform is larger than the top of the platform.

TPWD artificial reefs identified as fabricated material or natural rock were excluded from this analysis as dimensions were not available to calculate an area, and no lionfish observations were available to estimate densities. The dimensions for vessels: Kraken, Texas Clipper, George Vancouver Liberty Ship (BA-336), George Dewey (MI-616), and Jim Bridger (MI-616) were obtained from an online database (https://www.wrecksite.eu/). The surface area of vessels was calculated by assuming the surface area of a cylinder:

$$A = 2\pi rl + 2\pi r^2$$

where *r* is half the width of the vessel, and l is the length of the vessel.

TPWD provided lionfish siting data for their artificial reefs to be used in the analyses for this research. The number of lionfish TWPD reported ranged from 1 to 44 lionfish per structure, within the upper 40 m of the water column (Table 5.2). For each structure where lionfish observations were recorded, a density was calculated by dividing the number of lionfish by the surface area of the structure. In the event lionfish were observed more than once on the same structure, the most recent sighting was used (Table 5.2).

Table 5.2 Lionfish observations on artificial reefs

Year	Site name	Number of lionfish (n)	Structure type
2014	BA-A-28	2	Oil & Gas
	HI-A-271	13	Oil & Gas
	HI-A-298	3	Oil & Gas
	HI-A-447	37	Oil & Gas
	HI-A-497	2	Oil & Gas
	HI-A-532	1	Oil & Gas
	Texas Clipper	15	Vessel
2015	HI-A-271	5	Oil & Gas
	HI-A-298	6	Oil & Gas
	HI-A-497	9	Oil & Gas
	HI-A-515	6	Oil & Gas
2016	HI-A-447	1	Oil & Gas
	HI-A-497	1	Oil & Gas
	HI-A-555	9	Oil & Gas
2017	HI-A-270	3	Oil & Gas
	HI-A-555	10	Oil & Gass
2018	Kraken	44	Vessel

For the remaining platforms and vessels that were not surveyed, a uniformly distributed, random value for the number of lionfish were generated. Random values were bound between 1 to 37 for platforms, and 15 to 44 for vessels based on observations from Table 5.2, to avoid over-estimation of lionfish density. These randomly assigned values were divided by the surface area of the structure to extrapolate a lionfish density estimate for artificial habitat off the coast of Texas.

5.3.6 Hypothetical catch per unit effort for economically viable fishery

There will be variability in the costs associated with vessel usage for a lionfish fishery, dependent on the distance travelled offshore. As the distance from shore increases, the effort will also increase as it is intensified. In this sense, it can be expected that more lionfish will need to be removed as the distance from shore increases. CPUE can be determined if the total cost of the trip, unit price of lionfish, and total available time for removals is known. An initial model was devised to calculate hypothetical CPUE values (kg diver hr^{-1}) for a commercial lionfish fisher using the variables described in Table 5.3. Distance parameters are expressed in kilometers.

Table 5.3 Variables used to calculate hypothetical CPUE needed for a commercial lionfish fisher – Model 1

Distance	Time (hrs)	Fuel cost	Unit price of lionfish ($ kg^{-1})
40 km	0.75-1.0	\$8.45-\$14.50 km^{-1}	\$12.00
80 km	1.5-1.75	\$8.45-\$14.50 km^{-1}	\$12.00
120 km	2.25-2.5	\$8.45-\$14.50 km^{-1}	\$12.00
160 km	3-3.5	\$8.45-\$14.50 km^{-1}	\$12.00
201 km	3.75-4.5	\$8.45-\$14.50 km^{-1}	\$12.00

All time values were rounded to the nearest 15 minutes (i.e. 0.25 hours). Time estimates and fuel costs were based off personal communication with a commercial fisher (Cantrell pers. comm.). The estimate for the unit price of lionfish was obtained from personal communication with a commercial lionfish fisher in Florida (Bowman pers. comm.).

CPUE was calculated by:

$$CPUE = \frac{\left[\frac{[(D * C) + (D * C) * 0.15]}{P_l}\right]}{(T - t_n) - 2}$$

where D is distance travelled (km), C is fuel cost (US\$ km^{-1}), P_l is the unit price of lionfish (US\$ kg^{-1}), T is total vessel time (hours) between departure and return and t_n is total vessel travel time (hours). This model assumed a profit of 15% above the trip costs, and an hour of preparation for diving activities upon arrival and departure of the site (i.e. two additional hours).

This computation does not take into account the number of sites that would need to be visited, the available habitat, abundance of lionfish, optimal sustainable yield, or cumulative effort for an annual harvest. A second model was developed to attempt to account for these additional parameters. The hypothetical values from Model 1 were compared to refined values from Model 2 and CPUE computed from lionfish tournament statistics to test the validity of the model approaches.

5.3.7 Estimating lionfish abundance to quantify a harvestable "standing stock"

Lionfish dispersal capabilities are limited only by thermal and physical barriers [41]. In the NWGoM, no continental barriers exist off the Texas coast and the annual seawater temperatures are within the thermal tolerance of lionfish [42]. Owing to this, no considerations for physiological barriers were necessary when computing the expected lionfish abundance. Lionfish densities calculated following the methods in sections 5.3.4 and 5.3.5 were used to estimate a lionfish abundance for Texas by extrapolating these values for the total area of structure that was available.

At FGBNMS, it was assumed that the density distribution of lionfish were homogeneous across the reef substrata, as it is dominated by consistent scleractinian coral cover, that ranges from 60-75% [34]. Coral communities comprise 49, 219, and 5 ha at WFGB, EFGB, and STET, respectively. Lionfish abundance was calculated for each bank, for each year by multiplying the density and available coral area. A cumulative lionfish abundance for artificial habitat was determined by summing the number of lionfish that were estimated to inhabit BOEM and TPWD structures.

5.3.8 Optimal abundance for lionfish achieved with an optimum sustainable yield

Model 2 used an optimum sustainable yield (OSY), that was modified from Zabel et al. [43], as the lionfish yield that an ecosystem can sustain without having undesirable impacts, to achieve an abundance of lionfish that would remain in the environment (i.e. optimal abundance) at the end of the harvest season to maintain the longevity of the fishery. As lionfish have been recorded to decimate local native fish populations [14, 22, 44], a yield must be established that allows for a lionfish population that can economically sustain a fishery, but is ecologically responsible and reduces or eliminates the pressure on reef communities. Reducing lionfish densities 75-95% on targeted reefs in the Bahamas resulted in 50-70% recovery of native reef fish densities [45]. Alternatively, Barbour et al. [19] suggested that removal of 35-65% of lionfish could result in recruitment overfishing. Model 2 simulated two OSY scenarios, whereby 50% and 75% of the lionfish standing stock were removed to determine optimal abundance of lionfish for Texas. These OSY values are consistent with estimates in the literature, and reflect removal efficiencies that were achieved during lionfish research cruises to FGBNMS (see section 5.4.8).

5.3.9 Hypothetical CPUE to maintain ecological and economic viability

Model 2 assumed commercial fishers would depart from a single city, therefore, the distance from shore was calculated using the Buffer tool in ArcMap, with Galveston, TX as the point of reference. The distance from shore is displayed as concentric bands, which can be interpreted as fishing areas. Artificial structures and FGBNMS were included, to determine the available habitat that could be expected within each fishing area (Figure 5.4).

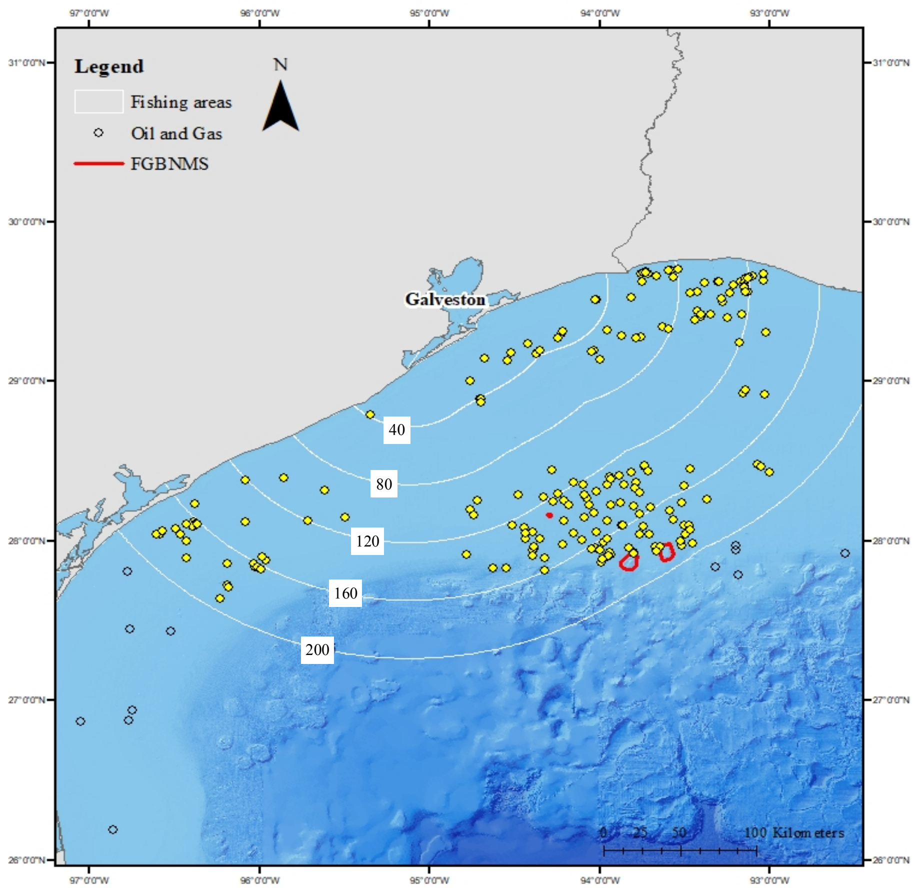

Figure 5.4 Map of the Texas coast in the northern Gulf of Mexico with artificial and natural habitat structures, and relative distances from shore. Yellow circles represent oil and gas and artificial reef structures that are within the 200 km buffer, while open circles are those outside of the range being considered in the model. Platform coordinates were obtained from BOEM's online data portal [66]; artificial reef data came from TPWD's online database [67]; topographic benthic coverage data was provided by USGS [68]; FGBNMS polygon shapefile was provided by FGBNMS [69]; and the Texas/Louisiana shapefile was obtained online from the U.S. Census Bureau of Statistics [71].

Model 2 sought to determine the CPUE that would be needed to achieve an OSY of 50% and 75%. Additionally, based on the annual number of trips, a CPUE was also computed that covered trip costs to determine if these two values were similar, and what the limiting factor would be for a commercial lionfish fishery. Model 2 also sought to determine the threshold with which a commercial fishery could no longer be viable, assuming each expedition was a one-day trip. It was assumed that the optimal lionfish abundance would be achieved at the end of the year.

Given the unpredictable nature of offshore conditions in the NWGoM, Model 2 only assumed 7 harvestable months out of the year. Additionally, Model 2 assumed 3 trips per week, 4 weeks out of the month, for a total of 12 trips per month. Model 2 adjusts the time buffer for diving operations by two-fold to allow for additional travel and prep time, assuming a commercial fisher would have to transit between habitats to achieve the total catch. This additional time was not based on measurements, rather included to help refine the second model as compared to the first. It was assumed more time may be needed, but it was not clear how much extra time would be allotted for transit, thus the time value was doubled. Model 2 accounted for net stock recruitment by estimating the monthly population growth, assuming the lionfish population has the ability to grow 2-3 times per year. Lionfish density and abundance doubled or tripled at FGBNMS with each consecutive year's trip, even with fishing pressure, so it was assumed this would be a reliable estimate (see section 5.4.2). Model 2 used the average fuel cost from Model 1 (\$7.13 mile^{-1}) to calculate the CPUE based on trip costs. Model 2 was computed following a series of equations:

1) Net recruitment (N_R): $N_R = A_{t+1} + (A_t * 0.15)$

where A is the abundance of lionfish within the fishing area, 0.15 is the scaling parameter for net monthly recruitment, and *t* refers to time in months.

2) Annual harvest (H): $H = \frac{\frac{(OSY*A)\overline{W}}{1,000}+N_R\overline{W}}{1,000}$

where OSY is the optimal sustainable yield expressed as a percentage (e.g. 50%, 75%), A is the abundance of lionfish within the fishing area, and $\overline{W}$ is the mean weight of lionfish (g). The annual harvest is expressed in kg.

3) Optimal lionfish abundance (L^*): $L^* = A - H$

4) $CPUE_{Ecol}$: $CPUE_{Ecol} = \frac{H}{T_D}$

where T_D is the total dive hours per month, computed by multiplying the dive hours per trip and trips per month. $CPUE_{Ecol}$ is reported as the total catch per diver hour (kg diver hr^{-1}).

5) $CPUE_{Econ}$: $CPUE_{Econ} = \frac{\left[\frac{[(D*C)+(D*C)*0.15]}{P_l}\right]}{(T-t_n)-4}$

$CPUE_{Econ}$ nearly mimics Model 1, however, the time to accommodate dive and travel operations between sites has been increased to 4 hours, rather than 2. Standard t-tests were used to compare CPUE results of Model 2 to Model 1 and research cruise statistics to determine the validity of this approach.

5.3.10 CPUE from tournament statistics

Catch per unit effort (CPUE) was standarized by restricting removal teams to two divers with a 45 minute total bottom time for each dive. The total catch for each team, for each cruise, was computed by summing the TW of all lionfish removed (kg). CPUE (kg diver $hour^{-1}$) was calculated by:

$$CPUE = \frac{\Sigma TW_{kg}}{n_{divers} * t}$$

where TW_{kg} is the total weight captured, n is the number of divers (n = 2), and t is the total dive time (number of dives*bottom time). Teams that used more than two persons during a removal dive were omitted from this analysis. An ANOVA analysis was run to determine if significant differences existed with respect to CPUE for each cruise. If differences were detected, a Tukey Post-hoc test was conducted to identify those significant differences.

CPUE computed for the two models were compared to tournament CPUE using t-test statistics. If data violated the assumptions of a two-sample t-test with equal variances, a Welch t-test was performed. Welch t-test assumes unequal variance between the two samples, with similar sample means. If data violated both of these assumptions, in that, the means and standard deviations were variable between the models, CPUE values were log transformed and then compared using a standard two sample t-test, as well as a Welch t-test to determine if significant differences existed between the model computations.

5.3.11 Dive team experience level

Removal divers were selected via a rigorous application process by which participants were required to apply online, to be certified as an advanced open water diver, to have NITROX certification, and to have previous experience handling and/or removing lionfish. Applications were reviewed by a selection committee to preferentially choose divers with more advanced diving (i.e. number of dives, time spent underwater) and lionfish removal experience. Although the majority of these divers had previously handled and removed lionfish, their experience level varied.

Experience level of each of the dive teams was assigned a value based on a scoring system, that was determined from a combination of their removal efficiency (ratio between lionfish collected and sighted) and the team collection relative to the total catch landed during the cruise (proportion removed). Teams were given a removal efficiency score (1-3) and a proportion removed score (1-5) which were summed to give an overall score that defined their level of experience (Table 5.4).

Table 5.4 Descriptions of scores assigned to teams based on their overall removal efficiency (lionfish collected/sighted) and their catch relative to the total landings of the cruise (proportion removed).

Removal Efficiency (%)	Removal Efficiency (RE) Score	Proportion Removed (%)	Proportion Removed (PR) Score	Total Score	Experience Level
<50	1	1-10	1	2	Novel
51-74	2	11-20	2	3-4	Moderate
75-100	3	21-30	3	5-6	Experienced
		31-40	4	7-8	Expert
		>41	5		

Scores were assigned for each of the criteria that were summed to determine a total score. This total score was used to determine the diving teams overall experience level.

5.3.12 Percent fillet yield

Fillet length, width, and weight were recorded for a subset of fish removed from FGBNMS (n = 27; mean TL = 286.5 mm ± 17.8 standard error (SE); mean weight = 473.3 g ± 67.6) in 2015 to compute a percent fillet yield for lionfish. Lionfish metrics were obtained with the same methods as described in section 5.3.3. Lionfish were scaled and filleted by hand, while paying careful attention to removing the maximum amount of meat from the flank. Fillet weight was then measured to the nearest gram by placing the meat flank on a scale. For each fish, the fillet weight was doubled as only one fillet was removed during processing. Percent fillet yield was then calculated by dividing the doubled fillet weight by the total weight of the fish, and multiplied by 100.

Fillet yield and current market price per kg ($/kg) for lionfish were compared to other commonly consumed marine teleost's in Texas to show how they relate to fish with similar flesh texture. Additionally, the size distribution of lionfish in all three sampling years were binned in 50 mm increments to assess whether or not fish were of marketable size based on the relationship between TL and fillet yield. Finally, fillet yield was overlain with age data that were summed according to mean TL to assess if there was a relationship with age.

All regression models and statistical analyses were carried out using Stata/IC 15.1 Mac version.

5.4 Results

5.4.1 Characteristics of lionfish sampled from natural reefs

The TL-TW relationship for lionfish removed from FGBNMS in 2015, 2016, and 2018 are represented in Figure 5.5. TW estimates were computed using WLR relationships. ANOVA revealed that lionfish TL differed significantly among years ($F_{3, 1816} = 10.91$, $p < 0.001$), therefore, each cruise was handled separately to calculate a WLR to estimate lionfish TW.

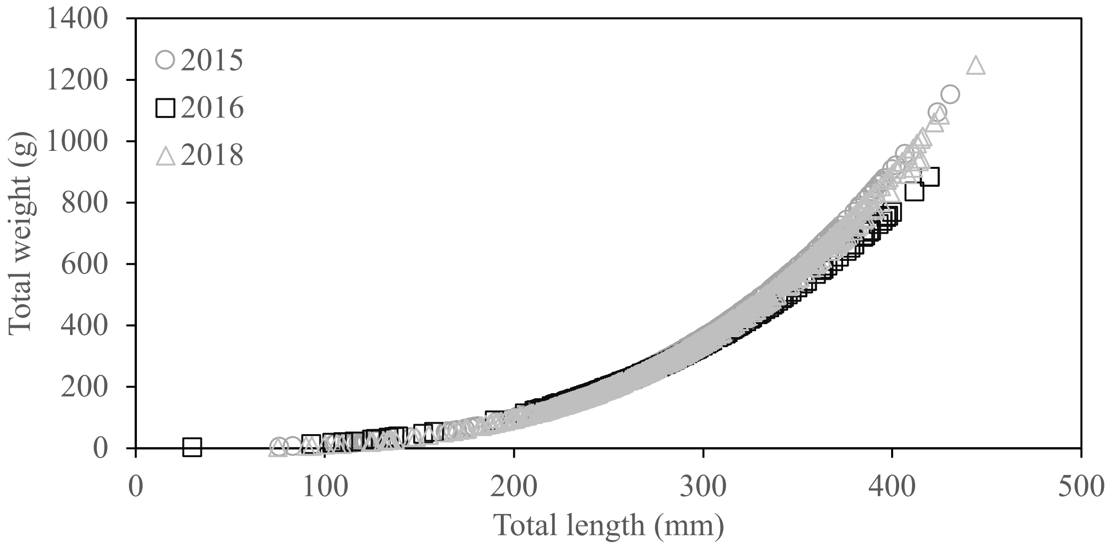

Figure 5.5 Total length (TL) – total weight (TW) relationship for lionfish removed from FGBNMS during research cruises in 2015, 2016, 2018.

Descriptive statistics for lionfish and WLR equations are provided for each of the cruises in Table 5.5. Lionfish TL was significantly different between research cruises ($F_{3,1816} = 10.91$, $p < 0.001$), with August 2018 having the largest mean TL (mean = 286.4 ± 54.8). Results of the Tukey post hoc test showed mean TL of lionfish in August 2018 was significantly larger than the June 2018 (mean = 269.4 ± 53.8) and 2016 (mean = 270.2 ± 50.8) cruises. Mean lionfish TL for the August 2018 was larger than those collected in 2015 (mean = 279.5 ± 67.8), but this was not signficant (p = 0.263). For all other cruises, lionfish mean TL was not signficantly different.

Table 5.5 Descriptive statistics and weight length relationship equations for lionfish from each research cruise to FGBNMS in 2015, 2016, and 2018.

Year	Total length (mm) min – max, mean (± SD)	Total weight (g) min – max, mean (± SD)	WLR equation
2015	76-431, 279.5 (± 67.8)	3-1093, 342.7 (± 218.8)	-2.192953 + 3.214528LogL
2016	30-420, 270.2 (± 50.8)	0.5-1037, 274.6 (± 164.7)	-1.759971 + 2.899103LogL
June 2018	155-415, 269.4 (± 53.8)	22-1099, 280.1 (± 189)	-2.077186 + 3.121818LogL
Aug. 2018	75-444, 286.4 (± 54.8)	4-1153, 347.5 (± 208.1)	-2.164028 + 3.193394LogL

5.4.2 Lionfish densities for natural reefs

Lionfish densities (individual ha^{-1}) were computed for each survey type (lionfish and prey fish survey) at each buoyed site, per bank, per year (Table C-3, Appendix C). Underwater surveys were completed at STET in 2015 and 2016, only. Figure 5.6 provides density estimates from lionfish surveys at the three banks over the sampling period. Results of the paired t-tests comparing survey methods for each year revealed no significant differences in density estimates between survey types in 2015 or 2018, but survey methods yielded significant differences in density estimates in 2016 (Table C-3, Appendix C).

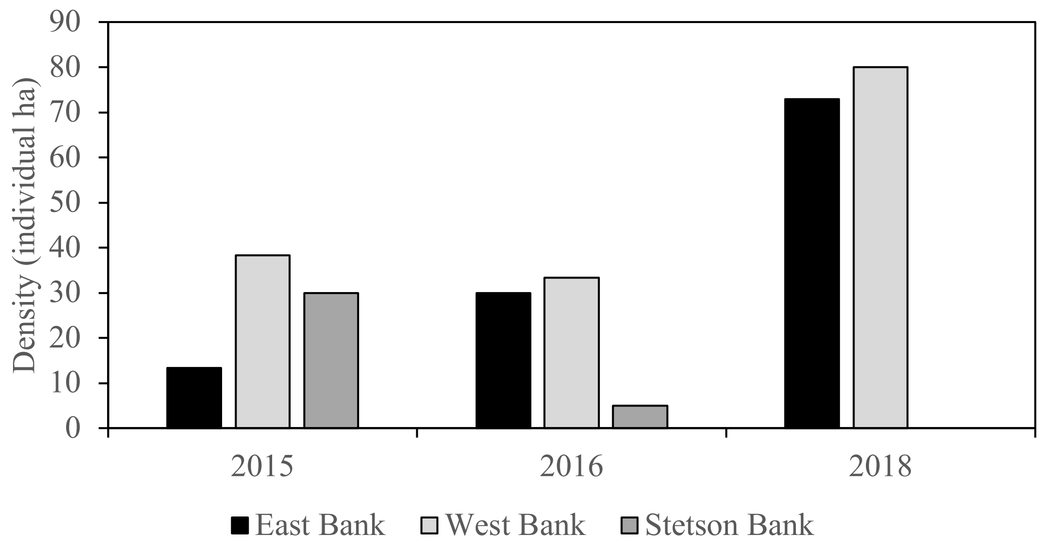

Figure 5.6 Lionfish densities (individual ha^{-1}) for Flower Garden Banks National Marine Sanctuary in 2015, 2016, and 2018 from 50 x 20 m lionfish surveys.

From herein, model analyses were computed using density estimates from lionfish surveys, as these are designed to detect lionfish in a reef environment with greater success than belt transects.

5.4.3 Lionfish densities on artificial habitat structures

According to 2019 data from BOEM, 276 oil and gas structures were present in the Western Planning Area (WPA) off the coast of Texas. Only 196 were retained for this analysis, as they were fixed structures and had material that was reachable within recreational dive limits. Artificial reef data were culminated from TPWD's online interactive mapping tool, which resulted in 91 reef systems; however, only 56 were retained for this analysis due to data constraints discussed above.

For oil and gas platforms, the width (w_2) and length (b) of the base were assumed to be 29 m and 42.7 m, while it was assumed to be 15.2 m (w_1) x 42.7 m (a) for the top, respectively [46]. The number of fish per structure was randomly assigned, bound within observations made on TPWD oil and gas platforms, to calculate lionfish densities for each offshore unit (Table C-4, Appendix C). The total number of structures, mean surface area (ha), and mean lionfish density by structure type are reported in Table 5.6.

Table 5.6 Mean values for surface area, number of lionfish, and lionfish density for TPWD artificial reefs and BOEM oil and gas platforms off the Texas coast.

Structure type	Number of structures (n)	Surface Area (ha)	Lionfish (n)	Lionfish density (ind ha^{-1})
TPWD Oil & Gas Platforms	52	0.83	0-37	25.03
TPWD Vessels	4	1.01	15-44	30.6
BOEM Oil & Gas Platforms	196	1.04	0-37	29.2

Surface area, lionfish numbers, and lionfish density were calculated for each offshore oil and gas platform and artificial reef using methods described in section 5.3.5. Here the mean for each of the categories is reported, for detailed values, see Table B-4, Appendix B.

5.4.4 Hypothetical CPUE – Model 1

Hypothetical CPUE values were generated to estimate the effort that would be needed to be a profitable commercial lionfish fisher in Texas, based on variables described in Table 5.3. CPUE reported in Table 5.7 are expected to be catch per trip. These values only consider the trip cost, plus 15% profit, to cover expenditures of each offshore expedition.

Table 5.7 Hypothetical values for the CPUE (kg diver hr^{-1}) needed to be a commercial lionfish fisher

Distance (D)	Trip Cost$_{(Min-Max)}$ (Mean ± SD)	Dive hours$_{(Min-Max)}$ (Mean ± SD)	Landings$_{(Min-Max)}$ (Mean ± SD)	CPUE$_{(Min-Max)}$ (Mean ± SD)
40 km	$389-667 ($528 ± 197)	8-8.5 (8.25 ± 0.5)	32.39-55.58 (43.99 ± 16.39)	4.05-6.54 (5.29 ± 1.76)
80 km	$778-1,334 ($1,056 ± 394)	6.5-7 (6.75 ± 0.5)	64.78-111.17 (87.98 ± 32.80)	9.97-15.88 (12.92 ± 4.18)
120 km	$1,167-2,001 ($1,584 ± 591)	4.5-5.5 (5 ± 0.75)	97.18-166.75 (131.96 ± 49.20)	21.59-30.32 (25.96 ± 6.17)
160 km	$1,555-2,668 ($2,112 ± 788)	3-4 (3.5 ± 0.75)	129.57-222.33 (175.95 ± 65.60)	43.19-55.58 (49.39 ± 8.76)
200 km	$1,944-3,335 ($2,640 ± 984)	1-2.5 (1.75 ± 1.25)	161.96-277.92 (219.94 ± 82.00)	161.96-11.17 (136.56 ± 35.92)

Values for trip cost are rounded to the nearest whole dollar amount. Dive hours are rounded to the nearest 15 minutes (i.e. 0.25 hours). Minimum, maximum, and mean values ± standard deviation are reported. Landings are reported as the total weight (kg) of lionfish that would need to be removed per trip, assuming an average weight of 317.4 g per lionfish. These estimates provide a per trip CPUE value, in that, e.g. each time a commercial fisher collects lionfish within 40 km from shore, their effort would need to be equivalent to 4.16-6.72 kg diver hr^{-1} across 8 dive hours.To achieve these CPUE values safely, we advise that it be completed with a minimum of two divers.

The number of artificial habitat structures within 40 km from shore was 20, which considerably increased further offshore, with cumulative 46, 95, 169, and 252 artificial structures within 80, 120, 160, and 200 km from shore, respectively. FGBNMS was split between two fishing areas, with STET within the 160-km area and EFGB and WFGB in the 200-km area. Given the values computed in Table 5.7, it is also important to determine if these landings are supported by the lionfish assumed to be available within these distances.

5.4.5 Lionfish abundance estimates off the Texas coast to quantify harvestable "standing stock"

Lionfish densities computed in Table C-3 (Appendix C) were used to estimate lionfish abundance at FGBNMS for each sampling year (Table 5.8). EFGB had the greatest number of lionfish; this was expected as total coral cover is highest at this bank. Consequently, STET had the lowest lionfish abundance as the benthic community is comprised of mostly claystone structure and sponges. Of the three, lionfish abundance at STET is likely the most under-represented, as this analysis focused on percent coral cover. It is possible that there is more than 5 ha of available structure for lionfish to colonize at STET. Results show total lionfish abundance doubling with each consecutive year at FGBNMS (Table 5.8). Similar calculations were made for artifical structures off the coast of Texas.

Table 5.8 Lionfish abundance estimates for Flower Garden Banks National Marine Sanctuary (FGBNMS) based on lionfish densities.

Year	East Bank	West Bank	Stetson Bank	Total	Mean
2015	2,913	1,877	150	4,940	1,647
2016	6,570	1,632	25	8,227	2,742
2018	15,965	3,920	-	19,885	9,943

Lionfish distribution was assumed to be homogenous across the available coral cover at each of the banks, by which coral communities comprised 219, 49, and 5 ha at East, West, and Stetson banks, respectively. Values reported in the table are total number of lionfish. Lionfish populations approximately doubled at FGBNMS with each consecutive year.

Lionfish abundance was assumed to be heterogenous across artificial substrate, as the distribution of lionfish can be highly variable on these artificial reefs [47]. The cumulative number of lionfish estimated to be residing on artificial habitat in the NWGoM was 4,661, with 1,028 and 3,633, on TPWD and BOEM structures, respectively. These abundance estimates were used to quantify the number of lionfish that were expected to be available within each fishing area. Cumulative abundance of lionfish on artificial habitat was summed with the mean abundance of lionfish on natural habitats to generate a total abundance with respect to distance from shore (Table 5.9).

Table 5.9 Lionfish available within each fishing area off the Texas coast.

Distance (mi)	**Lionfish (n)** ***Artificial habitat***	**Lionfish (n)** ***Natural habitat***	**Total lionfish (n)**	**Total weight of lionfish (kg)**
25	387	-	387	122.8
50	824	-	824	261.5
75	1,709	-	1,709	542.4
100	2,979	88	3,067	973.5
125	4,350	4,132	8,482	2,692

The total weight of lionfish (kg) uses the average weight of lionfish collected from the research cruises to FGBNMS (317.4 g). The mean number of lionfish at each bank across the three years (Table 5.8), was used to quantify the lionfish available on natural habitat.

Given the landing estimates from Table 5.7, and abundance estimates from Table 5.9, it appears that all of the CPUE’s would be achievable at the respective distances from shore in Model 1. Model 1 does not account for the ecologic benefits that need to be met by the fishery, therefore, it was refined to generate Model 2, which accounts for the optimal abundance of lionfish (i.e. OSY, total landings to be ecologically sustainable), as well as the cumulative time and number of trips needed on an annual basis to achieve this abundance.

5.4.6 Hypothetical CPUE – Model 2

Prior to computing CPUE, Model 2 was first tested to determine the threshold with which a commercial lionfish fishery would no longer be viable. It was assumed that the trip would not be viable if the harvest and/or trip cost exceeded the available dive time offshore. Based on these assumptions, and that this model only accounted for single-day expeditions, a commercial fishery would no longer be achievable past 120 km due to economic contraints (Figure 5.7, A), while it would no longer be attainable past 160 km offshore due to harvest constraints (Figure 5.7, B).

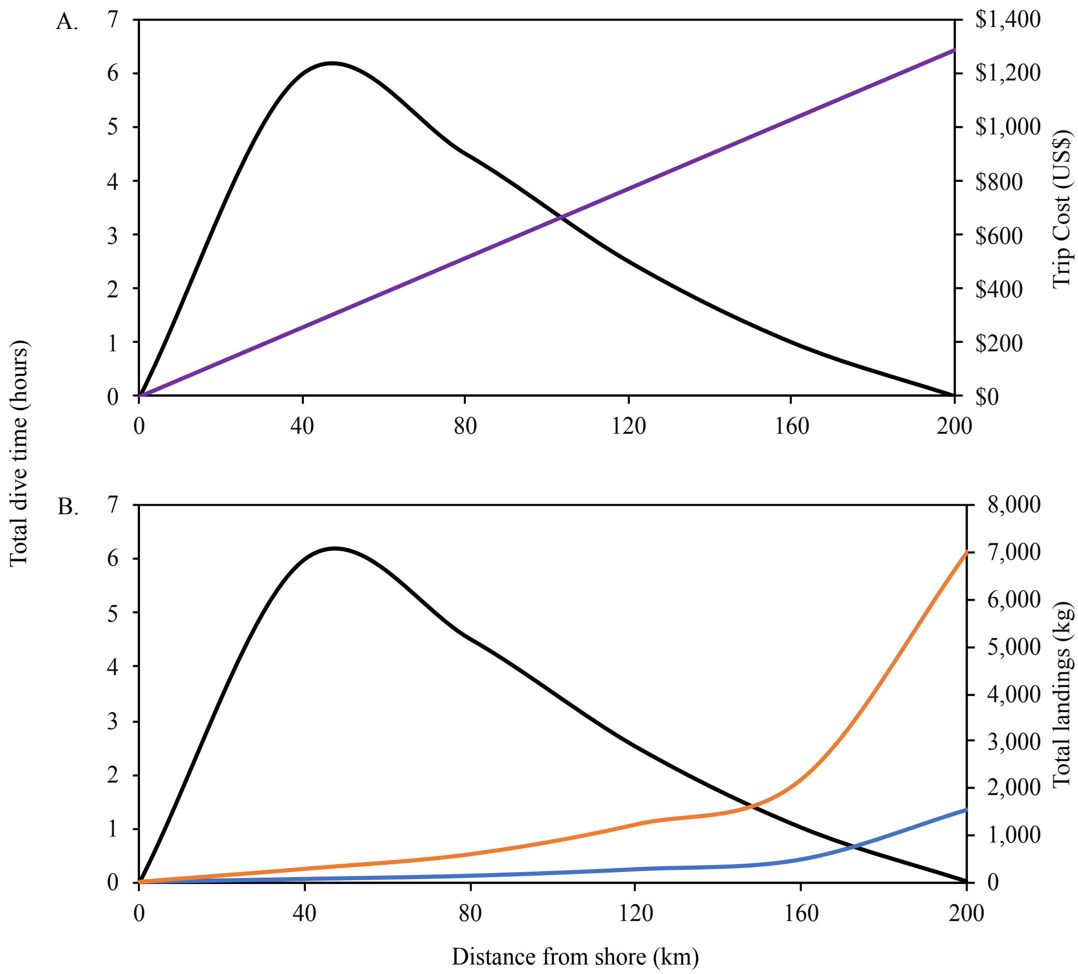

Figure 5.7 Thresholds for a commercial lionfish fishery off the coast of Texas based on economic and harvest constraints. A) Compares the total trip cost with the available dive time, indicating that past 120 km, a fishery would no longer be feasible. B) Compares the annual harvest needed to achieve OSY 50% and 75%, respectively, and indicates that a fishery would no longer be achievable past 160 km offshore. Both comparisons assume single-day expeditions.

Based on these results, computations were only made for 40-120 km offshore for the remainder of analyses. Net recruitment was estimated by month, assuming an annual increase of 2-3 fold (Figure 5.8). The parameters used for computation in Model 2 are presented in Table 5.10.

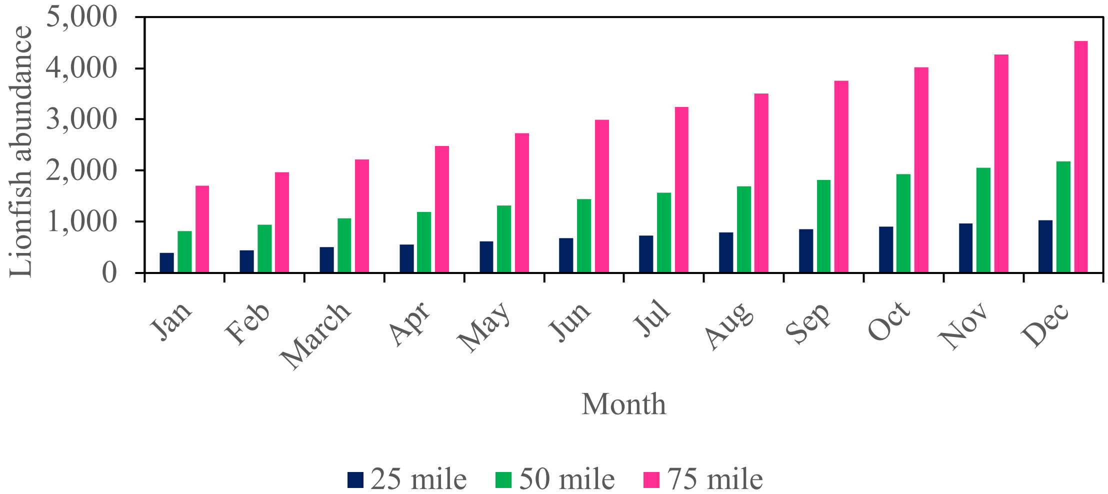

Figure 5.8 Net recruitment of lionfish based on abundance and distance from shore

Table 5.10 Parameter values used in computation for Model 2 based on distance from shore

Parameter	**25 mi**	**50 mi**	**75 mi**	**100 mi**	**125 mi**
Lionfish abundance (A)	387	824	1,709	3,067	8,482
Net recruitment (N_R)	0.15	0.15	0.15	0.15	0.15
OSY 50%	0.50	0.50	0.50	0.50	0.50
OSY 75%	0.75	0.75	0.75	0.75	0.75
Dive hours (T_D)	75	57	36	18	-
Fuel cost (C) ($ km^{-1})	$11.50	$11.50	$11.50	$11.50	$11.50

Net recruitment was a scaling parameter, adjusted to estimate a monthly population growth, based on an annual increase in lionfish abundance by 2-3 fold. Dive hours were computed by multiplying the estimated dive hours per trip (Table 4.3.3) with the number of trips per month (12). Dive hours were not computed for the 200 km category because it was no longer feasible given the additional time constraints from Model 2. The mean fuel cost from Model 1 was used in Model 2.

Model 2 computed harvest and $CPUE_{Ecol}$ under two different scenarios, with OSY 50% and 75%. The harvestable season was assumed to occur from April to October, with no harvest occurring November through March, due to weather and sea condition limitations that would render diving unsafe in the NWGoM. The net harvest was computed for each month, based on the harvest needed to achieve OSY and net recruitment, such that the estimated abundance of lionfish at the end of the year would not exceed the optimal abundance of lionfish (Figure 5.9).

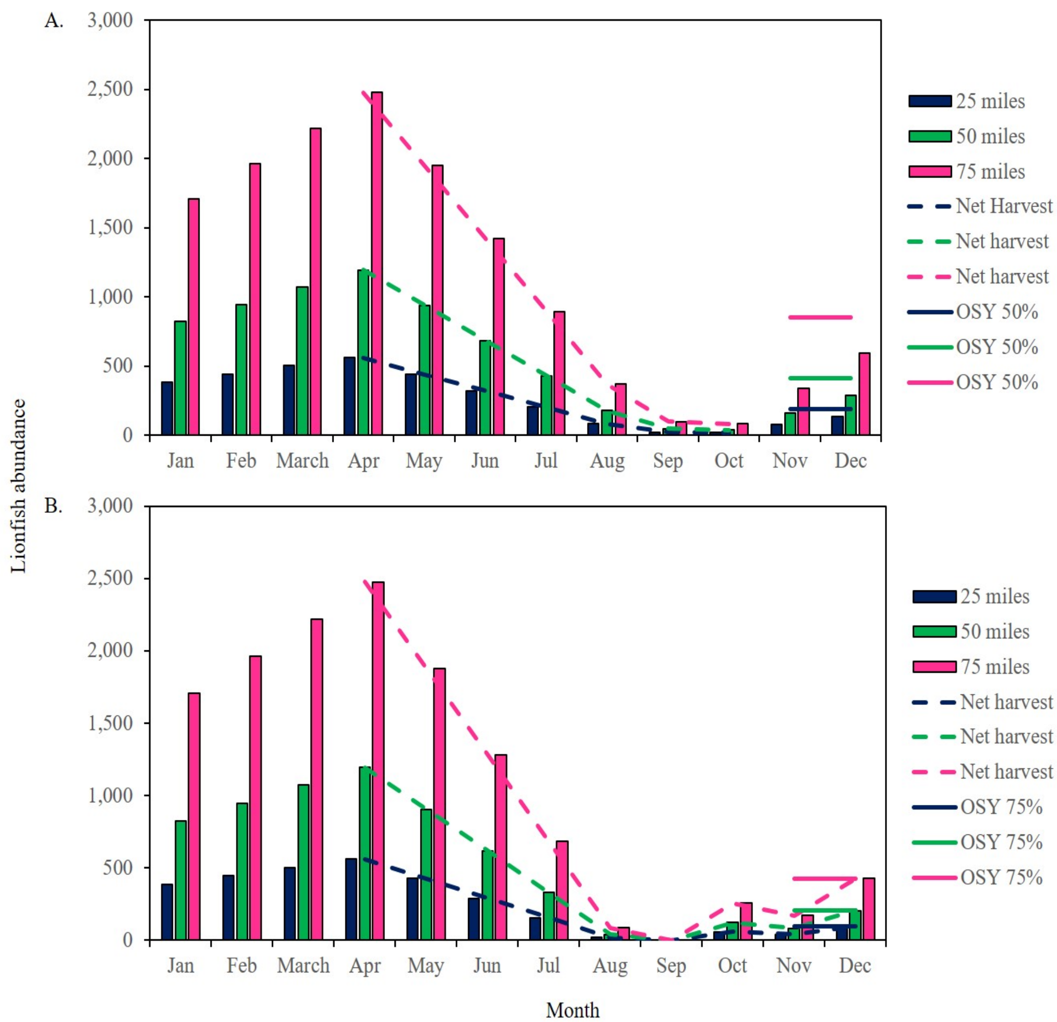

Figure 5.9 Net harvest to achieve optimal lionfish abundance with a commercial lionfish fishery in the northwestern Gulf of Mexico. A) Harvest needed to achieve OSY 50%. B) Harvest needed to achieve OSY 75%. Net harvest was assumed to be equiavalent to net recruitment each month and the harvest needed to achieve OSY.

In both scenarioes, net harvest was equivalent to the summation of net recruitment and harvest for OSY for May through August. Harvests decreased in September and October, to allow recruitment to stabilize the population for the final fishing months. In doing so, the optimal abundance of lionfish was maintained at the end of the fishing year, such that the ecological goal of the commercial fishery was met. Based on these results, $CPUE_{Econ}$ was computed for 25-75 miles to determine what the effort would need to be to ensure economic viability of the commercial fishery. All of the CPUE's computed for Model 2 are presented in Table 5.11.

Table 5.11CPUE (kg diver hr^{-1}) relative to distance from shore, optimal sustainable yield, trip costs, and harvest season.

Distance (D)	$CPUE_{(Min\text{-}Max)}$ OSY 50%	$CPUE_{(Min\text{-}Max)}$ OSY 75%	CPUE Economic
40 km	0.26-0.50	0.33-0.57	4.60
80 km	0.73-1.41	0.92-1.61	11.60
120 km	2.39-4.65	3.01-5.27	27.95

Values for trip cost are rounded to the nearest $25 whole dollar amount. Dive hours are rounded to the nearest 15 minutes (i.e. 0.25 hours). Minimum, maximum, and mean values ± standard deviation are reported. CPUE values are assumed to be accomplished with a minimum two diver team to maintain safe diving operations.

It is evident from the results in Table 5.10 that the trip costs would be the limiting factor in the viability of a commercial lionfish fishery, given the constraints of a single-day expedition. The $CPUE_{Econ}$ is considerably higher than $CPUE_{Ecol}$ under either of the OSY scenarios. To determine if the CPUE values computed in Model 1 and/or

Model 2 are reasonable, catch statistics from lionfish research cruises were used to compute CPUE of divers that removed lionfish in FGBNMS.

5.4.7 CPUE from tournament statistics

CPUE was calculated for each team, for each cruise, as this varied each year. The minimum, maximum, and mean CPUE's for each cruise are reported in Table 5.11.

Table 5.12 Descriptive statistics of CPUE (kg diver hr^{-1}) values for each cruise

Year	Minimum	Maximum	Mean (± SD)
2015	0.35	3.88	1.97 (± 1.37)
2016	0.25	3.05	2.04 (± 0.89)
June 2018	0.23	4.87	3.14 (± 1.78)
Aug. 2018	0.45	10.28	5.71 (± 3.89)

Mean CPUE noticeably increased with each cruise, of which an ANOVA analysis found these differences to be significant ($F_{3,\ 1832}$ = 238.49, $p < 0.001$). A pairwise comparison of the means revealed that all cruises differed from each other with respect to CPUE ($p < 0.001$), except 2015 and 2016 ($p = 0.986$). Following these results, regression analyses were used to determine what factors were signficant in contributing to removal success of lionfish at FGBNMS.

CPUE data were log transformed for the two models and tournament to be compared using a two sample t-test and Welch t-test. In all cases, the results of the two sample t-test and Welch t-test were the same. The CPUE computed in Model 1 (4.13 ± 1.68) was significantly different from CPUE values in Model 2 (1.36 ± 1.92; t_{23} =

4.4812, p = 0.001) and the tournament (1.48 ± 1.52; $t_{1844} = 7.7165$, $p < 0.001$). In both instances, Model 1 had a higher mean CPUE than Model 2 or the tournament. There were no signficant differences between CPUE values computed in Model 2 and the tournament (t_{1849}=-0.7616, p= 0.4464).

5.4.8 Dive team experience level

Each team was assigned a score for removal efficiency and proportion removed; the sum of the two was used to identify their experience level. Apart from 2015, the mean removal efficiency of divers remained consistent for cruises to FGBNMS, while proportion removed remained consistent on all cruises (Table 5.12); therefore, it was assumed to be equal across participating divers.

Table 5.13 Descriptive statistics of diver removal efficiency (lionfish collected/sighted), proportion removed (team catch/total landings), and total scores for cruises to FGBNMS.

Year	Total Observations (n)	Removal Efficiency Min – Max Mean (± SD)	Proportion Removed Min – Max Mean (± SD)	Total Score Min – Max Mean (± SD)
2015	321	13-72% 56% (± 18%)	0.7-33% 17% (± 12%)	2-6 3.87 (± 1.65)
2016	409	23-93% 76% (± 19%)	0.7-24% 15% (± 7%)	2-6 4.62 (± 1.26)
June 2018	366	22-94% 75% (± 20%)	1-33% 20% (± 11%)	2-7 5.14 (± 1.86)
Aug. 2018	740	27-92% 76% (± 18%)	0.6-36% 21% (± 14%)	2-7 5.05 (± 1.95)

5.4.10 Percent fillet yield

The mean percent fillet yield was 36.4% (± 6.7) for lionfish, which is consistent with Morris et al.'s [48] mean percent fillet yield of 30.5%. The relationship between TL and fillet yield provided insightful information that is useful for market development (Figure 5.10).

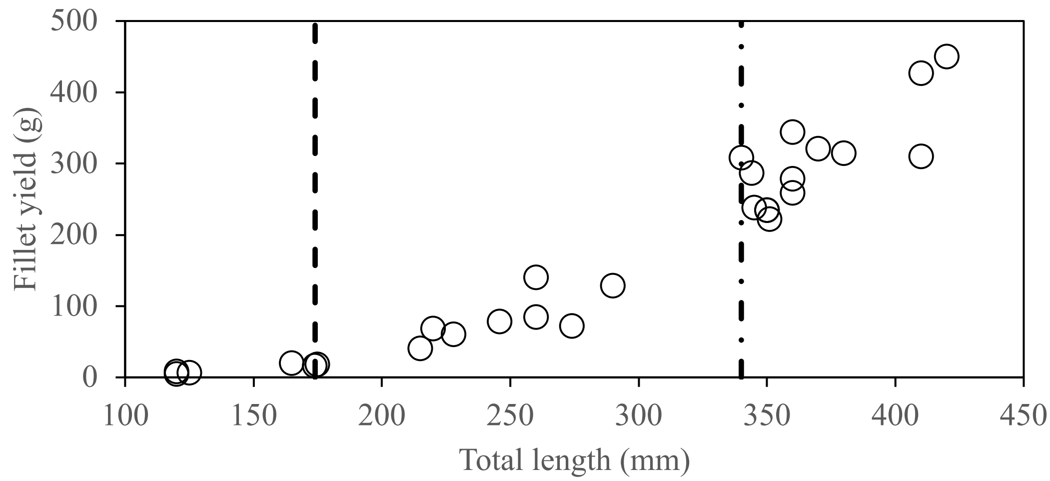

Figure 5.10 Relationship between TL (mm) and fillet yield (g) for lionfish collected from FGBNMS in 2015. Dashed lines indicate TL for juveniles (174 mm) and large adult fish (340 mm) that could be used for choice dishes in restaurants, such as a whole fillet.

The relationship reveals three natural groupings that are marked in Figure 5.10 by the dashed lines. The first grouping signifies lionfish that are too small to be marketable, which aligns with juvenile fish (<174 mm; [21]). The second grouping shows marketable lionfish, while the third grouping represents "choice" fish. Lionfish that grouped in the marketable category were those that were large enough to sell at seafood markets or in restaurants, that could be used for dishes that did not require a whole fillet (e.g. dips, ceviche). Lionfish that grouped in the “choice” category were those that yielded two 4 oz fillets that could be served whole in a seafood dish.

In addition to this, percent fillet yield was overlain with age data (see Section 3) that were obtained from lionfish collected from FGBNMS in 2018 (Figure 5.11). This too revealed interesting information that could be important for market development of lionfish in Texas. There were two natural groupings that were identified, signified in Figure 5.11 by the dashed boxes. Marketable lionfish, as explained above, ranged in age from 3-5 years, while choice fish ranged in age from 7-10 years. Given this information, it could be expected that lionfish would not become marketable until after 2 years of age in Texas. In congruence with fillet yield, market price of lionfish is an important characteristic to identify.

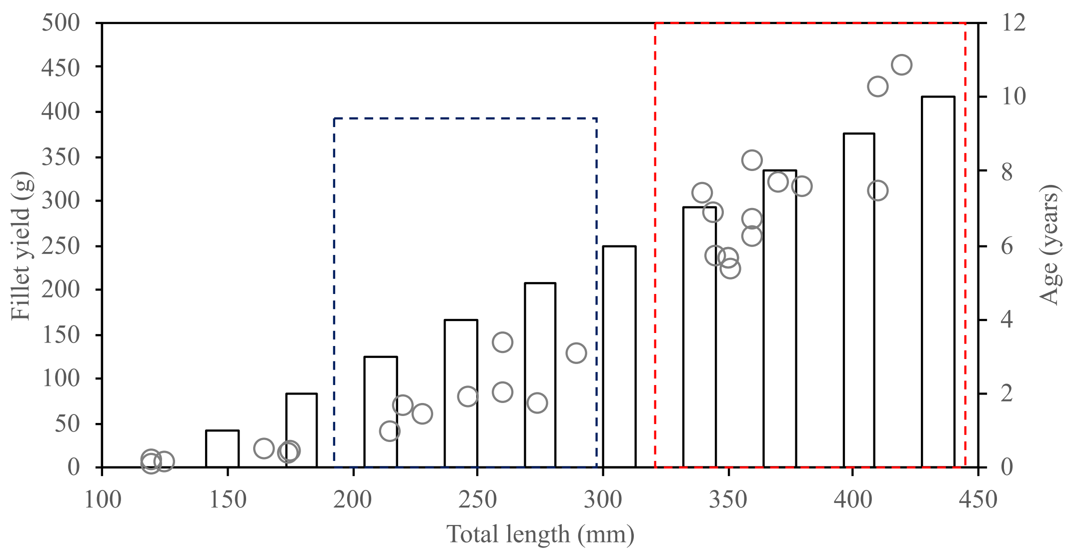

Figure 5.11 Relationship between fillet yield and age of lionfish with respect to total length. Dashed lines indicate natural groupings of fillet yield that correspond with respective ages of lionfish. Mean TL were used to report age data.

Current market prices of lionfish and percent fillet yield are lower-to-comparable to other popular marine fish consumed in Texas (Table 5.14). Lionfish fillet yield is most similar to Flounder, a fish with comparable flesh texture and composition. As whole fish, lionfish sale price is equivalent to Grouper (Serranidae) and Red snapper (*Lutjanus campechanus*); however, in general lionfish would sell at a much cheaper price than these other two species, as they are much smaller in overall size.

Table 5.14 Percent fillet yields and market price per pound ($/kg) for lionfish compared to other commonly consumed marine fish in Texas.

Species	Lionfish	Red snapper	Grouper	Flounder
Percent fillet yield	36.4%	52%	48%	35%
Market ($/kg) Whole fish, (fillet)	$21.98 ($66.00)	$20.90 ($55.00)	$20.90 ($55.00)	$17.05

Market prices for lionfish were obtained from Whole Foods market in Florida, while the other fish market prices were obtained from Katie's Seafood Market in Galveston, TX. Percent fillet yields for other species were obtained from: https://www.chefs-resources.com/seafood/seafood-yields/.

The size distribution of lionfish revealed that the majority of fish removed in all three sampling years ranged from 201-300 mm TL (Figure 5.12). This indicated that lionfish were consistently of marketable size in FGBNMS. For each year, 13%, 7%, and 14% of lionfish would be considered "choice" size in 2015, 2016, and 2018, respectively.

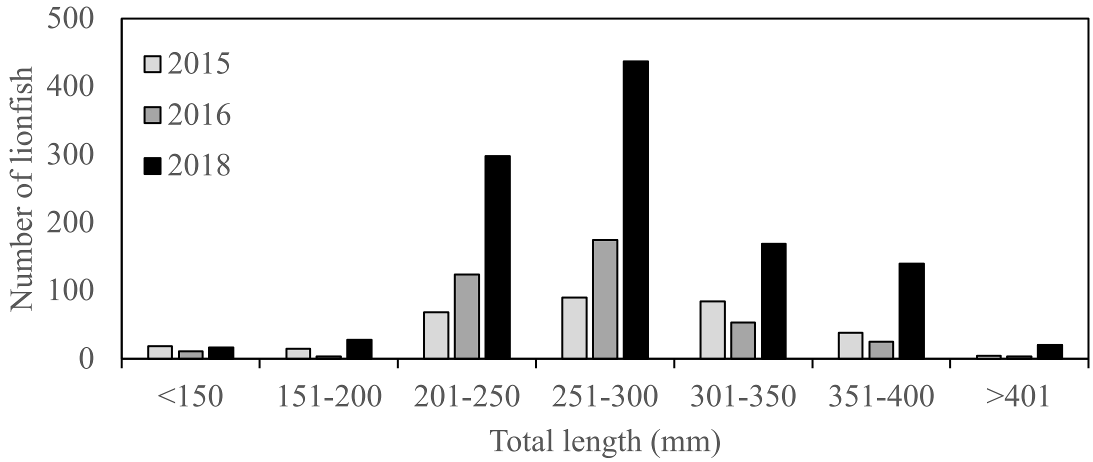

Figure 5.12 Size distribution of lionfish removed from FGBNMS in 2015, 2016, and 2018.

The proportion of lionfish removed from natural and artificial reefs were binned in 50 mm increments with respect to size (Figure 5.13) and pooled for all sampling years. Results indicated that lionfish sampled on natural reefs were typically larger than those on artificial reefs. In each instance, more lionfish were of marketable size than non-marketable size on natural and artificial reefs.

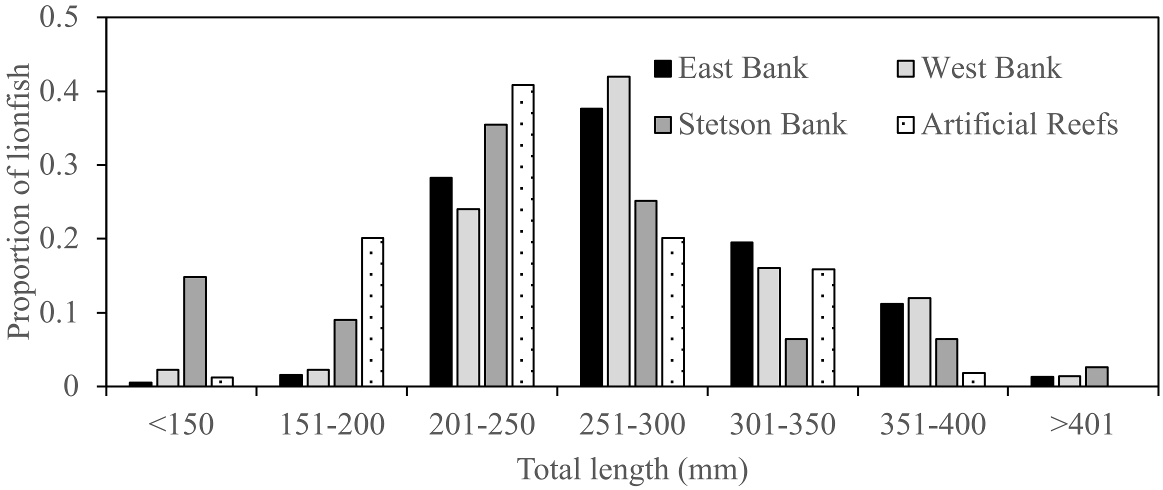

Figure 5.13 Proportion of lionfish removed from FGBNMS (2015, 2016, 2018) and TPWD's artificial reefs (2014-2018) pooled for all sampling years.

5.5 Discussion

5.5.1 CPUE and model comparisons

It has been assumed that an increasing CPUE reflects a stable population abundance [49]. Alternatively, a declining CPUE is typically believed to indicate a decline in relative abundance [49, 50], though there are some concerns over the validity of these assumptions [51-54]. In the present study, we see that CPUE increased with each consecutive cruise and a respective increase in lionfish population. This may reflect a stablized lionfish population, or, indicate that effort is not high enough to cause reductions in overall abundance. Fishing pressure on lionfish only occurs 1-2 times per year at FGBNMS, which may not provide a high enough exploitation to effectively reduce the population. We find the increase in CPUE interesting, as removal efficiency and proportion removed remained relatively stable over the four cruises. More expert divers were on the two 2018 cruises which may explain the higher CPUE; however, the ratio of novel to expert divers (1:2) remained nearly identical across the four samples.

Model 1 and 2 were compared to the tournament statistics to determine if either hypothetical model could be used to develop a CPUE measure, given the data inputs for each, that could be readily used by fisheries managers to investigate whether a lionfish fishery was worth pursuing in their region. We compared the two hypothetical models to the real catch data using t-test statistics, with the assumption, that if there were no significant differences between the hypothetical CPUE and real CPUE, that the model was a good predictor. Model 1 had the fewest variable inputs and estimated the highest CPUE values of the two. We chose to have two models, one to highlight economic needs, as well as one that highlighted both economic and ecologic needs of the fishery. It appears that Model 2, as we expected, was a much better predictor than Model 1. Because Model 2 CPUE was not significantly different from tournament data, we assumed that this meant a lionfish fishery in Texas could be achievable. Although there are additional measures that should be taken prior to implementing a commercial lionfish fishery, these results prove very promising for the furture management of lionfish off the Texas coast, and potentially wider Caribbean and North American regions.

The models were parsimonious in design, in effect, to maximize the user groups that could implement them within their management framework. Data that were used for the models are not particularly difficult or costly to collect; computations do not require advanced statistical software or mathematical interpretations; and the output remains consistent with real-time data. Future models could increase the complexity of the parameters. For example, we assumed a net recruitment based on the doubling of the lionfish population each year. This parameter could be replaced with a more detailed recruitment calculation that includes female fecundity, proportion of females, egg duration, mortality of different stages, etc. [21]. Research has shown that complexity does not necessarily result in greater accuracy, but does increase forecast error [55]. With this in mind, we feel confident that in the simplicity of our parameters and model design, we have devised an effective tool that can be widely applied in management schema of invaded regions.

5.5.2 Economic considerations

Currently, lionfish are sold at comparable rates to other commonly consumed fish that have similar flesh texture and composition. The current unit price of lionfish was used to determine the effort needed to economically sustain a commercial fishery, of which, could be altered with a change in the price of lionfish. Price has been shown to not be a signficant factor in affecting purchase decisions for eco-labeled fish [56]. Because of the ecological damages posed by lionfish, this species would be one of the most eco-friendly fish to consume in Texas. If consumers were willing to pay a higher price for lionfish, this could shift the market dynamics in such a way that more fishers could be supported and/or could achieve a higher profit. Consumer demand drives targeted fishery harvests [57]; therefore, we assume that as consumer requests for lionfish in seafood markets and restaurants increases, as well as their willingness to pay more for the fish, it is likely to support commercial harvest of the species.

There has been a transition among consumers to prioritize ecologic sustainability with respect to their food choices, driven primarily by their conern and knowledge of damages to the environment [58]. Additionally, consumers have shown a willingness to pay more for eco-friendly fish [56], of which could be applied to a lionfish fishery. Marketing should focus efforts on shifting the behavior of consumers to desire ecologically sustainable fish (e.g. [59]) to promote commercial utilization of an inavsive species. This also shows that marketing should prioritze educating the public about the environmental threats posed by lionfish and the benefits of their sustained harvest, if a shift is to occur.

In Texas, 69% of lionfish removed from FGBNMS were 3 years or older (see Section 3). Contrastingly, 86% of lionfish removed from Aruba were less than 3 years of age (see Section 3). Lionfish in Aruba grew much faster than those in FGBNMS, which indicates the fish may be marketable at an earlier age than those from Texas. As growth rate of lionfish varies greatly throughout their invaded region, it would be advantageous to investigate percent fillet yield with respect to age and growth in order to determine size-at-age data for marketability purposes. This is not to suggest that younger fish should be left in the environment, as juvenile lionfish have been found to cause more environmental damage than larger counterparts [21]. Additionally, creating a fishery that can market juveniles reduces the pressure to create a size-selective market that could result in undesirable effects. Though we feel this study was comprehensive and novel in addressing the varied socio-ecological systems that contribute to fisheries management, we acknowledge that limitations remain.

5.5.3 Limitations

The two models used to compute CPUE differed in their limitations, by which, some of the limitations from Model 1 were accounted for in Model 2 (e.g. net recruitment, abundance). However, both models were limited in that they assumed one-day expeditions for each fishing trip. This likely explains the threshold being 120 km for a commercial lionfish fishery, as it was assumed that this threshold would increase if multi-day expeditions were included in the analysis. The vessel fuel cost would be the same across a multi-day expedition, as a single-day trip, assuming the vessel uses the same amount of fuel to travel equivalent distances. However, costs associated with crew or incidentals would increase with a multi-day expedition. These models also do not account for cost to hire divers, as it was assumed that the divers would be working independently as a fisher. Similar to the crew composition of a catch-share commercial fishery, it seemed appropriate for a lionfish fisher to operate under the same structure to reduce costs and maximize profits.

As I am suggesting a commercial lionfish fishery be achieved with divers, a vessel would need the storage space to carry SCUBA tanks for a mutli-day dive trip or have the capacity to refill tanks on-board the vessel. This considerably increases the size and cost of the vessel that would be needed for a multi-day cruise. As these factors complicated the costs associated with travelling offshore, they were not considered for this analysis, but could be attempted in future studies. Incorportating this type of information could change the outcome of our models, and may expand the distance threshold for achieving a sustainble lionfish fishery.

Lionfish inhabit areas beyond recreational dive limits; however, as discussed in Section 2, this fishery model only targets harvest using divers and omits lionfish that would need to be removed by other gear types. Given the bycatch issues associated with traps, and hook and line fisheries, a commercial lionfish fishery would likely be most successful if collected by spearfishing and hand netting [20]. This does not negate the issue of lionfish being present at deeper depths, and we recognize the need to remove these populations as well. Lionfish-specific traps have been designed and are currently being tested in areas of Florida and many Caribbean nations [60]. Successful field trials have shown that it could be promising as an additional gear type in a fishery, but that diver removals are still more efficient [61]. Additional studies that combine CPUE and harvest information from diver- and trap-related landings will be essential to determine the overall success of employing both of these strategies.

Lionfish have been found to recolonize an area to pre-removal densities in less than one year following a single removal [62]. This recolonization has been mostly attributed to re-colonization by new juvenile recruits rather than lateral migration of adults [63]. Vertical migration of lionfish, e.g. from mesophotic reefs to shallow reefs or up the legs of oil and gas platforms, is not well understood. Investigating the transition of adult lionfish among depths on natural and artificial habitat will help to address this data gap and may strengthen future studies on the feasability of a lionfish fishery. We did not specifically address recolonization in this model; however, we did address net recruitment based on observations of lionfish abundance changes at FGBNMS. This value could arguably account for recruitment of new juveniles or lateral/vertical migration of adult lionfish from depth, though not differentiated. Future studies could attempt to differentiate between these recruitment mechanisms to determine if this has any significant impact on the success of a commercial fishery.

5.6 Conclusion

Understanding the contributions made by components of socio-ecological systems has proven to be an important tool to holistically assess the feasibility of creating a commercial fishery for lionfish in the NWGoM, as presented in this study. The effort needed to maximize the long-term environmental goals to reduce pressure on native reef species and the economic vitality of commercial lionfish fishers are greatly beneficial to local communities being impacted by this invader. A high exploitation rate fishery may produce sustainable and measurable results, but may not be suitable for all regions [19, 64, 65]. This present study shows the value in evaluating the complex socio-ecological dynamics between humans and the marine environment to better understand how this can influence commercial fishery harvests of an invasive species. More importantly, it has devised the first model and conceptual framework for local managers that can be easily understood and implemented at a large scale rather quickly to evaluate the utilization of commercially harvesting lionfish as a mitigation strategy. With slight modifications, these models could be adapted to be relevant for other marine invasive species, further indicating its value to the management and scientific communities.

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6. MANAGEMENT OVERVIEW AND EMERGING SOLUTIONS TO THE LIONFISH INVASION ISSUE IN THE UNITED STATES

6.1 Synopsis

Management of invasive species is often a challenging task that requires the cooperation of multiple stakeholders, dedicated working groups to develop sound response plans, and long-term research efforts to monitor the sustainability of these practices. Indo-Pacific lionfish (*Pterois* complex) are the first marine fish to have invaded the U.S. western Atlantic and Gulf of Mexico, and Caribbean Sea. To-date, most invaded communities have used haphazard approaches, primarily through opportunistic removals by government agencies and volunteers. Current legislation exists that addresses invasive species management in the U.S., though only two federal management plans have been developed specifically for lionfish. The implementation of scenario planning, stakeholder engagement, and building adaptive capacity are all useful tools that can be implemented on a local, regional, or national scale. Additionally, innovative solutions such as the use of conspicuous consumption, properly termed marketing schemes, and market-based approaches that balance economic and ecologic interests are sure to be beneficial to the commercial utilization of lionfish. The long-term sustainability of global marine fish production will require a diversification of species, whereby the inclusion of under-utilized and/or invasive fish may yield a supportive alternative. Multi-faceted management approaches for lionfish will likely be the most beneficial, as could be expected with most invasive species.

6.2 Introduction

Indo-Pacific lionfish (*Pterois volitans*/*miles*, herein referred to as lionfish) are the first marine teleost to have invaded the northwestern Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. Thought to be introduced from aquaria in the 1980s, lionfish pose a threat to ecologically, commercially, and recreationally important species throughout their invaded range [1-5]. Most management approaches have been indiscriminate throughout the U.S., with opportunistic removals through state or federal agencies and volunteer divers being the primary means to suppress populations. As a result, these control activities may be an inefficient use of resources, ineffective in population control, or cause unintended outcomes. It is evident a more directed approach is necessary.

Addressing the need for sustained lionfish control requires thoughtful and careful planning that protects and/or improves livelihoods of impacted communities. Using market-based incentives opens the possibility of achieving frequent, large volume removals of lionfish and generates income for local fishers. However, this strategy is also wrought with unintended consequences [6], so care must be taken when implementing this approach. Lionfish management practices will likely yield the best outcomes if a multi-pronged approach involving restaurants and fishers are used. The strategies outlined here are threefold: 1) highlight the use of market-based approaches, 2) identify current resource management principles that could be used on a local, regional, or national level, and 3) provide innovative solutions that may allow communities to capitalize on commercial utilization of lionfish. The vision of these strategies is to prioritize the protection of human livelihoods and the environment, while delivering socioeconomic benefits to coastal communities.

Challenges exist in effectively controlling lionfish, some of which are directly related to their ecological characteristics. Because lionfish reproduce and spread rapidly, occupy a breadth of different habitats, and can tolerate a wide range of conditions [7], the possibility of eradicating their populations is unlikely and unrealistic. A large proportion of lionfish have to be removed at regular intervals to counter their prolific fecundity and rapid growth rates [8, 9]. An effective means to remove lionfish is through spearfishing [10, 11], but this extraction method can only occur in areas physically accessible by divers in relatively shallow water (< 40m). Lionfish occupy water depths to 300 m [7], so this strategy cannot be employed in all areas effectively. There are no mechanisms that exist to control lionfish in deep-water environments, though the efficacy of traps has been recently tested [11]. Traps offer a promising solution, but will need to be tested in deep areas, such as mesophotic habitats, to determine whether it will be successful at combatting these populations. Additionally, long-term impacts of the commercialization of lionfish are unknown and have yet to be tested. These challenges, though difficult, also open opportunities in research and management.

Population suppression of lionfish opens the possibility for similar ecological outcomes as population extirpation [12], but would require long-term research initiatives to determine if this holds true. By anchoring lionfish population suppression in small-scale fisheries-based extraction, with divers and potentially traps, a geographically scalable and financially sustainable solution is generated in areas that are accessible to divers and/or fishers [13]. The regulatory framework that would need to be developed for a lionfish fishery is uncertain at this time, but generates interest for a multi-stakeholder working group that coordinates scientists, fishers, and resource managers to create sound strategies. Lionfish impacts to areas that are inaccessible to fishers (e.g. Marine Protected Areas, No Take Zones) would benefit from user groups that could participate in other control activities [13].

In an effort to address some of these challenges and opportunities, this section focused on providing an overview of management and legislative actions that are applicable to lionfish, describe current lionfish management plans, identify current governance strategies that can complement current management endeavors, and specify innovative solutions that could benefit market-based approaches. This information can hopefully be integrated into the development of new management plans, will render the justification for future research, and help further the understanding of the need to develop an innovative and integrated approach to managing this invasive species.

6.3 Status of the invasion in the United States

It has been widely accepted that lionfish were released from aquaria in the 1980s, accidentally or intentionally [5], and have since spread throughout U.S. coastal waters in the western Atlantic Ocean and Gulf of Mexico (GOM). Genetic analyses have confirmed both *P. volitans* and *P. miles* along the Atlantic Coast [14-16], but only *P. volitans* has been confirmed in the Gulf of Mexico [17]. Lionfish were introduced into the northern GOM (nGOM) by the Loop Current [18, 19], which are likely sourced from the Caribbean [17]. Investigation of mitochondrial DNA has shown a strong dispersal restriction between the North Atlantic Ocean and Gulf of Mexico, but a weak dispersal restriction between the GOM and Caribbean Sea [17]. Although larvae from the southern GOM and Caribbean are indicated to be sources of the expansion of lionfish into the nGOM, the western Florida shelf and nearshore Texas also act as an important source, and sink, for lionfish populations in this basin [19]. The first assessment of lionfish densities in the U.S. were reported from the Western Atlantic coast.

In 2004, lionfish were observed in densities of 21.2 individuals per hectare (ind ha^{-1}) across seventeen locations in North Carolina [20]. In just four years, the maximum lionfish density reported in North Carolina had increased to 450 ind ha^{-1}, with mean densities around 150 ind ha^{-1} [21]. Densities in south Florida were low in 2018, ranging from 0.6-9.0 ind ha^{-1} [22], likely a result of the ulcerative disease that lowered numbers [11]. In the nGOM, lionfish densities experienced nearly a three-fold increase from 12 ind ha^{-1} to 38 ind ha^{-1} at East Flower Garden Bank (EFGB) in Flower Garden Banks National Marine Sanctuary [23, 24]. Similarly, lionfish doubled at West Flower Garden Bank (WFGB) in FGBNMS from 14 ind ha^{-1} in 2013 to 28 ind ha^{-1} in 2014 [23]. In 2018, these numbers were significantly higher with 72.9 and 80 ind ha^{-1} at EFGB and WFGB, respectively (see Section 5, Sub-section 5.4.2). Lionfish densities reported on artificial reefs in the nGOM ranged from 0-9,040 ind ha^{-1} (0-90.4 ind 100 m^{-2}), with a mean of 1,470 ind ha^{-1} [24]. Densities in the invaded range tend to be much higher than those observed in the native range, in which the maximum density reported was 26 ind ha^{-1} [25]. It is obvious that continued monitoring of lionfish densities are needed throughout the U.S.; however, this can be costly and difficult given the expansive range of their invasion. A cost-effective strategy should be employed that prioritizes natural reef recovery and economic resilience.

6.4 Concept of commercializing lionfish removals

Population growth of an invasive species typically follow a predictable trajectory, whereby there is a lag phase after initial introduction, followed by exponential growth that peaks, and then settles into equilibrium ([26]; Figure 6.1). Equilibrium occurs once the invasive species population is limited by factors including competition, predation, parasitism or disease, and/or abiotic factors [10]. The lionfish invasion in the U.S. has appeared to follow this general course. Problems arise with allowing the population of an invasive species to remain at equilibrium. Not only does this create issues for the environment, it also impacts the ability of employing effective management strategies that can be used to minimize the species' impacts (Figure 6.1).

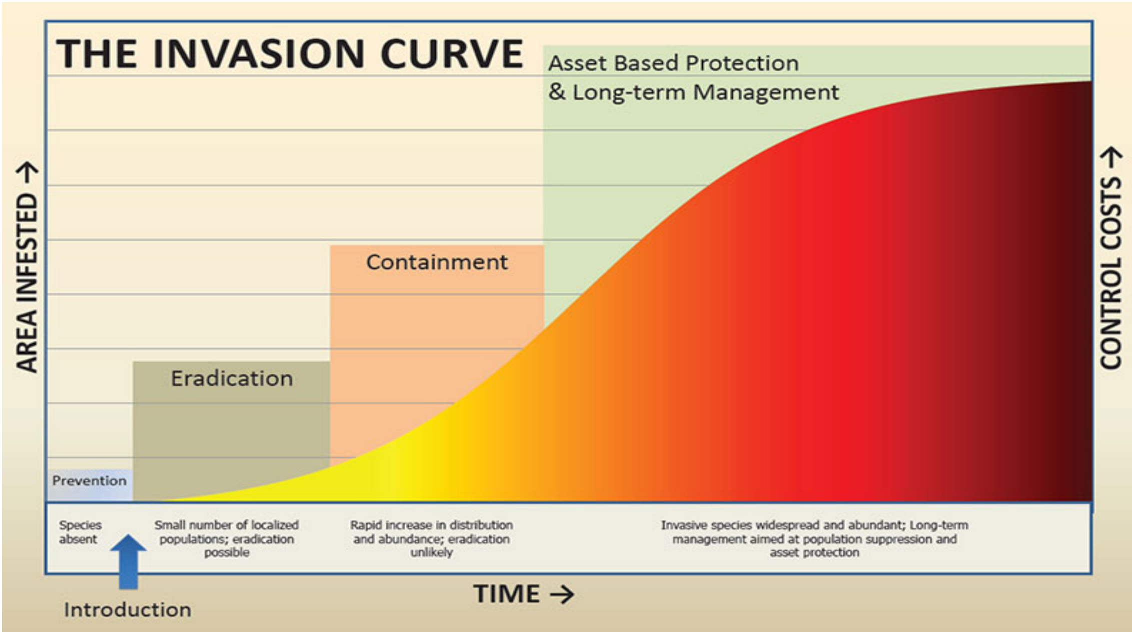

Figure 6.1 Typical invasive species curve shown with management implications with respect to invasion stage. Reprinted from Harvey and Mazzotti, University of Florida, Wildlife Ecology and Conservation Department, 2018 [68].

Because an invasive species is not native to the environment, its establishment often leads to habitat alteration, competition with and predation on native species, transmission of novel parasites or diseases, reduction of functional and species diversity, and changes in the genetic integrity of indigenous populations such as through hybridization [27, 28]. The ecological impacts of marine invasive species can be difficult to quantify, but more challenging is quantifying the socio-economic impacts to communities. It is apparent that a management strategy is needed that benefits biologic and socio-economic systems, by which stress to the natural environment is reduced, while user groups with economic interest capitalize on the approach. This level of effort, between the economy and ecology, is the only way to make management schemas sustainable. Thus, this section focuses on the management implications of the commercial utilization of lionfish in the U.S through exploitation with a fishery.

Using a commercial fishery to suppress lionfish has broadly been discussed throughout the literature, but to date, no quantifiable evidence has been published to suggest whether this is a viable option for invaded regions. The conceptual framework underlying the development of a commercial fishery is crucial when pursuing this strategy, as it inevitably dictates the composition of the managerial infrastructure. As previously discussed, lionfish and many other invasive species will undergo exponential population growth until equilibrium is reached; however, this is not typically sustainable for the environment or socio-economic systems. A sustainable yield can be determined that optimizes native fish community recovery and elevates the socio-economic system, whereby fishers and communities mutually benefit, herein referred to as the optimum sustainable yield (OSY). Unlike maximum sustainable yield (MSY) used in most fisheries management, OSY operates under conditions that consider socio-environmental systems holistically (Figure 6.2, see Section 5).

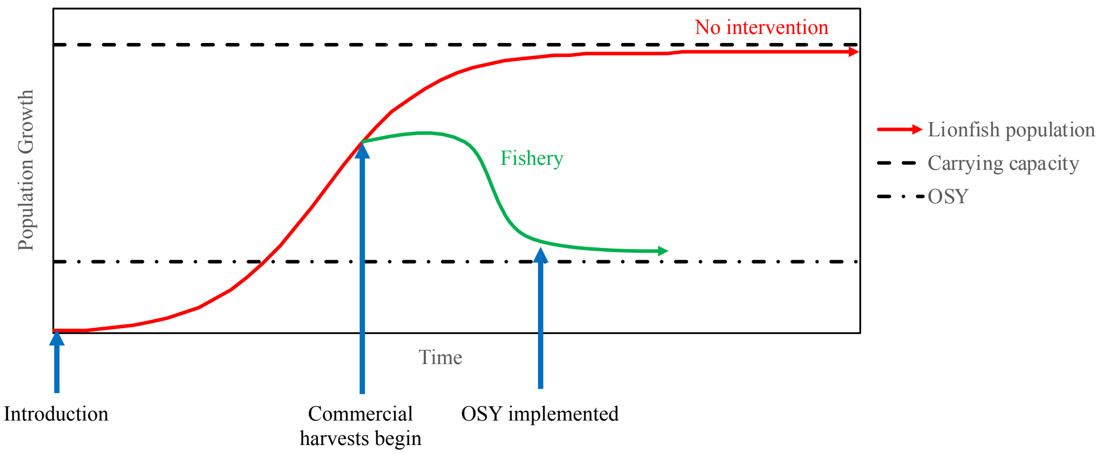

Figure 6.2 Conceptual model for a lionfish fishery that aims to balance native ecosystem recovery and economic interests, such that an optimum sustainable yield (OSY) is achieved. A marine invasion, left unchecked, will result in the fish's population reaching its' carrying capacity, which is unsustainable for the environment. Commercial harvest is used to interrupt that population growth, and lower abundance to a sustainable level by achieving the OSY. Once OSY is reached, the population is maintained at that threshold while the fish remains in the environment.

The goal is not to maximize the protection of the harvested invasive species, rather it is maximizing the recovery of the environment, while balancing the long-term economic viability of the fishers. This is a critical difference that must be acknowledged when creating a commercial fishery for an invasive species.

6.5 Management overview of lionfish

Since the 1990's, the U.S. has had legislation in place that defines protocols to prevent the introduction and spread of invasive species, with the Nonindigenous Aquatic Nuisance Prevention and Control Act (NANPCA) of 1990 (amended in 1996) and Executive Order 13112 (implemented in 1999). NANPCA identifies the management measures as those to prevent the unintentional introductions and dispersal of invasive species, but does not account for mitigation efforts for a species that has become established [29]. With Executive Order 13112, the first invasive species management plan was prepared, which provided approaches for preventing the introduction and spread of invasive species; identified pathways by which invasive species were introduced and research that was needed to minimize this; recommended measures to minimize risk of introductions and risks to economic, ecological, and human health; provided science-based processes to evaluate risks, and a systematic process to monitor and interdict the pathways involved with introductions [30]. The current National Invasive Species Council Management Plan (NISCMP) was adopted on July 11, 2016.

NISCMP identifies four general management strategies, dependent on the stage of the invasion, as prevention, eradication, control, and ecosystem restoration. These stages are analogous to Figure 6.1 that show prevention, eradication, containment (i.e. control), and asset based protection (i.e. ecosystem restoration). Prevention is the most effective strategy as it inhibits the introduction of potentially harmful organisms [31]. If a non-native species has already breached prevention, then rapid detection, containment, and eradication is necessary to impede the opportunity of becoming established. When populations become so well-established that eradication is no longer viable, control programs are necessary. These are often costly, requiring a lot of time, money, and socio-political will [31]. There are several different types of control programs: mechanical (physical removal), chemical (biocides or toxicants), biological (use other organism for suppression), and other (e.g. medicine), whereby integrated approaches are typically the most successful. Finally, ecosystem restoration must address habitat degradation caused by invasive species, and often their management, to restore the environment in order to build resistance [32]. In 2009, a lionfish management plan was developed by the National Oceanic and Atmospheric Administration (NOAA) to address specific needs for the invasive fish.

NOAA's management plan documented lionfish biology, ecology, and their status; described potential sources for their introduction and ecological and socio-economic consequences of their invasion; forecasted future conditions with no management intervention; and provided alternative management actions [21]. Finally, in 2015, NOAA's Office of National Marine Sanctuaries produced a lionfish response plan for National Marine Sanctuaries (NMS) that outlined the general concerns, issues, and threats of lionfish; challenges hampering effective control; and a national and regional response plan that described how lionfish would be monitored and controlled, education and outreach efforts, and identified research needs [32]. The plan provides generalized and site-specific information for Florida Keys NMS, Flower Garden Banks NMS, and Gray's Reef NMS [34]. The Florida Keys and Gray's Reef NMS identified consumption of lionfish, within their education and outreach chapter, through promotion of the "Eat Lionfish" campaign. None of the sites identified a research need to investigate the use of a commercial fishery for lionfish control. Although there are a few lionfish management plans available, there are no federal regulations to control and/or monitor lionfish. At the state level, lionfish are opportunistically monitored through citizen science programs and Texas Parks and Wildlife Department (TPWD). There are no direct management plans implemented in Texas for controlling the invasion.

The current methods used to remove lionfish in the U.S. include natural control and physical removal, with the latter being more successful [10]. There are other strategies that have been proposed, though not necessarily implemented, such as biologic control through sterilization, bounty programs, trap removal, and a targeted fishery [21]. Biologic controls are problematic environmentally and ethically, therefore, are not likely to be implemented for lionfish. Bounty programs were attempted in the Florida Keys early in the invasion, but were rapidly depleted of funds due to the sheer volume of fish in the region (Lad Akins, pers. comm.). Removal by lionfish-specific traps have recently shown to be effective in limiting by-catch and attracting lionfish; however, this gear type is not as successful as physical removal by divers [11]. Thus, the implementation of a targeted fishery, through use of divers, is likely to be the most effective method at recreational dive depths (up to 30 m).

6.6 Current governance strategies to address lionfish

The negative impacts induced by lionfish cascade across several functional groups of fishes, and thus have direct and indirect effects on the environment. For example, reduction of herbivorous fish leads to an increase in algal dominated reefs, which shifts the functional and ecological dynamics of the environment, such that it can no longer operate within its natural regimes [33]. This presents a serious concern when managing coastal and marine resources. To date, there are no sustained, unified management practices for controlling lionfish in their invaded ranges. Ad-hoc removals and lionfish tournaments have been the only long-term attempt at managing the populations, but these have not proven to be effective in mitigating the problems [34-

36]. Resource management principles are available that could be used to develop a structured approach in dealing with the invasion, which could be implemented on a state, federal, or international scale. By engaging in scenario planning, adaptive capacity, and stakeholder engagement, resource managers can develop long-term, restorative control strategies that allow native marine ecosystems to operate within their natural regimes.

Scenario planning is a systematic method for thinking creatively about complex and uncertain futures [37] that can be utilized to explore what *might* happen [38]. Scenarios can provide insight into drivers of change, reveal the implications of trajectories, and illuminate options for actions [37]. To successfully implement scenario planning into natural resource management, a focal issue must be identified, conditions of the system(s) (i.e. physical, social, and economic) must be assessed, and alternatives recognized that can be used to build, test, and screen the scenarios in order to influence policy changes [37]. Developing these scenarios does not attempt to make nature predictable or controllable, as this reduces resilience, and thus increases vulnerability of the environment [39, 40]. Instead, it is a strategic process to manage strategies in an attempt to actively plan for what may happen based on success and errors of applied strategies [38].

Several strategies have been proposed to manage lionfish populations including culling, biologic control (e.g. sterilization), incidental bycatch in trap fisheries, robotics, state and federal bounty programs, and human consumption [10]. However, most control efforts have been ad-hoc which does not ensure long-term success in the reduction of negative impacts, nor has the effectiveness of these strategies been quantified. By employing scenario planning in lionfish control management, it would devise 1) a structural framework for management options; 2) a basis of understanding of local impacts to the socio-economic communities; 3) afford comparison among different locations and the strategies employed; and 4) allow for quantifiable results of the management strategies. Data needed for scenario-based planning could include ecological information about the invasive species, measures of their environmental impacts, economic costs of control, stakeholder perceptions, and governance needed to sustain management schema. This type of strategy should be implemented on the local scale at the onset, to ensure proper data collection, analysis, and scenario implementation. However, as most marine invasive species are a regional issue in scope, this approach should be developed to include affected regions which may cross trans-national boundaries.

This is an example of an adaptive management strategy that aims to enhance resilience based on active planning [38]; as such, it would be advantageous for areas impacted by the lionfish invasion, as eradication is not probable [41]. An active, adaptive resource management strategy will likely be the most successful. Additionally, it is important to recognize that the environment is ever-changing, thus, complimenting scenario planning with adaptive capacity strategies will also be necessary.

Adaptability is the capacity of a system to manage resilience [38]. For management practices to be adaptive, there must be an acknowledgement that a natural system (social and environmental) will proceed through a four-phase recurring cycle. This is known as an adaptive cycle, characterized by rapid growth, conservation, release, and reorganization [38]. The manner in which a system behaves is dependent on the phase of the cycle. Understanding how a system responds to stressors and the strengths of the system's flexibility, resilience, and internal connections directly contributes to the success of the resource management [38]. Adaptation should encourage the evolution of new resilience management strategies that are sensitive to socio-ecological systems and address the specific nature of identified risks [42] within these phases as they relate to lionfish. For example, lionfish have a direct, negative impact to biodiversity in invaded regions.

Preserving biodiversity is crucial for maintaining livelihoods [39] and increases a location's resilience [38]. It is important that the desire to conserve biodiversity is met at a community level because this is an interface that exists between social and biological systems [39]. Species richness of a community can increase resistance to invasions because diversity increases stability of an ecosystem. A community rich in diversity is unlikely to experience detrimental impacts from immigrant species [43]. In addition, it is also critical to have a high-level of response diversity among organisms, as well as, functional diversity [38]. Environments naturally move through adaptive cycles under stress, in which characterization of these ecosystem responses is critical to restoration efforts. Understanding the adaptive cycles of a system under the pressure of lionfish will help to develop strategies to restore biodiversity and enhance the system's resilience. Lionfish are a highly adaptive invader [7], and as such, management will also be required to be adaptive in order to respond most effectively to varying impacts. Using scenario planning and adaptive capacity strategies requires active participation of a variety of stakeholders and is most effective if the gap between science and traditional knowledge is lessened.

In order to bridge the gap between science and traditional/local knowledge, the science must inform progress towards a goal, prioritize long-term solutions, and be committed to long-term sustainability [39]. Alternatively, traditional/local knowledge requires good leadership, an ability to renegotiate goals over time, recognition of local rights to organize and manage, and the aptitude to prioritize long-term solutions [39]. Collectively, these strategies can develop into a sound plan for co-management where scientists and the local community users feel a sense of place in the decision-making process, as well as, show a shared compassion for the conservation of their environment [39]. Constructing a shared vision among community members can be difficult; however, social acceptance of any management response strategy(s) is critical to the success of coastal and marine resource management [42]. The ability to convene, facilitate, and sustain open dialogues in a community about values, resource needs, and management approaches is important [44]. This is true for lionfish as their impacts are far-reaching across communities, user groups, and requires the active collaboration between scientists, citizens, and organizational groups. It is becoming increasingly apparent among fisheries managers that a fishery cannot be efficiently managed without the cooperation and input by resource users [45].

As lionfish negatively alter the community structure of the environment (e.g. reduction of prey, competition with predators), the effects imposed on community members and user groups will vary. In addition to that, lionfish negatively impact a variety of species (e.g. small herbivorous fishes, commercially valuable fish, coral reefs, artificial reefs) and socio-economic systems (e.g. tourism, diving, boating, fisheries); thus, an assortment of scientists with different expertise will be required to fully assess the issues. In order to best implement management strategies, scientists and local communities must collaborate to define priority areas geographically, determine the most vulnerable industries, and identify key areas of research that are needed. In doing so, scientists can be better directed on applying analyses that will provide the most beneficial and desired information to local communities. In return, local communities can provide the information to scientists regarding their concerns, priorities, and adapt local knowledge to benefit research. Alternatively, because there are no systematic strategies for mitigating problems associated with lionfish, there may be some innovative solutions and techniques that could be used to improve these management strategies.

6.7 Solutions and innovations for lionfish management

6.7.1 Conspicuous consumption practices

Conspicuous consumption has been understood as consumptive behavior dictated by the cultural appeal to show evidence of wealth [47]. This is often ceremonially differentiated by the consumption of intoxicating substances and food, whereby the more costly articles are considered to be more noble or honorable. These consumption practices become a marked component of an individuals identity, reputation, and honorability; converserly, the failure to maintain quality consumption can lead to an inferior and demerited social status [46]. Historically, some fisheries have been harvested to commercial extinction, in part, as a result of conspicuous consumption [47-49]. Though this is not likely the case with lionfish, the principle of conspicuous consumption could be applied to marketing the fish for a commercial fishery.

Scorpionfish are considered a delicacy in the French and Mediterranean cuisine, often the bases for dishes such as rascasse and bouillabaisse [21]. Lionfish possess mild, firm meat which are necessary and desirable qualities for palatable fish [21, 50]. Promoting local and regional consumption of lionfish as a delicacy, could create a demand for the fish that would generate a higher market value. Much of this can be achieved by finding an appropriate and pleasant preparation of lionfish, similar to the accomplishments of Paul Prudhomme with Redfish. Prudhomme debuted blackened Redfish (*Sciaenops ocellatus*), which resulted in the population being threatened in the Gulf of Mexico, due largely to the high demand from consumers [51]. It is not likely that the lionfish will become threatened, due to the nature of established invasive species, but it may help to advance the marketability of the fish.

As lionfish do not reach a large maximum size, it is not likely that the fish will generate revenue on par with other commercially important species, such as Red snapper (*Lutjanus campechanus*). Therefore, a higher market price would incentivize targeted harvests by fishers. Alternatively, if lionfish could not be marketed under the current definition of conspicious consumption, if the ceremonial appeal were restructured to prioritze the environment, the effort could prove promising for the commercial utilization of lionfish.

A shift in the cultural appeal, to favor ecologically sustainable practices over symbols of wealth, could alter the structure of commercial fisheries for invasive marine species. There has been a transition among consumers to prioritize ecologic sustainability with respect to their food choices, driven primarily by their conern and knowledge of damages to the environment [52]. The effort to maximize an individuals' concern for the environment is inextricably linked to formidable education about the risks and benefits associated with consumption of lionfish [53]. Consumer demand for sustainable food options are rising, but shifting behaviors to more sustainable consumptive practices can be challenging [54]. The benefits of replacing or subsidizing current commercial fishery harvests with utilization of marine invasive fish, such as lionfish, could prove to be an important practice in sustaining global fishery production in the future. To do so, the cultural definition of conspicuous consumption can be modernized to reflect the recent shift in consumer's concerns for the environment, by marketing lionfish as an ecologically sustainable food option, in an attempt to gain social support for a fishery.

6.7.2 Use of proper terminology in marketing schemes

Online articles have falsely identified lionfish as being poisonous [55, 56], which could be detrimental to the establishment of a commercial fishery. Lionfish possess venomous spines, that if contacted, can result in local edema, inflammation, and pain. The venom contains heat-labile proteins, that can be denatured with heat, to prevent the spread and reduce the severity of symptoms [57]. The injurious impacts of contact with the spines can be avoided in seafood markets if lionfish are sold without spines.

Additionally, care must be taken in restaurants that would serve the fish, to reduce injuries during preparation. Aside from care in handling, there are no precautions to the preparation of lionfish meat.

It is well-known that a poisonous fish, the blowfish (*Takifugu* spp.), is consumed in Japan [58, 59]. The blowfish, commonly referred to as Fugu, contains a potent neurotoxin in their organs, that if not properly prepared, can result in severe neurological illness or death [60]. However, Japanese consumers consider this fish to be a cultural delicacy and forgo the potential hazards to enjoy the comestible. Risk perceptions and preferences are linked with regards to their impact on food choices [60]. Risk perception is often systematically biased to typically overestimate the frequency of low-probability hazards, such as food poisoning [61]. By improperly marketing lionfish, consumer's perception of risk may be inflated, and their willingness to consume decreased. Marketing campaigns must be diligent in using the correct terminology when educating the public on associated risks of consuming lionfish, to minimize unintentional consequences that could hinder the progress towards a commercial fishery.

6.7.3 Balancing economic and ecologic interests

The idea to consume an invasive species is not novel, but the underlying goal of this study is. For example, very few individuals from Texas from the survey in Section 4 had previously consumed lionfish, so it was quite impressive that more than half of respondents were willing to purchase the fish in a restaurant or seafood market in some capacity. These results were consistent with another study that investigated the willingness of consumers to accept consumption of another invasive species, Asian carp

(*Hypophthalmichthys* spp.) in the United States [62]. Varble and Secchi [62] differ from our approach, in that, they recommend the final goal to be eradication of the species. Our approach acknowledges and values the ecologic benefits that may ensue from eradication of an invasive fish, but this remains a nearly impossible task [41]. Additionally, commercializing a market for an invasive species will inevitably result in the creation of new jobs and/or offer monetary support to current fishers. It would not be a responsible management approach to create a fishery, that generates revenue to fishers, with the intent of collapsing it. Alternatively, it would not be ecologically responsible for managers to allow native communities to be decimated by an invasive predator. With this in mind, the approach of this study aims to balance both the sustainability of the environment and the economic security of fishers.

6.8 Recommendations for future invasive marine fish management in the United States

6.8.1 Federally regulated management for established invasive species

Currently, federal legislation is in place that defines protocols to prevent the introduction and spread of invasive species in the United States; however, there are no federally mandated protocols defined for management once an invasive species becomes established. Although specific step(s) employed within each state or region may vary, ultimately, a federal regulatory framework can be developed that would advise states on the necessary strategies to take to devise a management plan, implement that plan, evaluate the efficacy of the plan, and then to establish the management practices best suited to fit the needs of each area.

The Magnuson-Stevens Fishery Conservation and Management Act (MSA) governs fisheries management in the U.S. Exclusive Economic Zone (EEZ), which defines rules and regulations for commercial and recreational fishing activities [63]. An amendment to the MSA could be created that mandates an approach for commercial and recreational management of invasive marine fish, which would result in the requirement of states to comply with managing an established invader. By amending the MSA for inclusion of an invasive marine fish component, fisheries managers, scientists, and stakeholders would need to redefine and reconsider their current conceptual understanding of what it means to sustainably and successfully manage a fishery.

Unlike the current approach to maximize the sustainability of standing stocks in an effort to support longstanding use of the resources through MSY, this amendment would prioritize the sustainability of the environment, environmental functionality, and human-user groups over the species itself. This must be approached delicately, in that, up until now, the main focus of controlling the establishment of a marine invasive species has been to eliminate it from the environment. This cannot be the case if an invasive fish is being commercially harvested to support seafood supply. Instead, an OSY (see Section 4) would be achieved. A commercial fishery for an invasive would require efforts to monitor the population to develop catch quotas, similar to other fisheries.

Multi-stock assessments would be necessary to establish quotas, as it is imperative that native fish populations recover, therefore, the invasive species as well as their prey and potential competitors must also be examined. Additionally, at the onset of the fishery, important market dynamics must be scrutinized (i.e. wholesale fish price, restaurant dish price), so that fishers receive compensation that ensures their commitment to continued harvest. This amendment would be unique in several aspects, but if successful, could be used to improve current regulations to maintain the longevity of other commercially harvested fish. To better illustrate how the management strategies discussed in Section 6.6 could be implemented, Sections 6.8.2-6.8.4 describe this dissertations' management approach in terms of the current governance strategies available.

6.8.2 Implementing scenario planning

By implementing scenario planning into management of marine invasive fish, resource managers can provide a structural framework for different strategies, gather an understanding of local impacts to socio-economic communities, have the ability to compare strategies among different locations, and generate quantifiable results. In the case of lionfish, Sections 2, 4, and 5 provide the structure for a scenario planning effort aimed at commercialization, whereby social, ecological, and economic components were evaluated. Firstly, it is important to gauge stakeholder and consumer perceptions and awareness of an invasive species, and their current support to consume and purchase the fish in seafood markets or restaurants (social evaluation, see Section 4). An ecological evaluation could be quite extensive, in that, it is important to understand life history characteristics, abundance, reproductive strategies, expansion potential, etc. Additionally, it is imperative to assess their impacts to native ecosystems. Finally, the economic evaluation must focus on fishers or user groups intended to commercially harvest the fish, market dynamics of buying and selling the fish, as well as costs to manage the fishery.

Socio-economic costs to the community related to lionfish or other marine fish invaders is difficult to fully assess, as these can be direct in terms of management costs, or indirect in the lowering of environmental services. This is especially true for fish species that impact the functional diversity of an ecosystem. Sections 2, 4, and 5 focused on providing the socio-economic benefits of commercializing lionfish harvest, by presenting evidence that fishers could be financially supported. However, this type of research could be expanded by, e.g. comparing costs between management strategies and evaluating losses to environmental services. It is important that the framework used to evaluate this scenario be repeatable and comparable between sites.

The model used in Sections 2, 4, and 5 conceivably allows for comparison of the results between Aruba and Texas. Although the models used different data in each location, catch per unit effort (CPUE) values were quite similar between the two. A more refined model, as shown in Section 4, could prove to be more useful in regions that have the resources to conduct more robust research. Regions that do not have the means to carry out extensive research, such as small Caribbean nations, would greatly benefit from the less rigorous model used in Section 2. Employing an easily repeatable model, that requires minimal data input, can be an effective way to compare regions or even sites within the same region. It is evident from the results in Sections 2 and 5 that a model can be generated that offers quantifiable results for commercializing the harvest of a marine invasive fish.

6.8.3 Building adaptive capacity

Adaptive capacity is difficult to build in the marine environment; however, it is likely to be more successful with a long-term understanding of how a system naturally operates over time. It is important to recognize the natural thresholds the environment can maneuver between, how resilient the system is to disturbance, and how it tends to recover when moving between the thresholds. For example, with lionfish, thresholds could be changed with altering the number of lionfish in the environment, the type of prey fish species available, the local competitors occupying the same space, etc. This is best obtained through longstanding monitoring efforts, such as that at Flower Garden Banks National Marine Sanctuary (FGBNMS).

The monitoring program at FGBNMS has characterized fish at EFGB and WFGB since the 1980's [64]. In 2011, this program began monitoring the lionfish invasion within designated 100m x 100m study sites at the two banks. Lionfish have irregularly been removed from the study sites, while consistent, annual removals occur once or twice a year at other sites on the reef. There are expansive areas of the reef cap at East and West Bank that have not been evaluated for lionfish density and have not been exposed to diver removals. This offers a particularly interesting and potentially significant case study, whereby, three different thresholds can be evaluated within the same marine sanctuary. A threshold exists without any human influence, one with some human disturbance to lionfish but minimal monitoring efforts, and one that lacks removal but has extensive monitoring. In each of these cases, it could be assumed that the densities of lionfish and native reef fish would vary immensely. However, what is not understood, is whether or not all of these thresholds are sustainable for the reef systems, or if one precludes the others. In this sense, adaptive capacity could be built in this sanctuary once all of the threshold regimes are better understood in terms of their resilience to disturbances from lionfish.

6.8.4 Engaging stakeholders

Stakeholder engagement is an important component of resource management, especially in the case where multiple user groups overlap in their exploitation of resources. In marine fisheries, the MSA requires marine fish management councils to oversee commercial and recreational harvest of different species within their region, and to provide advice about their future management. Similarly, national marine sanctuaries have sanctuary advisory councils that are comprised of stakeholder constituents with vested interest in the resources of the sanctuary, which provide guidance to resource managers on how to best manage the system. Advisory councils are an opportunistic forum that can be used to develop working groups to conduct embedded experiments, in an attempt to determine their reactions, beliefs, and suggestions for commercializing lionfish harvest. This can easily be expanded to the public, but overall affords readily available access to a wide variety of stakeholders.

6.9 Conclusions

There is a growing need to shift to more maintainable food systems that advocate for sustainability of the biosphere, improve consumer relationships with environmental stewardship, and reduce the pressure to current food systems [65]. It remains unclear how an increase in marine resource use for food and nutrition security can be done sustainably [66], though a shift towards commercially harvesting underutilized or invasive fish may be a viable alternative [6, 62, 67]. To do so, federal regulatory policies and approaches will have to be amended to include protocols for commercial harvest of an invasive marine fish. This will be most successful with OSY, as opposed to MSY, as it prioritizes stewardship of the oceans, maximizes the economic potential of user groups, and considers social benefits to humans. This section introduced a new concept for the MSA that should be considered for future fisheries management. Management plans that develop multi-faceted approaches, such as the inclusion of OSY, will be likely to yield the greatest benefits at suppressing local marine invasive populations, supporting socioeconomic security, and improving the overall well-being of coastal communities.

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7. CONCLUSION

Fisheries biology requires a harmonization of the three knowledge domains of biology, catch and effort, and socio-economic data [1]. Most commercial fishery assessments rely on landings and CPUE data in congruence with time series information on population abundance and size composition, but ignore the social and economic implications [2]. Too often, economic and social science data are not available or are provided informally in fisheries science and during decision-making processes [3]. There is a need to integrate socio-economic values into biological analyses to improve representation of the dynamic interrelationships between natural and socio-economic systems [4]. A paucity exists of economic and social performance of fisheries, which includes unit prices, harvest costs, and economic returns. Social indicators are highly underutilized to assess the sustainability of fisheries and are not formally included in fishery assessment protocols [2]. Assessing social and ecological outcomes of commercial fisheries requires novel frameworks that evaluate how management strategies interact with social, ecological, and economic systems to achieve sustainable catches, while also providing social and economic benefits [2]. This dissertation linked these components to highlight the importance of evaluating all of these factors collectively, as well as developed the first framework for assessing the likelihood of establishing a commercial fishery for lionfish.

This dissertation evaluated a critical gap in lionfish research and management, with the use of empirical and theoretical data, to develop a model to determine if a commercial fishery could be achieved. Additionally, this study addressed the important life history characteristics of age and growth of lionfish in the Southern Caribbean and northwestern Gulf of Mexico. The sectionss were presented chronologically and systematically built on one another, as such, the second case study was more complex than the first.

The research question addressed in this study was:

Is a commercial lionfish fishery, that balances ecologic sustainability of local marine systems and economic viability of fishers, achievable as a management strategy?

This study only evaluated the use of divers as a means to remove lionfish, as this is likely to be the most effective strategy for physical removals [5]. Harris et al. [6] evaluated the efficacy of lionfish traps as a means for removal, which confirmed that spearfishing was much more efficient. As such, this study is quite timely in providing much needed information about the efficacy of a diver-centric commercial lionfish fishery.

- Section 1 provided an overview of the issues associated with the introduction of an invasive species, as well as the difficulties of controlling their populations once established. Lionfish are an invasive species that have impacted the western Atlantic Ocean, Caribbean, and Gulf of Mexico. This section documented lionfish biology and ecology, reasons for their successful and continued invasion, and the negative impacts these fish pose to invaded environments. In effect, this sectionjustified why a long-term, sustainable management strategy was needed for lionfish and presented our approach of using a commercial fishery.

- Section 2 acted as a proof-of-concept study, in which the original research question was tested in Aruba. Lionfish were predicted to have arrived in Aruba in 2009 [7] and populations were relatively undisturbed, apart from occasional removal by recreational divers. To assess whether a commercial fishery could be implemented, biologic and socio-economic data were evaluated. A simple, conceptual model was developed that used data from existing literature. To gauge the effectiveness of this model, data collected during a field study in 2014 in Aruba were compared to the results. In 2014, 116 individuals were surveyed in Aruba about their awareness of lionfish and willingness to support a fishery. Eighty-nine percent of surveyed individuals had seen lionfish, while 66% were able to identify it. Of 74 individuals questioned, 32% had consumed lionfish, while 86% were willing to eat lionfish [8]. Divers collected 489 lionfish, within 40 m water depth, during an organized tournament in 2014. Lionfish abundance was computed using estimates found in existing literature, that was parameterized based on benthic composition data for Southern Caribbean reefs and the total available area in Aruba within 40 m water depth. A model was developed to compute the theoretical effort needed to achieve an optimum abundance for lionfish (i.e. reduce populations to allow native reef fish recovery) under three different removal scenarios (75%, 85%, 95%). Based on model results, the mean CPUE needed to achieve optimal abundance under the three removal scenarios was 29.3 LF diver hr^{-1}. Mean model CPUE computed was not significantly different from CPUE calculated from lionfish tournament statistics.

This suggested that a commercial lionfish fishery could be achievable in Aruba. It was evident from this study that establishing a commercial lionfish fishery in Aruba was socially viable and economically plausible, given the estimates for abundance and removal efforts. This study was limited in model complexity as it was missing valuable information. However, given that the CPUE values were not significantly different between the theoretical model and empirical data, I assumed it was accurate. Because data were assimilated from existing literature, this section provided a management framework that can be readily applied in other Caribbean regions.

- Section 3 assessed the important life history characteristics of age and growth for lionfish in Aruba and Texas. This section assessed annual increment formation in sagittal otoliths to document age from lionfish collected in Aruba in 2014 (n = 44) and the Flower Garden Banks National Marine Sanctuary (FGBNMS) in 2018 (n = 100). Additionally, Fulton's condition factor and asymptotic maximum lengths (L_∞) were calculated for each of the populations. Results of the analyses were compared to determine if there were any differences in age and condition of lionfish between Aruba and FGBNMS. Lionfish ranged in age from 0-6 yo and 0-10 yo in Aruba and FGBNMS, respectively. The back-calculated ages confirm the presence of lionfish in these two regions in 2008. It was determined that the populations were significantly different, with lionfish from Aruba exhibiting a greater maximum length, growth rate, and condition than lionfish from FGBNMS. The growth rate of lionfish from Aruba was comparable to that reported from one northern Gulf of Mexico (nGOM) study [10], while the growth rate of lionfish at FGBNMS was comparable to that reported from artificial and natural reefs from the nGOM [11]. Age/size and age structure measures of lionfish have not been comprehensively reported for all of their invaded ranges. This section provided vital life history metrics that can aid in sound management decisions, and also provided the first statistical comparison of lionfish age and growth in such spatially separated regions. As fisheries managers are concerned about the impacts these fish may have on the environment, we hope that information from this section can be incorporated into future management plans.

- Section 4 assessed the social implications of creating a commercial lionfish fishery in the northwestern Gulf of Mexico (NWGoM). Lionfish were first established in the NWGoM in 2008 (according to results in Section 3) and their population has since grown exponentially. This section used a survey instrument to gauge Texas Gulf Coast county residents (n = 420) perceptions of lionfish as a threat, their level of concern for the economy and the environment, their willingness to purchase and consume the fish, as well as their support/confidence in researchers and fisheries managers to manage lionfish successfully. An ordered logistic regression model estimated the likelihood of an individual to pay for lionfish given their awareness of lionfish as a threat, level of concern for the fish, and level of support/confidence for management. Surveys with Texas Gulf Coast county residents revealed that more than half were willing to purchase lionfish (56.7%), and that 45.2% thought a commercial lionfish fishery would be good for the economy and environment. Given the results of the social support for a lionfish fishery in Texas, important ecologic and economic data were evaluated to determine the feasibility of employing it as a management strategy.

- Section 5 evaluated the likelihood of a commercial lionfish fishery in the northwestern Gulf of Mexico (NWGoM) by investigating the ecologic and economic feasibility of accomplishing such a fishery, with data from natural and artificial habitats. Two lionfish fishery models were developed that were tested against data collected during lionfish research cruises to Flower Garden Banks National Marine Sanctuary (FGBNMS) 2015-2018. Model 1 predicted a catch per unit effort (CPUE) that ranged from 4.16-166.58 kg diver hr^{-1}, while Model 2 estimated a CPUE of 0.26-4.65 kg diver hr^{-1} at an optimum sustainable yield (i.e. yield to be ecologically sustainable) of 50%, and 0.33-5.27 kg diver hr^{-1} at an optimum sustainable yield of 75%. Catch statistics from lionfish research cruises ranged on average from 1.97-5.71 kg diver hr^{-1}, respectively. When compared to tournament catch data, Model 2 was not significantly different, which suggested it was effective in determining the effort needed to sustain a commercial fishery. Given the habitat available for lionfish to colonize and CPUE values, the results of this section revealed that a lionfish fishery was likely to be one of the few options available for future management in Texas.
- Section 6 provided a broad overview of federal and state management mandates that were currently in place, either directly or indirectly, related to managing lionfish and presented a new concept for federal management of invasive marine

fish. There were two federal management plans directly related to lionfish that were developed by the National Oceanic and Atmospheric Administration. However, there were no state or federal legislation that defined protocols specific to lionfish in the U.S. To better guide lionfish control strategies, the resource management principles of scenario planning, adaptive capacity, and stakeholder engagement were discussed in detail. By engaging these restorative principles, native marine ecosystems could be expected to operate within their natural regimes in the future. Alternatively, as a commercial fishery for an invasive species is relatively novel, this section also discussed solutions and innovations that may help improve the likelihood of communities employing this strategy. Innovative techniques to improve social acceptance of a lionfish are the modernization of conspicuous consumption to favor ecologically sustainable consumptive behaviors and proper use of terminology in marketing schemes (i.e. venomous vs. poisonous). Additionally, most management strategies aim to eradicate an invasive species, though this section argues that the goal should be to balance economic and ecologic interests of a fishery. This can be done by restructuring fisheries management, and including an amendment to the MSA, that defines an OSY for harvests rather than the conventional MSY. OSY targets harvests that offer ecological sustainability and economic viability to fishers. This multi-faceted approach may likely yield long-withstanding benefits to traditional fishery harvests, as well as, marine invasive fish.

Both studies that estimated CPUE only did so for a relatively short time-frame, single snapshot in Aruba and monthly harvest over a year in Texas. It is safe to assume that lionfish harvest effort would decrease along a multi-year fishery as the population stabilizes following substantial harvest pressure. That was not addressed in this dissertation, as it was beyond the intended scope of the research questions. However, this presents an interesting opportunity for future strategies, whereby research is directed to quantify harvest over a decadal or multi-decadal time scale.

Overall, the expected outcome for this dissertation was to provide a valuable tool for fishery managers, scientists, and educators by delivering a general framework to examine the interacting social, biologic, and economic factors that are necessary to holistically investigate implementing a sustainable, commercial lionfish fishery. This study was successful in identifying two models, that differed in complexity, that proved to be effective in estimating the effort that would be needed to sustain a lionfish fishery. Each of these models could be readily applied and required relatively minimal data. Future work should focus to incorporate both diver and trap fishery data, as this would provide a more robust estimate of the potential success of a lionfish fishery. This dissertation has provided valuable input that is applicable to all regions facing the lionfish invasion, and more broadly, it may be adjusted to evaluate the potential for commercial exploitation of other invasive species. This is the first study to have attempted such a dynamic interpretation of establishing a commercial fishery for lionfish, by conceptualizing the socio-economic and ecologic framework needed to devise a model for evaluating the feasibility of a commercial fishery. On a broader scale, this dissertation provides valuable insight into the future of managing invasive marine fish.

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APPENDIX A

Appendix A provides additional information that is associated with Section 2.

Survey for fishers

Age Category (*circle one*): 20-40 40-60 >60 Male/Female (*circle one*)

1. How long have you lived in Aruba? (*circle one*)
   a. <5 years
   b. 5-10 years
   c. 10-15 years
   d. >15 years

2. What brought you here if moving from another location (*circle one*)
   a. Family
   b. Job opportunity
   c. Retirement
   d. Other(specify):______________________________________

3. How long have you been fishing? (*circle one*)
   a. <5 years
   b. 5-10 years
   c. 10-15 years
   d. >15 years

4. How many times a week do you fish? (*circle one*)
   a. 1-3 times
   b. 3-5 times
   c. 5-7 times
   d. >7 times

5. How many pounds/kg of fish do you normally catch in a week? (*circle one*)
   a. <25lbs (<11.5kgs)
   b. 25-50lbs (11.5-22.25kgs)
   c. 50-75lbs (22.25-33.5kgs)
   d. 75-100lbs (33.5-44.5kgs)
   e. >100lbs (>44.5kgs)

6. What fish do you normally catch? (*List some common ones*)____________
____
____

7. Do you fish for yourself, a hobby, or is it your livelihood? (*check most appropriate*)
   - ☐ Self
   - ☐ Hobby
   - ☐ Livelihood

   a. What do you do with the fish? (*check all that apply*)
      - ☐ Sell **_If check, include question 7b_**
      - ☐ Keep
      - ☐ Release
      - ☐ Other(specify)_____________________________________

   b. Where do you sell the fish? (*check all that apply*)
      - ☐ Local market
      - ☐ Local restaurant
      - ☐ Export out of the country
      - ☐ Personal home
      - ☐ Family members home
      - ☐ Other(specify):____

   c. What methods of fishing do you commonly use? (*check all that apply*)
      - ☐ Hook and line
      - ☐ Net
      - ☐ Polespear
      - ☐ Slingshot spear gun
      - ☐ Other(specify):____

**I will show an image of a lionfish to those being surveyed to ask the next series of questions.*

8. Have you seen this fish before? **Y** or **N** (*circle one*) **_If NO, go to question 11_**

a. Do you know the name of it? **Y** or **N** (*circle one*)
b. What is it?______________________________________
c. Where did you see them (*check all that apply*)
   - ☐ News (online or televised)
   - ☐ Scientific journal
   - ☐ Personal research/interest
   - ☐ Diving/snorkeling/swimming ***If checked, see d and e***
   - ☐ Fishing
   - ☐ Documentary
   - ☐ Menu/seafood market
   - ☐ Other(specify)______________________________________
d. How many times did you see it in the ocean? (*check one*)
   - ☐ <5
   - ☐ 5-10
   - ☐ 10-15
   - ☐ >15
e. How many did you see? (*check one*)
   - ☐ <5
   - ☐ 5-10
   - ☐ 10-15
   - ☐ >15

9. Have you caught this fish before? **Y** or **N** (*circle one*) ***If NO, go to question 10***
   a. How many do you normally catch each time you fish? (*check one*)
      - ☐ <5
      - ☐ 5-10
      - ☐ 10-15
      - ☐ >15
   b. What do you do with the fish after being caught? (*check all that apply*)
      - ☐ Released
      - ☐ Discarded
      - ☐ Used for bait
      - ☐ Sold to restaurants
      - ☐ Personally consumed

- ☐ Other(specify):____

10. Have you been impacted by lionfish? **Y** or **N** (*circle one*) ***If NO, go to question 11***
    a. How have you been impacted by lionfish? (*check all that apply*)
        - ☐ Loss of income
        - ☐ Loss in capture of target fish
        - ☐ Loss of equipment
        - ☐ Bad reputation
        - ☐ Change in fishing techniques
        - ☐ Increased income
        - ☐ Improvements in fishing techniques
        - ☐ Increase capture of fish
        - ☐ None
        - ☐ Other(specify):____

11. Is there seasonality to the fish you catch? **Y** or **N** (*circle one*) ***If NO, go to question 12***
    a. Has this changed in the last 10 years? **Y** or **N** (*circle one*)
    b. **If so**, why do you think that is?________________________________
    ____
    ____

12. Would you participate in organized lionfish tournaments, competitions or hunts? **Y** or **N** (*circle one*)

13. Would you be willing to catch and sell lionfish if it were eco-friendly and/or if it benefited Aruba's economy? **Y** or **N** (*circle one*)

Survey for restaurant owners

Age Category (*circle one*): 20-40 40-60 >60 Male/Female (*circle one*)

1. How long have you lived in Aruba? (*circle one*)
    a. <5 years
    b. 5-10 years
    c. 10-15 years
    d. >15 years

2. What brought you here if moving from another location (*circle one*)
    a. Family
    b. Job opportunity
    c. Retirement
    d. Other(specify):______________________________________

3. What type of cuisine do you serve at your restaurant? (*check all that apply*)
    - ☐ Seafood ***If check go to question 4, if NO go to question 5***
    - ☐ Italian
    - ☐ American
    - ☐ Asian
    - ☐ German
    - ☐ Spanish
    - ☐ Other(specify):____

4. Where do you get the seafood you serve? (*check all that apply*)
    - ☐ Local fishermen
    - ☐ Local market
    - ☐ Imported
    - ☐ Self caught
    - ☐ Other(specify):____

    1. Are the fish you serve affected by seasonality? **Y** or **N** (*circle one*)

* *I will show an image of a lionfish to those being surveyed to ask the next series of questions.*

5. Have you ever seen this fish? **Y** or **N** (*circle one*) ***If NO, go to question 7***
   a. Do you know the name of it? **Y** or **N** (*circle one*)
   b. What is it?____
   c. Where did you see them? *(check all that apply*)
      i. News (online or televised)
      ii. Scientific journal
      iii. Personal research/interest
      iv. Diving/snorkeling/swimming
      v. Fishing
      vi. Documentary
      vii. Menu/seafood market
      viii. Other(specify):____

6. Do you serve lionfish? **Y** or **N** (*circle one*) ***If NO go to question 8***
   a. Where did you get it?_____________________________________
   b. When was the first time you served it?_____________________
   c. Why did you make that choice? (*briefly explain*)___________________
   ____
   ____
   d. How do you prepare it?____
   ____
   e. What are the reactions of customers?______________________________
   ____
   f. Do you advertise lionfish as a "special" cuisine? **Y** or **N** (*circle one*)
   g. Are people more willing to try it? **Y** or **N** (*circle one*)

7. Would you be willing to serve lionfish if it were eco-friendly and/or benefited the economy of Aruba? **Y** or **N** (*circle one*)

8. Would you be willing to support local fisherman if they were selling it? **Y** or **N** (*circle one*)
   a. Why/why not?____
   ____
   ____

9. Would you recommend that other restaurants serve lionfish? **Y** or **N** (*circle one*)

10. Have you been impacted by lionfish? **Y** or **N** (*circle one*) ***If NO go to question 13***
    a. How have you been impacted by lionfish? (*check all that apply*)
        i. Loss of income
        ii. Bad reputation
        iii. Increased income
        iv. Improvements to fishing techniques
        v. Increase capture of fish
        vi. None
        vii. Other(specify):____

11. Would you participate in organized lionfish tournaments, competitions or hunts? **Y** or **N** (*circle one*)

Survey for government officials

Age Category (*circle one*): 20-40 40-60 >60 Male/Female (*circle one*)

1. How long have you lived in Aruba?
    a. <5 years
    b. 5-10 years
    c. 10-15 years
    d. >15 years

2. How long have you held a position in office?
    a. <1 year
    b. 1-2 years
    c. 2-4 years
    d. >4 years

**I will show an image of a lionfish to those being surveyed to ask the next series of questions.*

3. Have you seen this fish? **Y** or **N** (*circle one*)
    a. Do you know the name of it? **Y** or **N** (*circle one*)
    b. What is it? ___________________________________

4. Do you consider this fish to be a problem for the island? Why and/or why not? Briefly describe.

5. Do you think this fish should be removed from Aruban waters? **Y** or **N** (*circle one*) **If NO go to question 6**
    a. Who is responsible for removing this fish? Briefly describe.

    b. What do you suggest is the most efficient way to do so? Briefly describe.

    c. Who should finance it? Briefly describe.

6. Are there any regulations currently in place for this fish? **Y** or **N** (*circle one*) **If NO go to 7c**
    a. What are they?

    b. Do you feel that the regulations are sufficient for their intended purposes?

    c. Do you feel that regulations should be implemented? Why or why not.

7. Would you help in (i.e. promote, sponsor, and/or fund) guided lionfish derbies, tournaments, or hunts if it benefited the economy and environment? **Y** or **N** (*circle one*)

8. Do you think lionfish could be used to benefit Aruba? If so, how? If not, why not?

9. If lionfish can benefit Aruba, would you be willing to help promote it or implement regulations that can help? **Y** or **N** (*circle one*)

Survey for locals

Age Category (*circle one*): 20-40 40-60 >60 Male/Female (*circle one*)

1. How long have you lived in Aruba? (*circle one*)
   b. <5 years
   c. 5-10 years
   d. 10-15 years
   e. >15 years

2. What brought you here if moving from another location (*circle one*)
   - □ Family
   - □ Job opportunity
   - □ Retirement
   - □ Other(specify):____

3. Have you participated in any diving, snorkeling, fishing, swimming, or other activities in the ocean here? (*check all that apply*) ***If NO move to question 5***
   - □ Diving
   - □ Snorkeling
   - □ Fishing
   - □ Swimming
   - □ Other(specify)_______________________________________

4. What is your greatest concern when entering the water? (*circle one*)
   - □ Currents
   - □ Waves
   - □ Sharks
   - □ Fish
   - □ Jellyfish
   - □ Corals
   - □ Other(specify):____

5. What type of cuisine have you ordered here? (*check all that apply*)
    - ☐ Seafood
    - ☐ Italian
    - ☐ American
    - ☐ Asian
    - ☐ German
    - ☐ Spanish
    - ☐ Other(specify)___________________________________

6. Where have you eaten on the island? (*check all that apply*)
    - ☐ Hotel restaurant
    - ☐ Local restaurant
    - ☐ Local's home
    - ☐ Other(specify)___________________________________

7. Do you intend to or normally eat seafood? **Y** or **N** (*circle one*) ***If NO skip to question 8***
    - ☐ If you ordered seafood, what did you choose?____________________
    ____
    ____

**I will show an image of a lionfish to those being surveyed to ask the next series of questions.*

8. Have you ever seen this fish before? **Y** or **N** (*circle one*) ***If NO skip to question 9***
    If yes, answer the following questions:

    - ☐ Do you know the name of it? **Y** or **N** (*circle one*)
    - ☐ What is it?___________________________________
    - ☐ Where have you seen them? (*check all that apply*)
        - ☐ News (online or televised)
        - ☐ Scientific journal

- ☐ Personal research/interest
- ☐ Diving/Snorkeling/Swimming ***If checked, see d and e***
- ☐ Documentary
- ☐ Menu/seafood market
- ☐ Other(specify)______________________________

☐ How many times did you see it in the ocean? (*check most appropriate*)

- ☐ <5
- ☐ 5-10
- ☐ 10-15
- ☐ >15

☐ How many did you see? (*check most appropriate)*

- ☐ <5
- ☐ 5-10
- ☐ 10-15
- ☐ >15

9. Has lionfish been served anywhere that you have eaten? **Y** or **N** (*circle one*)

10. Did you try it? **Y** or **N** (*circle one*) ***If NO go to question 11***

☐ Were you recommended to try it by your waiter, other clients, or a web search? (*check all that apply*)

- ☐ Waiter
- ☐ Other clients
- ☐ Online
- ☐ Other(specify)______________________________

☐ Would you eat it again or recommend it to friends/family? **Y** or **N** (*circle one*)

☐ If served in your hometown, would you eat it there also? **Y** or **N** (*circle one*)

11. Would you enjoy eating such a fish? **Y** or **N** (*circle one*)

Lionfish is a good, white tender meat fish with a taste and texture between a snapper and a grouper. It is not restricted on preparation or seasoning, as it is good fried, grilled, steamed, as sushi or seviche, and served whole or filleted.

12. Would you eat lionfish if it were eco-friendly and/or benefited the economy of Aruba? **Y** or **N** (*circle one*)

Survey for tourists

Age Category (*circle one*): 20-40 40-60 >60 Male/Female (*circle one*)

1. Where city/state or country are you visiting from?___________________________

2. Is this your first time to Aruba? **Y** or **N** (*circle one*) ***If NO move to 2a***
   a. How many times have you been here? (*check most appropriate*)
      - ☐ 0-5
      - ☐ 5-10
      - ☐ 10-15
      - ☐ >15

3. What made you choose Aruba as a destination? (*Circle all that apply*)
   a. Relatives
   b. Personal recommendation
   c. Natural attractions
   d. Cost
   e. Cuisine
   f. Other(specify)____

4. Have you participated in any diving, snorkeling, fishing, swimming, or other activities in the ocean here? (*check all that apply*) ***If NO move to question 5***
    - ☐ Diving
    - ☐ Snorkeling
    - ☐ Fishing
    - ☐ Swimming
    - ☐ Other(specify)______________________________________

5. What is your greatest concern when entering the water? (*circle one*)
    a. Currents
    b. Waves
    c. Sharks
    d. Fish
    e. Jellyfish
    f. Corals
    g. Other(specify):____

6. What type of cuisine have you ordered here? (*check all that apply*)
    - ☐ Seafood
    - ☐ Italian
    - ☐ American
    - ☐ Asian
    - ☐ German
    - ☐ Spanish
    - ☐ Other(specify)______________________________________

7. Where have you eaten on the island? (*check all that apply*)
    - ☐ Hotel restaurant
    - ☐ Local restaurant
    - ☐ Local's home
    - ☐ Other(specify)______________________________________

8. Do you intend to or normally eat seafood? **Y** or **N** (*circle one*) ***If NO skip to question 8***
   a. If you ordered seafood, what did you choose?______________________
   ____
   ____

**I will show an image of a lionfish to those being surveyed to ask the next series of questions.*

9. Have you ever seen this fish before? **Y** or **N** (*circle one*) ***If NO skip to question 9***
   If yes, answer the following questions:

   a. Do you know the name of it? **Y** or **N** (*circle one*)
   b. What is it?____
   c. Where have you seen them? (*check all that apply*)
      - ☐ News (online or televised)
      - ☐ Scientific journal
      - ☐ Personal research/interest
      - ☐ Diving/Snorkeling/Swimming ***If checked, see d and e***
      - ☐ Documentary
      - ☐ Menu/seafood market
      - ☐ Other(specify)_________________________________
   d. How many times did you see it in the ocean? (*check most appropriate*)
      - ☐ <5
      - ☐ 5-10
      - ☐ 10-15
      - ☐ >15
   e. How many did you see? (*check most appropriate)*
      - ☐ <5
      - ☐ 5-10
      - ☐ 10-15
      - ☐ >15

10. Has lionfish been served anywhere that you have eaten? **Y** or **N** (*circle one*)

11. Did you try it? **Y** or **N** (*circle one*) ***If NO go to question 11***
    a. Were you recommended to try it by your waiter, other clients, or a web search? (*check all that apply*)
       - ☐ Waiter
       - ☐ Other clients
       - ☐ Online
       - ☐ Other(specify)______________________________
    b. Would you eat it again or recommend it to friends/family? **Y** or **N** (*circle one*)
    c. If served in your hometown, would you eat it there also? **Y** or **N** (*circle one*)

12. Would you enjoy eating such a fish? **Y** or **N** (*circle one*)

Lionfish is a good, white tender meat fish with a taste and texture between a snapper and a grouper. It is not restricted on preparation or seasoning, as it is good fried, grilled, steamed, as sushi or seviche, and served whole or filleted.

13. Would you eat lionfish if it were eco-friendly? **Y** or **N** (*circle one*)

Survey for divers and/or dive shop owners

Age Category (*circle one*): 20-40 40-60 >60 Male/Female (*circle one*)

1. How long have you lived in Aruba? (*circle one*)
   f. <5 years
   g. 5-10 years
   h. 10-15 years

i. >15 years

2. What brought you here if moving from another location (*circle one*)
   a. Family
   b. Job opportunity
   c. Retirement
   d. Other(specify):____

3. How many times do you dive in a week? (*check one*)
   a. <5
   b. 5-10
   c. 10-15
   d. >15

4. Do you offer dives to tourists, locals, or both? (*check most appropriate*)
   - ☐ Tourists
   - ☐ Locals
   - ☐ Both

5. Do you educate clients on the natural environment such as identifying important fish, locations, plants, conservation efforts, etc. **Y** or **N** (*circle one*)

* *I will show an image of a lionfish to those being surveyed to ask the next series of questions.*

6. Have you ever seen this fish before? **Y** or **N** (*circle one*) ***If NO, go to question 7***
   a. Do you know what the name is? **Y** or **N** (*circle one*)
   b. What is it?_______________________________
   c. Where did you see them? (*check all that apply*)
      - ☐ News (online or televised)
      - ☐ Scientific journal

- ☐ Personal research/interest
- ☐ Diving/snorkeling/swimming ***If checked, go to d and e***
- ☐ Fishing
- ☐ Documentary
- ☐ Menu/seafood market
- ☐ Other(specify)_____________________________________

d. How many times do you see them each dive? (*check most appropriate*)
- ☐ <5
- ☐ 5-10
- ☐ 10-15
- ☐ >15

e. How many do you see at a time diving? (*check most appropriate*)
- ☐ <5
- ☐ 5-10
- ☐ 10-15
- ☐ >15

7. Have you experienced any of the following with regards to a lionfish? ***If NO, go to question 8***
   - ☐ Loss of money
   - ☐ Change in dive locations
   - ☐ Decrease in activities offered
   - ☐ Increased revenue
   - ☐ New dive locations
   - ☐ Increase in activities offered
   - ☐ None of the above

8. Do you participate in organized lionfish tournaments, competitions, hunts? **Y** or **N** (*circle one*)
   If NO, go to question 9

   a. How often do you or anyone in your shop hunt lionfish per week? (*check most appropriate*)
   - ☐ <5
   - ☐ 5-10

- ☐ 10-15
- ☐ >15

b. How many do you remove on a typical hunt? (*check most appropriate*)
- ☐ <5
- ☐ 5-10
- ☐ 10-15
- ☐ >15

c. What becomes of the fish after being caught? (*check all that apply*)
- ☐ Released
- ☐ Discarded
- ☐ Used for bait
- ☐ Sold to restaurants
- ☐ Personally consumed
- ☐ Other(specify)______________________________________

9. Would you be willing to participate in lionfish tournaments, competitions, or hunts if it were eco-friendly or benefited the Aruban economy? **Y** or **N** (*circle one*)

10. Have you eaten lionfish? **Y** or **N** (*circle one*) ***If NO go to question 12, If YES skip 12***

11. Would you eat lionfish if it were eco-friendly, tasty, or both? (*check one*)
- ☐ Eco-friendly
- ☐ Tasty
- ☐ Both

Table A-1. Benthic community composition values extracted from the literature.

Country	Depth (m)	Year	Area (m^2)	Hard Coral (%)	Soft Coral (%)	Algae (%)	Millepora (%)	Seagrass (%)	Sponge (%)	Sand (%)	CCA (%)	Total	Source
Aruba	9.37	2013	1975	5.6	6.4	39.1	0.1	0	0.9	46.3		98.4	[1]
Aruba	9.87	2013	2091	8.2	3.9	69.6	0.2	0	0.3	8.9		91.1	[1]
MEAN	**9.62**	**2013**	2033	**6.9**	**5.15**	**54.35**	**0.15**	**0**	**0.6**	**27.6**			[1]
Bonaire	11.69	2013	2029	13.9	10	59	0.9	0	1.4	10.1		95.3	[1]
Bonaire	9.77	2013	2051	26.4	5.4	42.8	0.3	0	0.8	2.6		78.3	[1]
Bonaire	12.73	2013	2327	6	1.4	61.9	0.2	0	1.2	21.3		92	[1]
Bonaire	10.47	2013	2373	25.4	5.5	51.4	0.4	0	1.5	2.8		87	[1]
Bonaire	4.11	2013	2097	15.5	3.2	52.1	0.5	0	2.5	19.5		93.3	[1]
Bonaire	11.11	2013	1991	13.8	6.1	68.3	0.5	0	0.3	5.5		94.5	[1]
Bonaire	9.5	2013	2518	13.6	13.5	50.7	2.3	0	2.1	11		93.2	[1]
Bonaire	10.45	2013	1766	12	24.7	41.3	1.7	0	1.5	6.5		87.7	[1]
Bonaire	9.84	2013	2020	15	6.8	47.2	0.5	0	1.7	19.8		91	[1]
MEAN	**9.96**	**2013**	2130	**15.73**	**8.51**	**52.74**	**0.81**	**0.00**	**1.44**	**11.01**			[1]
Curacao	9.21	2013	1369	8.3	1.8	66.2	0.2	0	1.7	19.5		97.7	[1]
Curacao	10.26	2013	1363	11.2	5.4	51.7	0.2	0	2.2	26.7		97.4	[1]
Curacao	9.9	2013	1409	20.7	14.3	53	1.4	0	1.1	4.8		95.3	[1]
MEAN	**9.79**	**2013**	1380	**13.40**	**7.17**	**56.97**	**0.60**	**0.00**	**1.67**	**17**			[1]
Saint Vincent	11.15	2013	1588	2.7	4	65.8	0.2	0	6	19.9		98.6	[1]
Saint Vincent	11.24	2013	2075	2.8	1.3	85.4	0.3	0	4.5	4.7		99	[1]
Saint Vincent	8.9	2013	1728	11.8	10.5	51.8	0.3	1.7	0.8	13.4		90.3	[1]

Saint Vincent	8.18	2013	1546	6.7	6.2	55.5	0.6	0.7	3	5.7		78.4	[1]
Saint Vincent	9.44	2013	1724	3.7	1.5	90.5	0	0	0.9	2.7		99.3	[1]
Saint Vincent	10.05	2013	1658	1.2	3.1	77.2	0.2	0	3.9	14.1		99.7	[1]
Saint Vincent	10.74	2013	1655	0.7	4	84.9	0	0	1.2	8.9		99.7	[1]
Saint Vincent	7.77	2013	1097	1.8	1.9	90.2	0.2	0	2.3	3.2		99.6	[1]
Saint Vincent	18.62	2013	410	8.4	9.8	54.6	0	0.4	6	16		95.2	[1]
Saint Vincent	10.68	2013	1775	1	0.5	88.3	0.1	0	1.3	8.7		99.9	[1]
Saint Vincent	7.48	2013	1726	5.2	2.2	73.6	0.3	0	3.9	13.2		98.4	[1]
Saint Vincent	9.75	2013	1871	3	9.7	75.8	0.3	0	2.8	7.7		99.3	[1]
Saint Vincent	10.43	2013	1480	4.2	5.6	77.8	0.2	0	2.2	9.3		99.3	[1]
Saint Vincent	9.3	2013	1199	1	0.5	90.3	0.1	0	2	6.2		100.1	[1]
Saint Vincent	8.17	2013	1416	6.6	1.6	45.2	0.4	25.8	4.9	11.1		95.6	[1]
Saint Vincent	10.35	2013	973	5.6	3.7	11	0.1	0.1	3	2.4		25.9	[1]
Saint Vincent	8.9	2013	1775	1.2	0.7	82.7	0.2	0	1.1	14		99.9	[1]
Saint Vincent	9.46	2013	1985	1.2	2.3	78.1	0.2	0	0.5	17.3		99.6	[1]
Saint Vincent	6.85	2013	207	7.6	6.1	49.8	0.6	0.1	3.5	29.3		97	[1]
Saint Vincent	9.35	2013	1219	2.9	7	55.1	0.2	1.3	1.4	29.6		97.5	[1]
MEAN	**9.8405**	**2013**	1455	**3.97**	**4.11**	**69.18**	**0.23**	**1.51**	**2.76**	**11.87**			[1]

Barbados	NA	2017	200	23.0	0.0	42.4	NA	NA	9.1	NA	12.6	87.1	[2]
Barbados	NA	2017	200	23.8	0.0	26.7	NA	NA	6.4	NA	20.3	77.2	[2]
Barbados	NA	2017	200	31.9	0.0	27.3	NA	NA	7.3	NA	25.6	92.1	[2]
Barbados	NA	2017	200	24.6	0.0	40.0	NA	NA	8.8	NA	13.2	86.6	[2]
Barbados	NA	2017	200	22.0	0.0	50.3	NA	NA	4.8	NA	15.0	92.1	[2]
Barbados	NA	2017	200	6.6	0.2	54.2	NA	NA	13.9	NA	16.5	91.4	[2]
Barbados	NA	2017	200	10.2	0.0	56.9	NA	NA	7.6	NA	11.4	86.1	[2]
Barbados	NA	2017	200	16.5	4.7	63.9	NA	NA	9.2	NA	0.5	94.8	[2]
Barbados	NA	2017	200	26.0	0.9	41.8	NA	NA	6.0	NA	3.9	78.6	[2]
Barbados	NA	2017	200	32.2	1.6	26.4	NA	NA	13.4	NA	9.0	82.6	[2]
Barbados	NA	2017	200	29.6	2.9	30.1	NA	NA	10.3	NA	13.9	86.8	[2]
Barbados	NA	2017	200	22.3	4.2	48.7	NA	NA	17.3	NA	2.2	94.7	[2]
Barbados	NA	2017	200	12.9	1.1	66.7	NA	NA	6.5	NA	2.9	90.1	[2]
Barbados	NA	2017	200	21.0	0.1	36.7	NA	NA	12.5	NA	6.5	76.8	[2]
Barbados	NA	2017	200	26.0	0.8	25.9	NA	NA	20.2	NA	21.7	94.5	[2]
Barbados	NA	2017	200	16.6	0.2	43.0	NA	NA	13.1	NA	16.0	88.8	[2]
Barbados	NA	2017	200	14.7	0.6	42.6	NA	NA	17.7	NA	11.8	87.4	[2]
Barbados	NA	2017	200	18.1	0.7	33.6	NA	NA	17.8	NA	22.3	92.5	[2]
Barbados	NA	2017	200	21.8	3.0	23.7	NA	NA	16.7	NA	21.4	86.6	[2]
Barbados	NA	2017	200	11.1	0.4	36.9	NA	NA	32.7	NA	9.5	90.6	[2]
Barbados	NA	2017	200	19.3	1.1	32.9	NA	NA	23.6	NA	13.7	90.6	[2]
MEAN	NA	**2017**	**200**	**20.5**	**1.1**	**40.5**	NA	NA	**13.1**	NA	**12.9**		[2]
Grenada	NA	2012	120	15.2	3.2	58.7	NA	NA	5.4	NA	12.1		[3]

Estimates for Saint Vincent were recorded in Saint Vincent and the Grenadine.

Table A-2. Logit regression analysis results of 116 participants surveyed in Aruba in 2014 on their support for a lionfish fishery (yes/no).

LF_fishery	Coef.	Std. Err.	z	P>|z|	[95% Conf. Interval]	
gender						
Male	1.000	0.7475	1.34	0.181	-0.4644	2.4658
group						
Fishermen	-0.9436	0.8819	-1.07	0.285	-2.6723	0.7850
Government	0	(empty)				
Locals	2.4332	1.0785	2.26	0.024*	0.3192	4.5472
Restaurants	-1.6396	1.0810	-1.52	0.129	-3.7583	0.4790
Tourists	1.6127	1.0533	1.53	0.126	-0.4516	3.6772
age						
40-60	-1.3039	0.6052	-2.15	0.031*	-2.4901	-0.1177
>60	-1.8128	0.9980	-1.82	0.069	-3.7689	0.1433
know_LF	0.9860	0.6053	1.63	0.103	-0.2004	2.1725
fish_ID	0.4955	0.8837	0.56	0.575	-1.2364	2.2275
1.where_see_LF	0.5459	0.6923	0.79	0.43	-0.8109	1.9028
_cons	-3.0431	2.7810	-1.09	0.274	-8.4938	2.4075

Explanatory variables were stakeholder group, gender, age, familiarity of lionfish, and where an individual had seen lionfish. Familiarity of lionfish was determined by showing survey participants a photograph of a lionfish and asking if they had seen the fish before (yes/no; know_LF)) and if they could identify it by name (fish_ID). Individuals were asked where they had seen lionfish before and given a list of options to choose from, whereby more than one option could be selected. These were divided among activities associated with the water and those that were not for this analysis (where_see_LF). Statistically significant terms are denoted with an asterisk*. The log likelihood value was -44.065 and Pseudo $R^2 = 0.2527$.

Table A-3. Results of the Tukey-post hoc test comparing CPUE (LF $diver^{-1}$ hr^{-1}) between the different quadrants in Aruba.

CPUE	Contrast	Std. Err.	t	P>|t|	[95% Conf. Interval]	
quadrant						
II vs I	12.57441	1.381624	9.1	0.000*	9.012636	16.13618
III vs I	10.87781	0.7579133	14.35	0.000*	8.923943	12.83168
IV vs I	7.849202	0.8123183	9.66	0.000*	5.755078	9.943326

III vs II	-1.696594	1.359052	-1.25	0.596	-5.200175	1.806987
IV vs II	-4.725205	1.390126	-3.4	0.004*	-8.308894	-1.141516
IV vs III	-3.028611	0.773304	-3.92	0.001*	-5.022158	-1.035064

An asterisk* denotes statistically significant values.

Table A-4. Results of the ordinary least squares regression analysis to determine the significant factors that contributed to the removal of lionfish in Aruba in 2014.

Total_W_kg	**Coef.**	**Robust Std. Err.**	**t**	**P>|t|**	**[95% Conf. Interval]**	
quardant						
II	-10.19213	1.569801	-6.49	0.000*	-13.27676	-7.107495
III	-5.120238	0.1641708	-31.19	0.000*	-5.44283	-4.797645
IV	-22.78666	1.922309	-11.85	0.000*	-26.56396	-19.00935
Depth	0.4360476	0.0328342	13.28	0.000*	0.3715291	0.5005661
Divers_n						
3	3.704048	0.0328342	112.81	0.000*	3.63953	3.768567
4	5.189524	0.3611757	14.37	0.000*	4.479821	5.899228
5	5.797716	0.1970049	29.43	0.000*	5.410605	6.184827
team						
2	-2.711322	0.3806562	-7.12	0.000*	-3.459304	-1.96334
3	-7.879154	0.056035	-140.61	0.000*	-7.989262	-7.769046
4	-7.900513	1.134812	-6.96	0.000*	-10.1304	-5.670628
5	-22.77485	1.364437	-16.69	0.000*	-25.45594	-20.09375
6	-13.57042	0.382157	-35.51	0.000*	-14.32135	-12.81949
7	-34.67904	2.184892	-15.87	0.000*	-38.97231	-30.38577

8	-23.95953	1.881587	-12.73	0.000*	-27.65681	-20.26224
_cons	1.205941	0.6417673	1.88	0.061	-0.0551197	2.467002

The dependent variable is total weight captured (kg), with independent variables: quadrant hunted (see Figure 2.1), depth, number of divers (Divers_n), and the team. As the number of divers and team were categorical variables, results are presented such that the results of the categories that remain in the model are compared to the missing category. Statistically significant values are indicated with an asterisk*. Number of observations = 489, R-squared = 0.9778, root MSE = 1.0364.

References

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2. Valles H, Oxenford HA, Henderson A. Switching between standard coral reef benthic monitoring protocols is complicated: proof of concept. Peerj. 2019:e8167.

3. Anderson R, Morrall C, Jossart J, Nimrod S, Bolda E, Musser K, et al. Marine Protected Area monitoring in the nearshore waters of Grenada, Eastern Caribbean: benthic cover and fish populations. Rev Biol Trop. 2014;62:14.

APPENDIX B

Appendix B provides additional information that is associated with Section 4.

Lionfish - Texas Coast Counties Survey

Start of Block: Quotas

Q39 Please select your age range.

- ◯ Less than 18 years (1)
- ◯ 18 - 24 (2)
- ◯ 25 - 39 (3)
- ◯ 40 - 64 (4)
- ◯ 65 years and over (5)

Q42 What is your gender?

○ Male (1)

○ Female (2)

Q43 Which of the following do you most closely identify with?

○ White (1)

○ Hispanic or Latino (2)

○ African American (3)

○ Asian (4)

○ Other race/ethnic group (please specify) (5)

____

Q37 In which county do you reside?

○ Aransas County (1)

○ Brazoria County (2)

○ Calhoun County (3)

○ Cameron County (4)

○ Chambers County (5)

○ Galveston County (6)

○ Harris County (7)

○ Jackson County (8)

○ Jefferson County (9)

○ Kenedy County (10)

○ Kleberg County (11)

○ Liberty County (12)

○ Matagorda County (13)

○ Nueces County (14)

○ Orange County (15)

○ Refugio County (16)

○ San Patricio County (17)

○ Victoria County (18)

○ Willacy County (19)

○ Other county (20)

End of Block: Quotas

Start of Block: Consent

Q40 Thank you for your interest in completing our survey. This survey will ask you about your perceptions of lionfish, their management, and willingness to consume the fish. Participation in this survey is voluntary. To participate you must be 18 years of age or older. You must also be a resident of a coastal county in Texas.

You have a right to withdraw from the study at any time without consequences. The information you share is anonymous. People who have access to this information include the Principal Investigators and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Research Protection Program may access your records to make sure the study is being run correctly and that information is collected properly.

If you have any questions or concerns about this research, you can contact one of the following Principal Investigators: Dr. Glenn Jones, Texas A&M University at Galveston, jonesg@tamug.edu, or Raven Blakeway, Texas A&M University at Galveston, rwalke09@email.tamu.edu.

For questions about your rights as a research participant, to provide input regarding research, or if you have questions, complaints, or concerns about the research, you may call the Texas A&M University Human Research Protection Program office by phone at 1-979-458-4067, toll free at 1-855-795-8636, or by email at irb@tamu.edu.

Do you agree to participate?

Note that you may print this for your records.

○ Yes (1)

○ No (2)

End of Block: Consent

Start of Block: Lionfish Ecology

Q48 *This survey will ask you questions about lionfish, an invasive species of fish not native to the Gulf of Mexico.*

What would you say is your level of knowledge of lionfish? Rate yourself on the following scale, where 0 "no knowledge" and 10 "expert knowledge".

	0 1 2 3 4 5 6 7 8 9 10
()	

Q19 *An invasive species is any kind of living organism, such as a* plant or animal, that is not native to an area and whose presence causes harm. The harm can be to the environment, the economy, native plants and animals, or even human health.

Lionfish (picture shown below) are a marine invasive fish species that has become established in the Atlantic, Gulf of Mexico, and Caribbean regions. These fish pose impacts to coastal environments and communities.

Q1 Indicate your level of concern for the impacts lionfish can have on each of the listed items.

	Not concerned (1)	Somewhat concerned (2)	Neutral (3)	Concerned (4)	Very concerned (5)

Recreational fisheries (1)	○	○	○	○	○
Commercial fisheries (2)	○	○	○	○	○
Coral reefs (3)	○	○	○	○	○
Native fish populations (4)	○	○	○	○	○
Coastal economy (5)	○	○	○	○	○
Tourism and Recreation (6)	○	○	○	○	○
SCUBA diving operations (7)	○	○	○	○	○

Offshore energy production (8)	○	○	○	○	○

Q2 *Lionfish have invaded important areas for native fish and marine species such as coral reefs, marine protected areas, artificial reefs, estuaries, boat docks and ports, and coastal regions used for recreational activities.*

Would you support control efforts aimed at reducing the impacts of lionfish in the Gulf of Mexico?

○ Yes (1)

○ No (2)

End of Block: Lionfish Ecology

Start of Block: Management and Control

Q3 *Once an invasive species becomes established in a region, removing them from the environment is not possible. This is true for lionfish. It is important to effectively control lionfish populations in their invaded region to reduce their negative impacts.*

Indicate how important it is to you to have the following areas managed to control lionfish populations.

	Not important (1)	Somewhat important (2)	Neutral (3)	Important (4)	Very important (5)

Coral reefs (1)	○	○	○	○	○
Marine Protected Areas (2)	○	○	○	○	○
Artificial reefs (3)	○	○	○	○	○
Estuaries (4)	○	○	○	○	○
Boat docks and Ports (5)	○	○	○	○	○
Coasts used for recreational activities (6)	○	○	○	○	○
Offshore oil and gas platforms (7)	○	○	○	○	○

Q4

A stakeholder is a person, group, or organization that has interest or concern in an organization or cause (businessdictionary.com).

Some experts have suggested that managing lionfish requires collaboration among stakeholders.

Who do you think should be responsible for controlling the lionfish populations?

- ○ Federal government fishery managers (e.g. National Marine Fishery Service) (1)
- ○ State government fishery managers (e.g. Texas Parks and Wildlife) (2)
- ○ Recreational water-sport owners and operators (e.g. dive boats, jet ski rentals) (3)
- ○ Recreational volunteers (4)
- ○ All of the above. (5)
- ○ I do not know enough to say. (6)

Q5 Do you support collaboration between researchers, fishermen, and managers to develop a strategy to control lionfish?

◯ Yes I support collaboration. (1)

◯ No I do not support collaboration. (2)

◯ I do not know enough to say. (3)

Q6 Do you have confidence that researchers, fishermen, and managers can develop a sound management strategy to effectively control lionfish populations?

◯ Yes (1)

◯ No (2)

◯ I do not know enough to say. (3)

Q7 Do you think lionfish can be managed at a local (such as Galveston County) or regional scale (such as the entire Gulf of Mexico Coast)?

○ Local scale (1)

○ Regional scale (2)

○ I do not know enough to say. (3)

Q8 *Some scientists and fisheries managers have suggested creating a fishery for lionfish to control their population.*

Do you think establishing a lionfish fishery would be good for the economy and the environment?

- ◯ It would be good for the economy and the environment. (1)
- ◯ It would ONLY be good for the economy. (2)
- ◯ It would ONLY be good for the environment. (3)
- ◯ It would NOT be good for the economy or the environment. (4)
- ◯ I do not know enough to say. (5)

Q10 Have you ever eaten lionfish?

- ◯ Yes (1)
- ◯ No (2)

Q9 *Lionfish have white, tender meat that, when cooked, has a mild taste and texture (similar to Snapper, Grouper, or Cod). It is a versatile fish for cooking, as it can be prepared in a variety of ways.*

How willing would you be to order lionfish at a restaurant or purchase fillets in a seafood market?

- ◯ Not willing (1)
- ◯ Somewhat willing (2)
- ◯ Very willing (3)
- ◯ Undecided (4)

Q11 *Lionfish are imported from the Indo-Pacific for the aquarium industry. Scientists believe lionfish were introduced into the Gulf of Mexico by release from aquariums.*

Do you think that banning the importation of lionfish from the Indo-Pacific could help with control efforts in the Gulf of Mexico?

○ Yes banning lionfish will be very helpful. (1)

○ Yes banning lionfish will be somewhat helpful. (2)

○ No banning lionfish will not be helpful. (3)

○ I do not know enough to say. (4)

End of Block: Management and Control

Start of Block: Education and Outreach

Q12 What would be your preferred method to receive information about lionfish in the Gulf of Mexico?

- ○ Television program (1)
- ○ Radio broadcast (2)
- ○ Newspaper article (3)
- ○ Scientific article (4)
- ○ Text message (5)
- ○ Email (6)
- ○ In-person presentation (7)

Q13 Would you be willing to attend an educational program, activity, or presentation to learn more about lionfish?

- ○ Yes (1)
- ○ No (2)

Q14 Have you ever attended an educational program, activity, or presentation to learn more about lionfish?

◯ Yes (1)

◯ No (2)

Skip To: Q15 If Have you ever attended an educational program, activity, or presentation to learn more about lion... = Yes

Skip To: End of Block If Have you ever attended an educational program, activity, or presentation to learn more about lion... = No

Q15 Thinking about that educational activity you attended to learn more about lionfish, how would you rate the information presented?

◯ The information was helpful and easy to understand. (1)

◯ The information was helpful but was too difficult to understand. (2)

◯ The information I received was not helpful. (3)

Q17 Did the presenter discuss the need to control the lionfish invasion?

- Yes (1)
- No (2)
- I do not remember. (3)

Q41 Did the presenter recommend eating lionfish as a means of controlling the invasion?

- Yes (1)
- No (2)
- I do not remember. (3)

End of Block: Education and Outreach

Start of Block: Personal contribution

Q18 Finally, please indicate how willing you would be to contribute to the following lionfish control efforts.

Not willing (1)	Somewhat willing (2)	Neutral (3)	Willing (4)	Very willing (5)

Donate money to organizations that are working to control lionfish. (1)	○	○	○	○	○
Donate money to organizations that are working to educate the public about lionfish. (2)	○	○	○	○	○

Donate money to organizations that are working to research lionfish. (3)	○	○	○	○	○
Participate in diving excursions to remove lionfish. (4)	○	○	○	○	○
Purchase lionfish merchandise to profit businesses or individuals (e.g. jewelry, shirts). (5)	○	○	○	○	○

Encourage friends and family to learn about lionfish. (6)	○	○	○	○	○
Eat lionfish if prepared in a restaurant or sold in a seafood market. (7)	○	○	○	○	○
Volunteer to participate in scientific research efforts. (8)	○	○	○	○	○

End of Block: Personal contribution

Start of Block: Science Exposure

Q21 Have you ever voluntarily collected scientific data without monetary compensation (e.g., a citizen science project, using iNaturalist or field work)?

○ Yes (1)

○ No (2)

Q22 Have you ever worked in an official capacity (e.g. intern, lab assistant) with scientists doing research (data collecting)?

○ Yes (1)

○ No (2)

Q23 Have you ever used publicly available data - such as Census Bureau statistics - for your own work?

○ Yes (1)

○ No (2)

Q24 Do you consider yourself a scientist (currently or retired)?

○ Yes (1)

○ No (2)

End of Block: Science Exposure

Start of Block: Environmental Relationship

Q25 Do you belong to any environmental or conservation groups?

○ Yes (1)

○ No (2)

Q26 Do you or a family member work for an environmental company or conservation organization (e.g. Texas Parks and Wildlife, other environmental non-profit)?

○ Yes (1)

○ No (2)

Q27 In which of the following fields is (or was if you are retired) your primary occupation?

- ○ Management, professional, and related (1)
- ○ Service (2)
- ○ Sales and office (3)
- ○ Farming, forestry (4)
- ○ Fishing (5)
- ○ Construction, extraction, maintenance (6)
- ○ Production, transportation, and material moving (7)
- ○ Government (8)
- ○ Homemaker (9)
- ○ Oil and gas (10)
- ○ Leisure, tourism and recreation (11)
- ○ Restaurant (12)

○ Research, science (13)

○ Other (14) ____

Q34

Do you believe an environmental or conservation organization has the responsibility to act in the best interest of...

○ The environment (1)

○ The public (2)

○ Both, but more so the environment (3)

○ Both, but more so the public (4)

○ Both equally (5)

Q47 From the list below, please indicate your level of participation in the following **marine-based recreational** activities.

	Always (1)	Sometimes (2)	Never (3)

Fishing (1)	○	○	○
Scuba Diving (2)	○	○	○
Boating (3)	○	○	○
Beach combing (4)	○	○	○
Snorkelling (5)	○	○	○
Canoeing, kayaking, paddle boarding (6)	○	○	○
Swimming (7)	○	○	○
Visit parks, sanctuaries (8)	○	○	○

End of Block: Environmental Relationship

Q36 Please answer the following questions in terms of *the way you generally feel*. There are no right or wrong answers. Using the scale provided, simply select as honestly and candidly as you can what you are generally experiencing.

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
The problems of the environment are not as bad as most people think. (1)	○	○	○	○	○
I think of the natural world as a community to which I belong. (2)	○	○	○	○	○

People worry too much about human progress harming the environment. (3)	○	○	○	○	○
I feel a sense of oneness with nature. (4)	○	○	○	○	○
When I think of my life, I imagine myself to be a part of a larger cyclical process of living. (5)	○	○	○	○	○

I often feel a kinship with plants and animals. (6)	○	○	○	○	○
I feel as though I belong to the Earth as equally as it belongs to me. (7)	○	○	○	○	○
I have a deep understanding of how my actions affect the natural world. (8)	○	○	○	○	○

We are spending too little money on improving and protecting the environment. (9)	○	○	○	○	○
I never feel a personal bond with things in my natural surroundings, like the plants and animals. (10)	○	○	○	○	○

My personal welfare is independent of the welfare of the natural world. (11)	○	○	○	○	○

End of Block: Connectedness to Nature Scale (Mayer and Frantz 2004; Dutcher et al. 2007)

Start of Block: Trust/Social Capital

Q29 How much of the time do you think you can trust the government, in general, to do what is right?

○ Just about always (1)

○ Most of the time (2)

○ Only some of the time (3)

Q30 How much confidence (or trust) do you have in scientists to act in the best interest of the public?

- A great deal (1)
- A fair amount (2)
- Not too much (3)
- No confidence (or trust) (4)

Q32 How much confidence (or trust) do you have in environmental managers to act in the best interest of the public?

- A great deal (1)
- A fair amount (2)
- Not too much (3)
- No confidence (or trust) (4)

Q33 How much confidence (or trust) do you have in environmental managers to act in the best interest of the environment?

○ A great deal (1)

○ A fair amount (2)

○ Not too much (3)

○ No confidence (or trust) (4)

End of Block: Trust/Social Capital

Start of Block: Ideology

Q35 Here is a 7-point scale on which the political views that people might hold are arranged from extremely liberal to extremely conservative. Where would you place yourself on this scale?

○ Extremely Liberal (1)

○ Liberal (2)

○ Slightly Liberal (3)

○ Moderate; middle of the road (4)

○ Slightly Conservative (5)

○ Conservative (6)

○ Extremely Conservative (7)

End of Block: Ideology

Start of Block: Zip Code

Q45 Please enter the zip code of your current residence.

____

Table B-1. Descriptive characteristics of the independent variables used in the ordered logistic regression model.

BINARY VARIABLES						DESCRIPTION
Variable	**Yes**	**No**				
eat_lf	34	386				Have you eaten lionfish before?
supp_cont	372	48				Would you support control to reduce impacts of lionfish?
educ_lf	35	385				Have you attended an educational program to learn about lionfish?
env_group	52	368				Do you belong to any environmental or conservation groups?
CATEGORICAL VARIABLES (3 RESPONSES)						DESCRIPTION
Variable	**Yes**	**No**	**I don't know**			
conf_man	279	37	104			Do you have confidence that researchers, fishers, and managers can develop an effective management
supp_coll	354	5	61			Do you support collaboration between researchers, fishers, and scientists to manage lionfish?
ban_lf	264	59	97			Do you think banning the importation of lionfish could help control efforts in the Gulf of Mexico?
CATEGORICAL VARIABLES (4 RESPONSES)						DESCRIPTION
Variable	**limited knowledge**	**some knowledge**	**knowledgable**	**expert**		
know_lf	215	101	74	30		What would you say is your level of knowledge of lionfish?
CATEGORICAL VARIABLES (5 RESPONSES)						DESCRIPTION
Variable	**1**	**2**	**3**	**4**	**5**	
con_env	54	106	93	124	43	Indicate your level of concern for the impacts lionfish can have on these areas in the environment. 1=not concerned; 2=somewhat concerned; 3=neutral; 4=concerned; 5=very concerned
con_econ	43	117	137	93	30	Indicate your level of concern for the impacts lionfish can have on these areas of the economy. 1=not concerned; 2=somewhat concerned; 3=neutral; 4=concerned; 5=very concerned
fish_good2	190	25	25	45	135	Do you think establishing a lionfish fishery would be good for the economy and the environment? 1=both; 2=economy only; 3=environment only; 4=neither; 5=I don't know
CNS	49	177	120	72	2	Connectedness to Nature - answer the questions in terms of the way you generally feel. 1=neither agree/disagree; 2=somewhat agree; 3=somewhat disagree; 4=strongly agree; 5=strongly disagree
contol	188	11	3	168	50	Who do you think is responsible for controlling lionfish populations? 1=government; 2=recreational operators; 3=volunteers; 4=all of the above; 5=I don't know

Table B-2. Results of the ordered logistic regression analysis on a Texas Gulf Coast County resident's willingness to purchase lionfish.

buy_lf	Coef.	Std. Err.	z	P>|z|	[95% Conf. Interval]	
sex						
Male	0.5458917	0.2302747	2.37	0.018*	0.0945615	0.9972218
1.minority	-0.0320992	0.2403724	-0.13	0.894	-0.5032205	0.4390221
polid						
2	0.0081093	0.264635	0.03	0.976	-0.5105658	0.5267845
3	0.344039	0.2780681	1.24	0.216	-0.2009645	0.8890425
eat_lf						
Yes	1.3713	0.5240585	2.62	0.009**	0.3441638	2.398436
con_env	0.214377	0.1301406	1.65	*0.100*	-0.0406939	0.469448
con_econ	-0.27548	0.1469624	-1.87	*0.061*	-0.563521	0.012561
know						
1	0.3084199	0.2657481	1.16	0.246	-0.2124369	0.8292766
2	0.141903	0.2969111	0.48	0.633	-0.4400321	0.723838
3	0.7532077	0.5184307	1.45	0.146	-0.2628977	1.769313
supp_cont						
Yes	0.6257931	0.367833	1.7	*0.089*	-0.0951464	1.346733
conf_man						
No	0.4796167	0.4357933	1.1	0.271	-0.3745226	1.333756

Yes	0.1158419	0.270892	0.43	0.669	-0.4150967	0.6467804
supp_coll						
No	1.323926	1.193496	1.11	0.267	-1.015282	3.663135
Yes	0.2939149	0.3400213	0.86	0.387	-0.3725146	0.9603443
fish_good						
2	-1.092806	0.4678829	-2.34	0.02*	-2.00984	-0.1757723
3	-0.2924511	0.4357551	-0.67	0.502	-1.146515	0.5616132
4	-0.185465	0.3568488	-0.52	0.603	-0.8848757	0.5139458
5	0.1740359	0.2790981	0.62	0.533	-0.3729863	0.721058
ban_lf						
2	-0.1772851	0.3143122	-0.56	0.573	-0.7933258	0.4387556
3	0.2805696	0.2924525	0.96	0.337	-0.2926268	0.853766
educ_lf						
Yes	-0.6313216	0.5699642	-1.11	0.268	-1.748431	0.4857877
env_group						
Yes	0.6187476	0.3852907	1.61	0.108	-0.1364082	1.373903
cns	0.2508856	0.1361697	1.84	*0.065*	-0.0160021	0.5177733
control						
2	-0.9035883	0.6420325	-1.41	0.159	-2.161949	0.3547723
3	-2.177793	1.373404	-1.59	0.113	-4.869617	0.5140298
4	0.3304634	0.2277306	1.45	0.147	-0.1158804	0.7768072
5	-0.4780521	0.4075653	-1.17	0.241	-1.276866	0.3207612

Ordered logit regression analyses estimated. Age and County were omitted for collinearity. Statistical significance denoted as: *** p < 0.001, **p < 0.010, *p < 0.050, *italicized* p < 0.100.

Table B-3. Results of the pairwise comparisons of marginal effects to determine differences in willingness to purchase lionfish based on sex.

Variable: Sex	Contrast	Std. Error	Outcome
Male vs. Female	-0.1080**	0.0453	Not willing
Male vs. Female	0.0138	0.0086	Somewhat willing
Male vs. Female	0.0941**	0.0400	Very willing

Statistical significance denoted as: *** p < 0.001, **p < 0.010, *p < 0.050.

Table B-4. Results of the pairwise comparisons of marginal effects to determine differences in willingness to purchase lionfish based on an individual's previous experience eating lionfish.

Variable: Eat_lf	Contrast	Std. Error	Outcome
Yes vs. No	-0.2195***	0.0627	Not willing
Yes vs. No	-0.0575	0.0521	Somewhat willing
Yes vs. No	0.2769**	0.1120	Very willing

Statistical significance denoted as: *** p < 0.001, **p < 0.010, *p < 0.050.

Table B-5. Results of the pairwise comparisons of marginal effects to determine differences in willingness to purchase lionfish based on whether an individual felt that a lionfish fishery was good for the economy, the environment, both, or neither.

Variable: fish_good	Contrast	Std. Error	Outcome
2 vs 1	0.2281*	0.0969	Not willing
3 vs 1	0.0587	0.0892	Not willing
4 vs 1	0.0368	0.0717	Not willing
5 vs 1	-0.0330	0.0523	Not willing
3 vs 2	-0.1695	0.1218	Not willing
4 vs 2	-0.1914	0.1132	Not willing
5 vs 2	-0.2611**	0.1009	Not willing
4 vs 3	-0.0219	0.1049	Not willing
5 vs 3	-0.0917	0.0942	Not willing
5 vs 4	-0.0698	0.0771	Not willing
2 vs 1	-0.0778	0.0482	Somewhat willing
3 vs 1	-0.0106	0.0214	Somewhat willing
4 vs 1	-0.0057	0.0134	Somewhat willing
5 vs 1	0.0018	0.0032	Somewhat willing
3 vs 2	0.0672	0.0513	Somewhat willing
4 vs 2	0.0721	0.0497	Somewhat willing
5 vs 2	0.0796	0.0481	Somewhat willing
4 vs 3	0.0049	0.0244	Somewhat willing
5 vs 3	0.0124	0.0213	Somewhat willing
5 vs 4	0.0075	0.0131	Somewhat willing
2 vs 1	-0.1503**	0.0521	Very willing
3 vs 1	-0.0481	0.0684	Very willing
4 vs 1	-0.0311	0.0586	Very willing

5 vs 1	0.0312	0.0502	Very willing
3 vs 2	0.1023	0.0757	Very willing
4 vs 2	0.1192	0.0689	Very willing
5 vs 2	0.1815**	0.0603	Very willing
4 vs 3	0.0169	0.0807	Very willing
5 vs 3	0.0792	0.0754	Very willing
5 vs 4	0.0623	0.0662	Very willing

Responses included: a lionfish fishery would: be good for the economy and environment (1), not be good for either the environment or economy (2), be good for the economy only (3), would be good for the environment only (4), or I don't know enough to say (5). Statistical significance denoted as: *** $p < 0.001$, **$p < 0.010$, *$p < 0.050$.

Table B-6. Results of Pearson correlation analysis of independent variables that were investigated to identify differences among individual's that responded "undecided" in their willingness to purchase lionfish.

	sex	**eat_lf**	**age**	**race**	**polid2**	**supp_cont**	**con_econ**	**con_env**
sex	1							
eat_lf	0.1468	1						
age	0.278	-0.0883	1					
race	0.2929	0.1907	0.0447	1				
polid2	-0.0032	-0.1986	0.0684	0.1392	1			
supp_cont	0.1659	0.0669	0.1387	0.0128	-0.0271	1		
con_econ	-0.1566	-0.0392	-0.0774	-0.1488	0.1796	0.0799	1	
con_env	-0.027	0.1097	-0.1746	-0.15	0.2123	0.1354	0.8893*	1

Variables that show multicollinearity are indicated by an asterisk*.

APPENDIX C

Appendix C provides additional information that is associated with Section 5.

Table C-1. List of dive sites for the lionfish invitational trips each year at Flower Garden Banks National Marine Sanctuary.

Year	Bank	Buoy	Latitude	Longitude
2015	East Flower Garden	1	27°52’54.84”	93°37’41.84”
	East Flower Garden	4	27°57’31.68”	93°38’33.81”
	East Flower Garden	6	27°59’02.38”	93°35’32.29”
	West Flower Garden	1	27°49’11.14”	93°50’45.83”
	West Flower Garden	2	27°50’13.34”	93°52’11.04”
	West Flower Garden	3	27°51’13.81”	93°52’52.20”
	Stetson	2	28°10’10.20”	94°18’30.21”
2016	East Flower Garden	4	27°57’31.68”	93°38’33.81”
	East Flower Garden	6	27°59’02.38”	93°35’32.29”
	West Flower Garden	1	27°49’11.14”	93°50’45.83”
	West Flower Garden	2	27°50’13.34”	93°52’11.04”
	West Flower Garden	3	27°51’13.81”	93°52’52.20”
	Stetson	3	28°10’07.84”	94°17’25.68”
June 2018	East Flower Garden	1	27°52’54.84”	93°37’41.84”
	East Flower Garden	4	27°57’31.68”	93°38’33.81”
	West Flower Garden	1	27°49’11.14”	93°50’45.83”
	West Flower Garden	3	27°51’13.81”	93°52’52.20”
	Stetson	2	28°10’10.20”	94°18’30.21”
August 2018	East Flower Garden	1	27°52’54.84”	93°37’41.84”
	East Flower Garden	3	27°55’14.61”	93°38’40.89”
	East Flower Garden	4	27°57’31.68”	93°38’33.81”
	West Flower Garden	1	27°49’11.14”	93°50’45.83”
	West Flower Garden	2	27°50’13.34”	93°52’11.04”

	West Flower Garden	3	27°51’13.81”	93°52’52.20”
	Stetson	4	28°09’28.66”	94°17’25.68”

Coordinates for the buoyed sites are listed on the sanctuary’s website and are shown here for reference.

Lionfish survey protocol

1. Divers must complete all sections of the datasheet before survey begins. Header information includes:

- Diver: Full name of the diver completing the survey.
- Date: Date, in mm/dd/yyyy format, that the survey is conducted.
- Buddy: Full name of the divers buddy.
- Station ID: Predetermined unique identifier for the survey issued by PI. For the Lionfish study, this must include the bank, buoy, and survey direction, such as North line.
- Station Depth: The depth at the center of the survey, measured in feet. Surveyors can use dive computers or depth gauges to obtain this measurement.
- % Cloud Cover: Surveyors estimate cloud cover, such as 25%.
- Visibility: Horizontal distance that can been seen by the surveyor, measured in feet.
- Current: Surveyors circle “None,” “Moderate,” or “High” depending on the observed current at the center of the survey.
- Water Temp: Water temperature, measured in °F, recorded at the center of the survey. Surveyors can use dive computers to obtain this measurement.
- Start Time: The time at which the fish survey starts, in 24:00 format.
- End Time: The time at which the fish survey ends, in 24:00 format.

2. Once the dive team reels out their meter tape in the selected direction, staying within visual contact of one another, the lionfish survey diver begins the 50 m long x 20 m wide survey back along the 100 m line starting at the 75m mark. It should be noted on the second survey occurring on the next dive, surveys start at the 25m mark on the line.

    a. All lionfish falling within the survey area should be recorded – the diver may move off the centerline (10 m on either side of line) of the transect to observe and identify fish as long as they stay within the 20m transect width.

    b. The diver should take time to look under crevices and ledges to identify lionfish.

    c. Potential lionfish predators, including grouper, barracuda, eel, snapper, etc. should be identified.

    d. The survey should take approximately 20-30 minutes to complete.

    e. For each fish identified, note where on the transect they were seen, and how far from the line. For example, a lionfish may be recorded at the 50 m mark and 5 m from the line. You can also use the diagram at the bottom of the data sheet to note lionfish locations.

    f. The total length of each fish (both lionfish and predators) is estimated and whether the fish was exposed (EXP) or sheltered (SH) on the reef.

    g. Behavior notes are also made for resting (RST), hovering (HOV), swimming (SWIM), and hunting (HUNT).

    h. Sections for additional notes can be made in the NOTES section.

3. Surveys begin in the early morning (after 0700), and are repeated throughout the day until dusk.

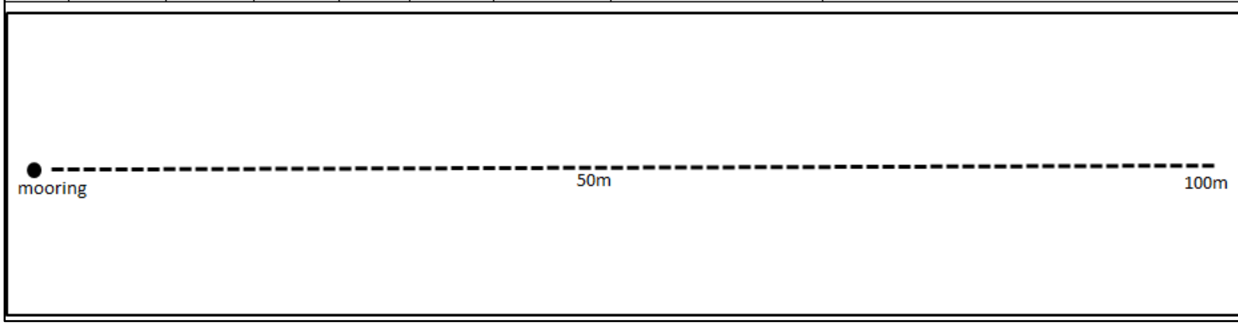
Science diver lionfish survey 50 m x 20 m datasheet

Name:__________________ **Date:**_______________ **Buddy:**______________ Bank:_____ _________ Buoy and Direction:__________

Depth: __________(ft) **% Cloud Cover:**_________ **Visibility:**__________(ft) **Current:** None / Mod (<1kt) / Heavy (>1kt)

Water temp: __________(F) **Start Time:**_____________ **End Time:**_____________

Fish #	Species	Transect Distance (m)	Distance from line (m)	TL (cm)	Habitat (Sand, Reef, Sponge, Seagrass)	Visibility	Behaviour notes	Notes
1						EXP / SH	RST HOV SWIM HUNT	
2						EXP / SH	RST HOV SWIM HUNT	
3						EXP / SH	RST HOV SWIM HUNT	
4						EXP / SH	RST HOV SWIM HUNT	
5						EXP / SH	RST HOV SWIM HUNT	
6						EXP / SH	RST HOV SWIM HUNT	
7						EXP / SH	RST HOV SWIM HUNT	
8						EXP / SH	RST HOV SWIM HUNT	
9						EXP / SH	RST HOV SWIM HUNT	
10						EXP / SH	RST HOV SWIM HUNT	
11						EXP / SH	RST HOV SWIM HUNT	
12						EXP / SH	RST HOV SWIM HUNT	
13						EXP / SH	RST HOV SWIM HUNT	
14						EXP / SH	RST HOV SWIM HUNT	
15						EXP / SH	RST HOV SWIM HUNT	
16						EXP / SH	RST HOV SWIM HUNT	
7						EXP / SH	RST HOV SWIM HUNT	
18						EXP / SH	RST HOV SWIM HUNT	



Datasheet used during the lionfish research cruises to Flower Garden Banks National Marine Sanctuary in 2015, 2016, and 2018.

Prey fish survey protocol

1. Divers must complete all sections of the datasheet before survey begins. Header information includes:

    - Station ID: Includes the bank and buoy.

- Diver: Full name of the diver completing the survey.
- Buddy: Full name of the divers buddy.
- Date: Date, in mm/dd/yyyy format, that the survey is conducted.
- Start Time: The time at which the fish survey starts, in 24:00 format.
- End Time: The time at which the fish survey ends, in 24:00 format.
- Station Depth: The depth at the center of the survey, measured in feet. Surveyors can use dive computers or depth gauges to obtain this measurement.
- Bearing: The compass direction of the line you are surveying, such as North line.
- Visibility: Horizontal distance that can been seen by the surveyor, measured in feet.
- Water Temp: Water temperature, measured in ^{o}F, recorded at the center of the survey. Surveyors can use dive computers to obtain this measurement.
- Current: Surveyors circle "None," "Mild," "Moderate," or "High" depending on the observed current at the center of the survey.
- Hard Substrate Relief Coverage: Divers survey the hard substrate relief that occurs within their study area, and record the percentage of each relief grouping observed. The sum of all relief groupings should be 100%. The maximum observed relief within the survey area is recorded, in meters.
- Aboitic Footprint: Within the survey area, divers should quantify the percentage each of the abiotic habitat type. Divers should view the reef with no biological components. Hardbottom represents all hard surfaces, including stony corals. Rubble represents coral and hardbottom rubble that can be easily picked up by divers.
- Comments: Any additional information of interesting observations can be recorded here.

4. Once the dive team reels out their meter tape in the selected direction, staying within visual contact of one another, the belt transect diver begins the 25 m long x 4 m wide survey back along the 100 m line starting at the 75m mark. It should be noted on the second survey occurring on the next dive, surveys start at the 25m mark on the line.

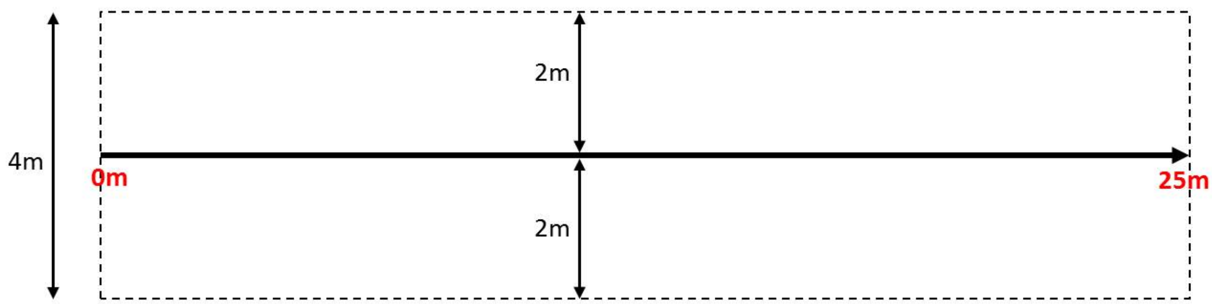
a. All fish falling within the survey area should be recorded – the diver may move off the centerline (2 m on either side of line) of the transect to observe and identify fish as long as they stay within the 4m transect width.

b. The diver may look forward, to the end of the transect, but does not look back along the area already covered.

c. The survey should take approximately 15 minutes to complete (roughly 8 m covered every 5 minutes).

d. The abundance (number of individuals per species) and fork length (within size bins) of each individual encountered on the survey is recorded. Size is binned into eight groups; 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm, 25-30 cm, 30-35 cm, and >35 cm, where each individuals size is recorded.

5. Surveys begin in the early morning (after 0700), and are repeated throughout the day until dusk.



Science diver prey fish survey 25 m x 4 m datasheet

Station ID:______________ Date:___________ Visibility:_______ft
Diver:__________________ Start Time:________ Water Temp:_______F
Buddy:__________________ End Time:________ Current:
Station Depth:_______ft None Mild
Bearing:________ Moderate High

Hard Substrate Relief Coverage	
<0.2m	%
0.2-0.5m	%
0.5-1.0m	%
1.0-1.5m	%
>1.5m	%
Max Relief	m

Abiotic Footprint	
SAND	%
HARD-B	%
RUBBLE	%
Total	100%

Comments

	Fish ID	<5	5-10	10-15	15-20	20-25	25-30	30-35	>35
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									

Datasheet used during the lionfish research cruises to Flower Garden Banks National Marine Sanctuary in 2015, 2016, and 2018.

Lionfish removal dive protocol

1. Divers must complete all sections of the datasheet before removal dive begins.

   Header information includes:

   - Team: Full name of the diver completing the survey and buddy.
   - Date: Date, in mm/dd/yyyy format, that the survey is conducted.

- Site: For the Lionfish study, this must include the bank, buoy, and survey direction, such as Northeast.
- Station Depth: The average depth measured in feet. Surveyors can use dive computers or depth gauges to obtain this measurement.
- % Cloud Cover: Surveyors estimate cloud cover, such as 25%.
- Visibility: Horizontal distance that can been seen by the surveyor, measured in feet.
- Current: Surveyors circle “None,” “Moderate,” or “High” depending on the observed current at the center of the survey.
- Water Temp: Water temperature, measured in ^{o}F, recorded at the center of the survey. Surveyors can use dive computers to obtain this measurement.
- Start Time: The time at which the fish survey starts, in 24:00 format.
- End Time: The time at which the fish survey ends, in 24:00 format.

2. Once the dive team enters the water, they swim to their selected quadrant, staying within visual contact of one another, to begin lionfish removals. One diver removes lionfish, while the other diver records information on lionfish seen, number of attempts for removal, and lionfish not removed.

    a. All lionfish observed and removed within the survey area should be recorded.

    b. The divers should take time to look under crevices and ledges to locate lionfish.

    c. The total length of each fish is estimated and whether the fish was exposed (EXP) or sheltered (SH) on the reef.

    d. Behavior notes are also made for resting (RST), hovering (HOV), swimming (SWIM), and hunting (HUNT).

    e. The time the lionfish was sighted is recorded.

f. The number of removal attempts is recorded and whether the lionfish was captured (Yes or NO).

g. The time the lionfish was captured is recorded, along with gear type (SPEAR).

h. Sections for additional notes can be made in the NOTES section.

6. Removals begin in the early morning (after 0700), and are repeated throughout the day until dusk.

Lionfish removal dive datasheet

Team:____________ Date:________ Site:________ Start Time:________

Depth: ________ (ft) % Cloud Cover:________ End Time:________

Water temp: ________(F) Current: None / Mod (<1kt) / Heavy (>1k Visibility:________(ft)

Lionfish #	Size TL (cm)	Visibility	Behaviour notes	Time sighted	Tally attempts	Capture (Y/N)	Time Captured/ Conceted	Gear type	Notes
1		EXP / SH	RST HOV SWIM HUNT						
2		EXP / SH	RST HOV SWIM HUNT						
3		EXP / SH	RST HOV SWIM HUNT						
4		EXP / SH	RST HOV SWIM HUNT						
5		EXP / SH	RST HOV SWIM HUNT						
6		EXP / SH	RST HOV SWIM HUNT						
7		EXP / SH	RST HOV SWIM HUNT						
8		EXP / SH	RST HOV SWIM HUNT						
9		EXP / SH	RST HOV SWIM HUNT						
10		EXP / SH	RST HOV SWIM HUNT						
11		EXP / SH	RST HOV SWIM HUNT						
12		EXP / SH	RST HOV SWIM HUNT						
13		EXP / SH	RST HOV SWIM HUNT						
14		EXP / SH	RST HOV SWIM HUNT						
15		EXP / SH	RST HOV SWIM HUNT						
16		EXP / SH	RST HOV SWIM HUNT						
17		EXP / SH	RST HOV SWIM HUNT						
18		EXP / SH	RST HOV SWIM HUNT						
19		EXP / SH	RST HOV SWIM HUNT						
20		EXP / SH	RST HOV SWIM HUNT						
21		EXP / SH	RST HOV SWIM HUNT						
22		EXP / SH	RST HOV SWIM HUNT						
23		EXP / SH	RST HOV SWIM HUNT						
24		EXP / SH	RST HOV SWIM HUNT						
25		EXP / SH	RST HOV SWIM HUNT						

Datasheet used during the lionfish research cruises to Flower Garden Banks National Marine Sanctuary in 2015, 2016, and 2018.

Table C-2. Available artificial structures off the Texas coast according to the Bureau of Ocean and Energy Management's (BOEM) oil and gas lease blocks in the western planning area.

Gas Block Area Code	Number of structures (n)
Alaminos Canyon	0
Brazos Area	9
Corpus Christi	0
East Breaks	3
Galveston Area	8
Garden Banks	5
High Island Area	74
Keathley Canyon	0
Matagorda Island	17
Mustang Island Area	4
Padre Island Area	0
Port Isabel	0
Sabine Pass Texas	1
West Cameron Area	75

Data were reduced to include only fixed structures that were still in place, had material reachable within recreational dive limits (40 m). Source: BOEM

Table C-3. Computations for lionfish densities using lionfish surveys and prey fish surveys.

Year	Bank	Lionfish survey density	Prey fish survey densities	Paired t-tests p-value
2015	East	13.3	58.3	0.402
	West	38.3	8.3	
	Stetson	30	75	
2016	East	30	50	0.05*
	West	33.3	45.5	
	Stetson	5	66.7	
Jul-2018	East	38.8	25	0.177
	West	30	12.5	
	Stetson	-	-	
Aug-2018	East	34.17	16.7	0.424
	West	50	41.7	
	Stetson	-	-	

Densities were compared between each transect method for each year using a paired t-test, of which the results are also included. The mean difference in computations of lionfish density was -8.67 (SD = 32.805, n = 10). All densities are reported in number of lionfish per hectare (LF ha^{-1}).

Table C-4. Surface area calculations and lionfish density estimates for artificial habitat off the Texas Gulf Coast in the northern Gulf of Mexico.

Organization	Structure Type	Latitude	Longitude	Surface Area	Abundance	Density
BOEM	FIXED	28.39665	-95.86191	0.553	13	23.5
BOEM	FIXED	27.83877	-96.02819	1.251	10	8.0
BOEM	FIXED	28.31464	-95.62058	0.683	5	7.3
BOEM	FIXED	27.83517	-96.01394	1.251	1	0.8
BOEM	FIXED	27.88217	-95.96551	1.167	32	27.4
BOEM	FIXED	27.83513	-96.01263	1.251	13	10.4
BOEM	FIXED	27.90278	-95.98764	1.167	3	2.6
BOEM	FIXED	27.85450	-96.03642	1.230	12	9.8
BOEM	FIXED	27.83514	-96.01306	1.251	21	16.8
BOEM	FIXED	27.81874	-94.32284	4.681	32	6.8
BOEM	FIXED	27.82740	-94.62602	4.999	8	1.6
BOEM	FIXED	27.83273	-94.55131	5.056	33	6.5
BOEM	FIXED	27.91656	-94.78619	2.078	22	10.6
BOEM	FIXED	29.00030	-94.76462	0.506	14	27.7
BOEM	FIXED	29.13028	-94.54657	0.491	31	63.2
BOEM	FIXED	29.12999	-94.54596	0.491	14	28.5
BOEM	FIXED	28.89360	-94.70425	0.543	4	7.4
BOEM	FIXED	29.13036	-94.54597	0.491	28	57.1
BOEM	FIXED	28.19410	-94.76399	1.110	26	23.4
BOEM	FIXED	28.16048	-94.73975	1.126	25	22.2
BOEM	FIXED	27.92260	-92.55400	3.005	34	11.3
BOEM	CT	27.73335	-91.99362	8.768	17	1.9
BOEM	FIXED	27.78785	-93.18794	3.942	2	0.5
BOEM	FIXED	27.84032	-91.98776	3.796	13	3.4
BOEM	FIXED	27.87553	-91.98640	3.859	36	9.3
BOEM	FIXED	28.26515	-94.07739	1.136	27	23.8
BOEM	FIXED	28.35598	-93.95511	1.136	2	1.8
BOEM	FIXED	28.40485	-93.94138	1.110	28	25.2
BOEM	FIXED	28.25510	-94.20883	1.089	18	16.5
BOEM	FIXED	28.29094	-94.08953	1.141	27	23.7
BOEM	FIXED	29.29857	-94.22407	0.397	32	80.6

BOEM	FIXED	29.51063	-94.01913	0.407	5	12.3
BOEM	FIXED	28.22846	-93.93706	1.178	18	15.3
BOEM	FIXED	29.23758	-94.42271	0.470	32	68.1
BOEM	FIXED	28.47115	-93.73930	0.970	28	28.9
BOEM	FIXED	28.47029	-93.73997	0.970	9	9.3
BOEM	FIXED	29.18171	-94.36986	0.454	6	13.2
BOEM	FIXED	29.31356	-94.21886	0.423	28	66.2
BOEM	FIXED	27.95564	-94.02712	1.662	36	21.7
BOEM	FIXED	29.19561	-94.03750	0.470	27	57.5
BOEM	FIXED	28.22774	-94.18563	1.126	33	29.3
BOEM	FIXED	28.47115	-93.73945	0.970	10	10.3
BOEM	FIXED	27.94862	-94.38900	1.891	33	17.5
BOEM	FIXED	27.88612	-93.98439	2.000	33	16.5
BOEM	FIXED	27.99581	-93.97641	1.584	28	17.7
BOEM	FIXED	28.09076	-93.74355	1.386	34	24.5
BOEM	FIXED	29.13540	-93.99898	0.496	26	52.4
BOEM	FIXED	27.90341	-93.95893	1.938	8	4.1
BOEM	FIXED	27.96197	-93.67089	1.896	31	16.3
BOEM	FIXED	29.23826	-94.42257	0.470	2	4.3
BOEM	FIXED	29.27174	-93.78466	0.444	32	72.1
BOEM	FIXED	27.95639	-94.02739	1.662	13	7.8
BOEM	FIXED	28.46944	-93.73932	0.970	29	29.9
BOEM	FIXED	29.23781	-94.42252	0.470	22	46.8
BOEM	FIXED	27.86669	-93.99111	2.245	12	5.3
BOEM	FIXED	29.51481	-94.03023	0.402	6	14.9
BOEM	FIXED	27.91319	-93.93510	1.985	30	15.1
BOEM	FIXED	28.04915	-94.43834	1.230	11	8.9
BOEM	FIXED	29.18052	-94.52121	0.470	8	17.0
BOEM	FIXED	27.92977	-93.80148	2.219	27	12.2
BOEM	FIXED	29.18423	-94.04834	0.470	26	55.3
BOEM	FIXED	29.27273	-94.24895	0.459	34	74.0
BOEM	FIXED	29.28406	-93.87256	0.454	25	55.0
BOEM	FIXED	28.09531	-93.86949	1.449	13	9.0
BOEM	FIXED	27.98545	-93.45840	2.011	27	13.4
BOEM	FIXED	27.92592	-93.94451	1.891	7	3.7
BOEM	FIXED	29.18160	-94.36982	0.454	12	26.4
BOEM	FIXED	27.95585	-93.83149	1.875	5	2.7
BOEM	FIXED	28.01487	-93.95569	1.506	24	15.9
BOEM	FIXED	27.97170	-93.51782	1.969	10	5.1

BOEM	FIXED	27.94633	-94.39757	1.891	33	17.5
BOEM	FIXED	27.96213	-93.64458	1.917	21	11.0
BOEM	FIXED	28.41133	-93.88792	1.334	4	3.0
BOEM	FIXED	28.04334	-93.49524	1.667	15	9.0
BOEM	FIXED	29.17523	-94.37101	0.459	0	0.0
BOEM	FIXED	28.08467	-94.44392	1.230	25	20.3
BOEM	FIXED	29.28126	-93.75547	0.444	13	29.3
BOEM	FIXED	27.86727	-93.99103	2.245	3	1.3
BOEM	FIXED	28.01370	-94.43766	1.355	5	3.7
BOEM	FIXED	28.22846	-93.93706	1.178	8	6.8
BOEM	FIXED	27.96405	-94.38891	1.776	12	6.8
BOEM	FIXED	29.19119	-94.35126	0.465	15	32.3
BOEM	FIXED	28.05827	-94.39707	1.230	1	0.8
BOEM	FIXED	27.91045	-93.95183	1.907	3	1.6
BOEM	FIXED	29.27174	-93.78466	0.444	0	0.0
BOEM	FIXED	27.91869	-93.80441	2.052	12	5.8
BOEM	FIXED	28.39027	-93.93341	1.084	0	0.0
BOEM	FIXED	28.09734	-93.50274	1.516	8	5.3
BOEM	FIXED	28.00138	-93.52504	1.823	32	17.6
BOEM	FIXED	28.00637	-94.10236	1.626	36	22.1
BOEM	FIXED	27.91023	-94.39644	2.479	1	0.4
BOEM	FIXED	29.23800	-94.42254	0.470	37	78.7
BOEM	FIXED	27.93360	-93.66939	1.964	33	16.8
BOEM	FIXED	28.04903	-94.43823	1.230	36	29.3
BOEM	FIXED	28.47116	-93.73961	0.970	9	9.3
BOEM	FIXED	28.35291	-94.09682	1.048	26	24.8
BOEM	FIXED	28.05664	-94.02298	1.412	18	12.7
BOEM	FIXED	29.32032	-93.95593	0.423	16	37.8
BOEM	FIXED	27.89310	-94.32367	2.672	22	8.2
BOEM	FIXED	28.04120	-96.58611	0.564	14	24.8
BOEM	FIXED	28.10144	-96.38139	0.642	25	39.0
BOEM	FIXED	28.10659	-96.42991	0.610	36	59.0
BOEM	FIXED	28.00251	-96.42956	0.673	25	37.2
BOEM	FIXED	28.11804	-96.39118	0.626	22	35.1
BOEM	FIXED	28.08984	-96.39167	0.631	29	45.9
BOEM	FIXED	28.10178	-96.38107	0.642	29	45.2
BOEM	FIXED	28.10284	-96.38142	0.642	24	37.4
BOEM	FIXED	28.04208	-96.60497	0.564	4	7.1
BOEM	FIXED	28.04095	-96.46465	0.631	25	39.6

BOEM	FIXED	28.37878	-96.08429	0.548	32	58.4
BOEM	FIXED	28.06624	-96.57158	0.548	20	36.5
BOEM	FIXED	28.07444	-96.49307	0.590	31	52.6
BOEM	FIXED	28.10239	-96.38130	0.642	35	54.5
BOEM	FIXED	28.08949	-96.39846	0.652	6	9.2
BOEM	FIXED	28.10214	-96.36987	0.636	20	31.4
BOEM	FIXED	28.10625	-96.43024	0.610	20	32.8
BOEM	FIXED	27.72705	-96.19106	1.542	29	18.8
BOEM	FIXED	27.63830	-96.23476	1.771	5	2.8
BOEM	FIXED	27.80938	-96.78077	0.626	10	16.0
BOEM	FIXED	27.80937	-96.78026	0.626	16	25.6
BOEM	FIXED	29.52713	-93.81864	0.423	5	11.8
BOEM	FIXED	29.55750	-93.23298	0.413	12	29.1
BOEM	FIXED	29.40710	-93.40497	0.413	17	41.2
BOEM	FIXED	29.60715	-93.21587	0.387	19	49.2
BOEM	FIXED	29.59281	-93.14872	0.387	2	5.2
BOEM	FIXED	28.47675	-93.07164	0.959	3	3.1
BOEM	FIXED	29.34491	-93.63433	0.413	25	60.6
BOEM	FIXED	29.44121	-93.42790	0.397	3	7.6
BOEM	FIXED	29.69338	-93.58144	0.298	5	16.8
BOEM	FIXED	29.24334	-93.17832	0.501	32	63.9
BOEM	FIXED	29.59281	-93.14872	0.387	9	23.3
BOEM	FIXED	28.92406	-93.15464	0.558	2	3.6
BOEM	FIXED	29.68573	-93.73019	0.293	14	47.8
BOEM	FIXED	28.92073	-93.03165	0.314	28	89.3
BOEM	FIXED	29.41863	-93.40796	0.397	28	70.5
BOEM	FIXED	29.42280	-93.16509	0.423	17	40.2
BOEM	FIXED	29.55970	-93.42438	0.407	15	36.8
BOEM	FIXED	29.38769	-93.44152	0.428	11	25.7
BOEM	FIXED	29.38768	-93.44231	0.428	25	58.4
BOEM	FIXED	29.51904	-93.28400	0.397	26	65.5
BOEM	FIXED	29.68602	-93.72924	0.293	21	71.7
BOEM	FIXED	29.62755	-93.17242	0.371	7	18.9
BOEM	FIXED	29.62776	-93.17214	0.371	4	10.8
BOEM	FIXED	29.38766	-93.44314	0.428	22	51.4
BOEM	FIXED	29.55721	-93.47186	0.397	23	57.9
BOEM	FIXED	29.49652	-93.28120	0.402	23	57.2
BOEM	FIXED	28.34908	-93.50171	1.136	37	32.6
BOEM	FIXED	28.43271	-93.00474	1.032	28	27.1

BOEM	FIXED	29.56188	-93.12626	0.392	6	15.3
BOEM	FIXED	29.64630	-93.14204	0.350	23	65.7
BOEM	FIXED	29.51829	-93.28436	0.397	21	52.9
BOEM	FIXED	28.43268	-93.00522	1.032	14	13.6
BOEM	FIXED	29.32959	-93.59601	0.423	11	26.0
BOEM	FIXED	29.51829	-93.28404	0.397	0	0.0
BOEM	FIXED	28.94391	-93.14059	0.590	25	42.4
BOEM	FIXED	29.39627	-93.25159	0.418	16	38.3
BOEM	FIXED	29.62145	-93.38259	0.376	35	93.1
BOEM	FIXED	27.94556	-93.20170	2.245	3	1.3
BOEM	FIXED	29.61688	-93.15095	0.376	33	87.7
BOEM	FIXED	29.62733	-93.30322	0.376	22	58.5
BOEM	FIXED	29.39627	-93.25130	0.418	15	35.9
BOEM	FIXED	29.55916	-93.14566	0.407	25	61.4
BOEM	FIXED	29.62448	-93.75062	0.371	16	43.1
BOEM	FIXED	27.83959	-93.32175	2.708	28	10.3
BOEM	FIXED	28.45388	-93.47170	1.016	27	26.6
BOEM	FIXED	29.59244	-93.14864	0.387	31	80.2
BOEM	FIXED	28.43170	-93.00571	1.032	29	28.1
BOEM	FIXED	29.30568	-93.02510	0.496	7	14.1
BOEM	FIXED	29.42008	-93.34948	0.381	14	36.7
BOEM	FIXED	29.63257	-93.03831	0.371	9	24.3
BOEM	FIXED	29.55939	-93.14570	0.407	13	31.9
BOEM	FIXED	29.62748	-93.30288	0.376	29	77.1
BOEM	FIXED	29.67815	-93.71669	0.324	28	86.4
BOEM	FIXED	28.48120	-93.07549	0.959	9	9.4
BOEM	FIXED	27.97179	-93.20366	2.073	6	2.9
BOEM	FIXED	28.25849	-93.37104	1.188	34	28.6
BOEM	FIXED	29.39628	-93.25099	0.418	12	28.7
BOEM	FIXED	28.46727	-93.05357	0.980	33	33.7
BOEM	FIXED	29.68610	-93.72904	0.293	3	10.2
BOEM	FIXED	28.45314	-93.47145	1.016	23	22.6
BOEM	FIXED	29.70257	-93.54003	0.324	30	92.6
BOEM	FIXED	29.60035	-93.15226	0.407	33	81.0
BOEM	FIXED	29.66001	-93.10217	0.355	1	2.8
BOEM	FIXED	29.59281	-93.14872	0.387	7	18.1
BOEM	FIXED	29.24270	-93.17852	0.501	21	41.9
BOEM	FIXED	29.65205	-93.12185	0.350	15	42.8
BOEM	FIXED	29.65965	-93.66733	0.355	23	64.7

BOEM	FIXED	29.62110	-93.38250	0.376	6	16.0
BOEM	FIXED	29.69358	-93.59751	0.334	13	38.9
BOEM	FIXED	29.67495	-93.76041	0.298	5	16.8
BOEM	FIXED	29.65248	-93.56901	0.366	0	0.0
BOEM	FIXED	29.67291	-93.03821	0.345	10	29.0
BOEM	FIXED	29.68298	-93.74736	0.319	24	75.3
BOEM	FIXED	29.55898	-93.14586	0.407	34	83.5
BOEM	FIXED	29.68532	-93.72954	0.293	30	102.4
BOEM	FIXED	29.64890	-93.13122	0.350	34	97.1
TPWD	OG	27.82312	-95.98980	0.787	5	6.4
TPWD	OG	28.12707	-95.71546	0.610	1	1.6
TPWD	OG	28.15001	-95.49496	0.527	2	3.8
TPWD	OG	28.89213	-94.69576	0.293	32	109.3
TPWD	OG	28.86805	-94.69875	0.293	13	44.4
TPWD	OG	28.25173	-94.72285	0.610	3	4.9
TPWD	VS	28.79301	-95.34779	0.779	25	32.1
TPWD	OG	28.42767	-93.81562	0.600	3	5.0
TPWD	OG	28.43949	-93.71694	0.579	5	8.6
TPWD	OG	28.36416	-93.78532	0.709	12	16.9
TPWD	OG	28.35600	-93.85523	0.709	21	29.6
TPWD	OG	28.33017	-93.79772	0.746	32	42.9
TPWD	OG	28.30343	-93.76647	0.746	6	8.0
TPWD	OG	28.24200	-93.87875	0.850	8	9.4
TPWD	OG	28.24165	-93.52013	0.850	33	38.8
TPWD	OG	28.18962	-93.58775	0.860	22	25.6
TPWD	OG	28.21413	-93.69899	0.860	14	16.3
TPWD	OG	28.21533	-93.79961	0.876	31	35.4
TPWD	OG	28.16678	-93.76926	0.944	14	14.8
TPWD	OG	28.13487	-93.56647	0.928	4	4.3
TPWD	OG	28.09784	-93.47735	1.126	28	24.9
TPWD	OG	28.09515	-93.86512	1.069	26	24.3
TPWD	OG	28.06929	-93.47088	1.193	25	20.9
TPWD	OG	28.04033	-93.70768	1.334	34	25.5
TPWD	OG	28.04508	-93.76379	1.089	17	15.6
TPWD	VS	28.44400	-94.28504	0.732	44	60.1
TPWD	OG	28.36391	-94.15640	0.595	1	1.7
TPWD	OG	28.29614	-94.24363	0.673	2	3.0
TPWD	OG	28.31182	-94.01944	0.699	13	18.6
TPWD	OG	28.27388	-94.32827	0.600	36	60.0

TPWD	OG	28.28705	-94.47865	0.553	27	48.8
TPWD	OG	28.24814	-94.27213	0.631	2	3.2
TPWD	OG	28.22813	-94.05962	0.761	28	36.8
TPWD	OG	28.17833	-94.03421	0.892	1	1.1
TPWD	OG	28.12970	-94.21416	0.798	6	7.5
TPWD	OG	28.15097	-94.09280	0.845	18	21.3
TPWD	OG	28.12471	-93.95655	0.985	27	27.4
TPWD	OG	28.10020	-94.51309	0.746	1	1.3
TPWD	OG	28.04785	-94.15235	0.944	32	33.9
TPWD	OG	28.01332	-94.35408	1.542	10	6.5
TPWD	OG	27.97550	-94.21764	1.245	5	4.0
TPWD	OG	27.95040	-94.04677	1.152	18	15.6
TPWD	OG	27.94577	-93.99890	1.266	32	25.3
TPWD	OG	27.88731	-93.98301	1.516	28	18.5
TPWD	VS	28.11635	-96.08739	1.557	23	14.8
TPWD	OG	28.23216	-96.38522	0.376	9	23.9
TPWD	OG	27.89458	-96.42968	0.595	6	10.1
TPWD	OG	27.85550	-96.19074	0.777	28	36.0
TPWD	OG	29.14290	-94.68057	0.241	36	149.5
TPWD	OG	27.43199	-96.52372	1.167	27	23.1
TPWD	OG	27.71161	-96.18250	1.173	33	28.1
TPWD	OG	27.44885	-96.76310	0.605	10	16.5
TPWD	OG	26.86614	-97.05119	0.397	33	83.1
TPWD	OG	26.93557	-96.75103	1.058	33	31.2
TPWD	OG	26.87281	-96.77221	0.996	28	28.1
TPWD	VS	26.18915	-96.85922	0.974	15	15.4

Surface area calculations for BOEM oil and gas platforms located in the Western Planning Area, and TPWD artificial reefs sites, off the Texas coast. BOEM platforms were restricted to those that were fixed in place and had material that was within recreational dive limits (40 m). Structure codes are provided for the structure types: FIXED – fixed leg platform, CT – compliant tower, OG – Oil and gas, VS – vessel, as well as the organization which manages the structure. The surface area for each of the structures was computed following methods in section 4.3.6 where each vessel had a specific length and width (https://www.wrecksite.eu/), while oil and gas platforms were assumed to be homogeneous in composition. The width (w_1) and length (a) of the top portion of the platform was assumed to be 15.2 m x 42.7 m, whereas the width (w_2) and length (b) of the bottom portion was assumed to be 29 m x 42.7 m (El-Din and Kim, 2014). The height needed to derive total surface area was assumed to be equivalent to the water depth (m).