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Lessons From the Western Atlantic Lionfish Invasion to Inform Management in the Mediterranean

Aylin Ulman[1†], Fadilah Z. Ali[2†], Holden E. Harris[3†], Mohammad Adel[4], Sara A. A. Al Mabruk[5], Michel Bariche[6], Allison C. Candelmo[7], Jennifer K. Chapman[8], Burak Ali Çiçek[9,10], Kaylin R. Clements[11], Alexander Q. Fogg[12], Stacy Frank[13,14], Stephen R. Gittings[15], Stephanie J. Green[16], Jason M. Hall-Spencer[17,18], Jim Hart[13,14], Summer Huber[7], Philip E. Karp[19], Fabian C. Kyne[8], Demetris Kletou[20,21], Lauryn Magno[7], Shevy B. S. Rothman[22], Jennifer N. Solomon[11], Nir Stern[23] and Taner Yildiz[24]*

[1] Mersea Marine Consulting, Fethiye, Turkey, [2] Gulf and Caribbean Fisheries Institute, Marathon, FL, United States, [3] Nature Coast Biological Station, Institute of Food and Agriculture Sciences, University of Florida, Gainesville/Cedar Key, FL, United States, [4] Unaffiliated, Alexandria, Egypt, [5] Department of General Nursing Technology, Higher Institute of Science and Technology, Cyrene, Libya, [6] Biology Department, American University in Beirut, Beirut, Lebanon, [7] Reef Environmental Education Foundation (REEF), Key Largo, FL, United States, [8] Blue Ventures, Corozal, Belize, [9] Department of Biological Sciences, Faculty of Arts and Sciences, Eastern Mediterranean University, Famagusta, Cyprus, [10] Underwater Research and Imaging Center, Eastern Mediterranean University, Famagusta, Cyprus, [11] Department of Human Dimensions of Natural Resources, Colorado State University, Fort Collins, CO, United States, [12] Okaloosa County Board of County Commissioners, Destin - Fort Walton Beach, FL, United States, [13] Lionfish University, New York, NY, United States, [14] Lionfish University, Asheville, NC, United States, [15] National Oceanic & Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD, United States, [16] Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada, [17] Department of Biological and Marine Sciences, University of Plymouth, Plymouth, United Kingdom, [18] University of Tsukuba, Shizuoka, Japan, [19] Unaffiliated, Scottsdale, AZ, United States, [20] Marine & Environmental Research (MER) Lab, Limassol, Cyprus, [21] Frederick University, Limassol, Cyprus, [22] Steinhardt Museum of Natural History, Tel Aviv University, Tel Aviv, Israel, [23] National Institute of Oceanography, Israel Oceanographic and Limnological Research, Haifa, Israel, [24] Faculty of Aquatic Sciences, Istanbul University, Istanbul, Turkey

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Edited by:
Thanos Dailianis,
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***Correspondence:**
Aylin Ulman
uaylin@hotmail.com

[†]These authors share first authorship

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Major invasions of Indo-Pacific lionfish (*Pterois volitans* and *P. miles*) are underway in the Western Atlantic Ocean and the Mediterranean Sea. While the establishment of lionfish in the Western Atlantic is perhaps the most well-studied marine fish invasion to date, the rapidly expanding invasion in the Mediterranean is more recent and has received less attention. Here we review and synthesize successes and failures from two decades of lionfish management in the Western Atlantic to give policy recommendations for their management in the Mediterranean. Two failed approaches that were attempted multiple times in the Western Atlantic and that we advise against are (1) feeding lionfish to native fish to promote predation and (2) implementing bounty programs to incentivize lionfish harvest. Broadly, the most important management lessons that we recommend include (1) conducting routine removals by spearfishing with scuba, which can effectively suppress local abundances of lionfish; (2) encouraging the development of recreational and commercial lionfish fisheries, which can promote long-term, sustainable lionfish population control; and, (3) engaging local communities and resource users (e.g., with lionfish removal tournaments), which can concurrently achieve multiple objectives of promoting lionfish removals, market-development, research, and public education.

Managers in the Western Atlantic often needed to adapt current conservation policies to enable lionfish removals in areas where spearfishing with scuba was otherwise prohibited for conservation purposes. The risk of abusing these policies was mitigated through the use of gear restrictions, diver trainings, and through participatory approaches that integrated scuba divers and stakeholder organizations in lionfish research and management. Our review of policies and practices in the Mediterranean Sea found that many of our recommended lionfish management approaches are not being done and indicate potential opportunities to implement these. We expect and fully recommend that work continues towards multinational cooperation to facilitate regional coordination of research, control, and management efforts with respect to the Mediterranean lionfish invasion. As with other major biological invasions, lionfish are unconstrained by political borders and their control will require rapid and strategic management approaches with broad cooperation among and between governments and stakeholders.

Keywords: fisheries management, invasive species, marine policy, Mediterranean sea, *Pterois sp*

INTRODUCTION

Indo-Pacific lionfish (collectively *Pterois volitans* (Linnaeus, 1758) and the visually indistinguishable *Pterois miles* (Bennett, 1828) represent some of the most successful marine fish invasions on record (Albins and Hixon, 2008; Savva et al., 2020). Their expansion, establishment, and densities have been facilitated by their broad diet (Dahl and Patterson, 2014; Peake et al., 2018), foraging techniques novel to naïve prey (Albins and Lyons, 2012; Akins et al., 2014; Green et al., 2019), a relative lack of biotic resistance to their establishment (Valdivia et al., 2014); and an opportunistic life history strategy (Fogg et al., 2017). Lionfish are also defended against predators by venomous spines and have few natural predators (Ulman et al., 2021), and natural control of lionfish appears limited due to resistance to parasites (Sikkel et al., 2014; Fogg et al., 2016; Tuttle et al., 2017; but see Harris et al., 2018; Harris et al., 2020a). Within their invaded range, lionfish have reached densities up to ten times that of their native range and this has caused demonstrable negative impacts on native species and ecological processes (Côté and Smith, 2018; Savva et al., 2020). They remain a key concern for marine conservation and management (Morris et al., 2012; Sutherland et al., 2017).

Two lionfish invasions are currently underway. In the Western Atlantic, lionfish (*P. volitans* and *P. miles*) were likely introduced *via* aquarium releases in SE Florida and were first detected in 1985 (Morris and Akins, 2009), and their range expansion began in the early 2000s (Schofield, 2009). Populations are now established throughout the Gulf of Mexico, Caribbean Sea, and southeastern seaboard of the United States of America (**Figure 1A**). Their year-round northern range reaches North Carolina, and their southern range is actively expanding along the South American seaboard (Kimball et al., 2004; Luiz et al., 2021). Given the species' thermal tolerances, continued southward expansion is expected along the coast of Brazil (Kimball et al., 2004; Biggs, 2009; Luiz et al., 2021). The first recorded lionfish in the Eastern Mediterranean Sea was in 1991, but their initial establishment in the region in 2012 was in Lebanese waters (Bariche et al., 2013). Their introduction into the Eastern Mediterranean was *via* the Suez Canal (Bariche et al., 2017), which accounts for over half of over 600 established non-native species in the Mediterranean (Galil et al., 2018; see also Galil et al., 2015; Samaha et al., 2016; Mavruk et al., 2017; Stern et al., 2019; Zenetos and Galanidi, 2020). In the last decade, the range of lionfish has expanded to the Central Mediterranean and is progressing towards the Western Mediterranean region (**Figure 1B**) (Kletou et al., 2016; Azzurro et al., 2017; Ulman et al., 2020; Ulman et al., 2021; Dragičević et al., 2021).

This study aims to help inform lionfish management in regions where the species recently invaded or are expected to invade. Given the longer invasion, much of the current biological and ecological knowledge of lionfish comes from research in the Western Atlantic (Fishelson, 1975; Darling et al., 2011; Cure et al., 2012; Kulbicki et al., 2012; Pusack et al., 2016; Savva et al., 2020; Watkins et al., 2021). We synthesize key lessons learned from the Western Atlantic for the management approaches that were successful—or failed—to help control lionfish. The information we collected about existing policies and adaptive management in the Western Atlantic and Mediterranean are provided in full *via* our companion data repository published online (Candelmo et al., 2022). While our synthesis and recommendations were developed with the objective of guiding marine invasive species management in the Mediterranean Sea, we expect that these can also be applied to the expanding range of lionfish in South America.

LESSONS FROM THE WESTERN ATLANTIC

Unsuccessful Approaches

Training Native Fish to Become Lionfish Predators

In the early phases of the lionfish invasion, well-intentioned divers attempted to train native predators to prey on lionfish by

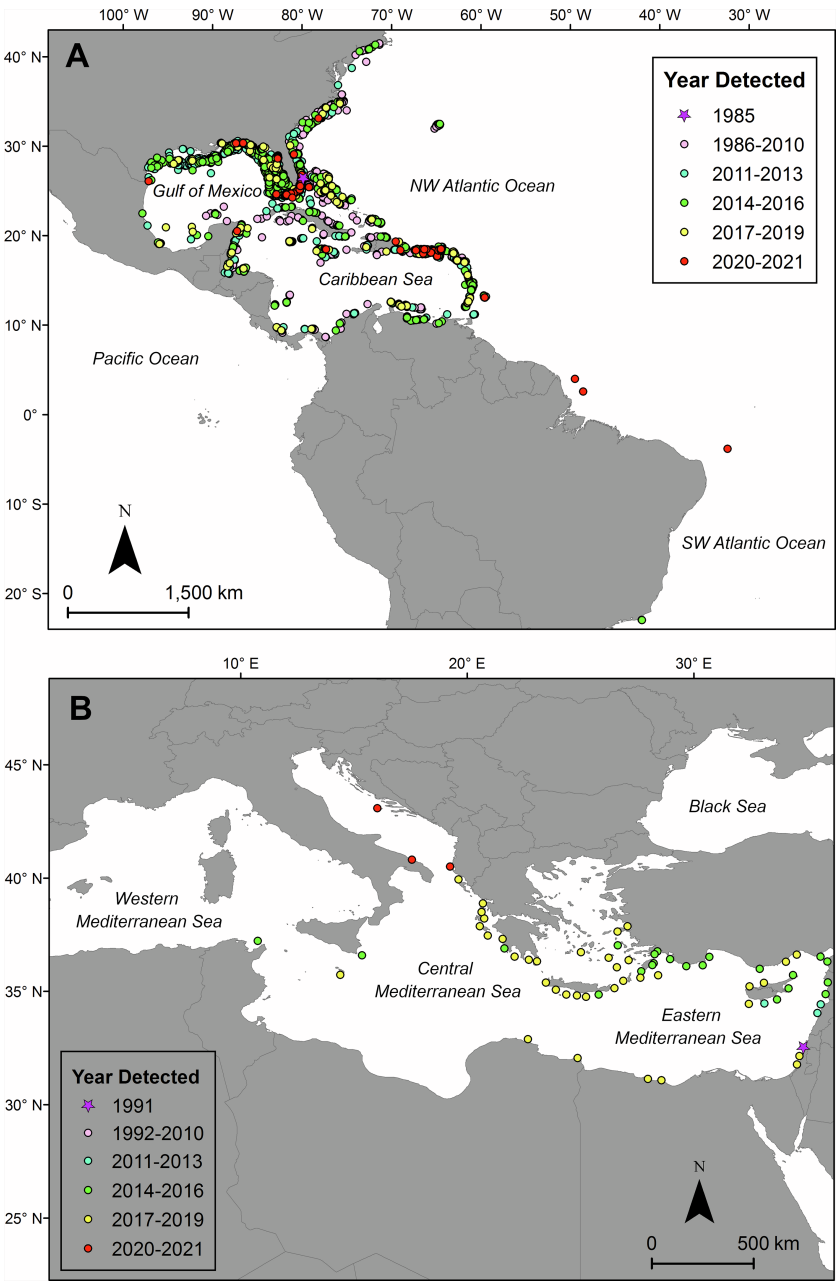

FIGURE 1 | Recorded sightings and chronology documenting the expansion of non-native lionfish (*Pterois volitans* and *P. miles*) in the **(A)** Western Atlantic Ocean and **(B)** Mediterranean Sea to 2021.

feeding them speared fish (Kilgo, 2014). For example, there are accounts of resident Nassau groupers that learned to lead divers to lionfish, stopping and turning when they reached one (pers. Obs., S. Gittings). Although there were instances of many native fish willingly ingesting speared lionfish, there is little evidence that native fish have become independent predators on lionfish as a result of this training. Moreover, dangerous interactions with marine predators increased due to this feeding practice. For example, nurse sharks (*Ginglymostoma cirratum*), Caribbean reef sharks (*Carcharhinus perezi*), bull sharks (*Carcharhinus leucas*) and moray eels (*Gymnothorax funebris*) began to associate divers with food (pers. Obs., authors). These predators will follow divers closely and even attempt to take them from containment devices (pers. Obs., A. Fogg). Lionfish removal activities were halted in Saba due to dive staff being attacked by a shark while spearing lionfish (Carballo-Cárdenas and Tobi, 2016). The issue has led some authorities to restrict lionfish removals to trained personnel (Candelmo et al., 2022). In

some places, divers now dedicate one to watch for and repel aggressive sharks or eels, while the other diver or divers search for and remove lionfish. The degree to which this problem occurs varies from place to place, but presenting lionfish to native fish in an attempt to promote predator control has made lionfish removal efforts more dangerous and difficult. We advise that all culled lionfish be contained and removed.

Bounty Programs to Motivate Lionfish Hunters

Bounty programs incentivize lionfish removal by paying individuals for each lionfish collected. The government of Belize initially offered $25 BZD per lionfish. However, the program exhausted its funds in less than six months (Chapman et al., 2016). A $5 USD bounty per lionfish was similarly tried early in the invasion of the northern Gulf of Mexico by the state of Mississippi, but funds for this program were also rapidly depleted. Additionally bounty programs may also fail to engender stewardship ethics that would promote sustained harvest (Akins, 2012). With the current recognition that lionfish cannot be eradicated due to refuge and metapopulation dynamics (Johnston and Purkis, 2014; Johnston and Purkis, 2015; Andradi-Brown, 2019), we advise the use of economically self-sustaining control measures (discussed below).

Successful Approaches

Organized Removals Can Control Lionfish Densities

Since lionfish eradication is not possible, functional eradication can mitigate their impacts on invaded fish communities and the fisheries they support (Bogdanoff et al., 2021; Green and Grosholz, 2021). Human removals are currently considered the most effective means of controlling densities and impacts (Morris et al., 2011; Chapman et al., 2019). These removals are accomplished primarily *via* spearfishing with short pole spears on scuba (Frazer et al., 2012; de León et al., 2013; Côté et al., 2014; Dahl et al., 2016; Malpica-Cruz et al., 2016; Green et al., 2017; Côté and Smith, 2018; Harms-Tuohy et al., 2018; Harris et al., 2019; Kleitou et al., 2021a). Most jurisdictions within the Western Atlantic invaded range allow for removal of lionfish, either as a general policy or by special permission (Candelmo et al., 2022). Many jurisdictions allow for lionfish removal *via* spearfishing within MPAs (ibid). For example, in Honduras, Roatan Marine Park distributes pole spears and provides training specifically for removing lionfish (Peiffer et al., 2017). The dive sites where these removals took place resulted in lower lionfish densities compared to non-removal sites (ibid). Culling frequency is an important factor in minimizing negative ecological effects from the invasion (Dahl et al., 2016). Implementing control programs early in the invasion is also recommended (Côté et al., 2014). In Bonaire, a spearfishing removal program led by volunteers was immediately initiated after the first lionfish sighting in 2009 (Ali et al., 2013) and a similar program began on Curaçao two years later (de León et al., 2013). More than a decade later, lionfish densities within recreational dive limits at marked dive sites in Bonaire have remained low relative to similar areas elsewhere (pers. Obs., F. Ali).

Even dive destinations visited less frequently (e.g., due to remoteness, lack of dive infrastructure, access restrictions, or seasonally unfavorable weather) can benefit from organized removal efforts. At the Flower Gardens Banks National Marine Sanctuary, 160 km offshore in the northwest Gulf of Mexico, culling events have been organized since 2015 by specifically licensed dive operators. These "lionfish invitationals" have only been able to be conducted once or twice per year; however, the events remove hundreds of lionfish within the sanctuary. Evaluation of these removal efforts by Davis et al. (2021) showed that the efficiency of removals can be maximized by using experienced lionfish hunters and when removals take place during dawn and dusk (due to higher foraging rates of lionfish and detection by divers during these crepuscular periods). The densities of lionfish in the sanctuary have remained low compared to Western Atlantic reefs, although additional removal effort may be needed to reverse upward trends in lionfish abundances (M. Johnston, pers. Comm.).

Lionfish Tournaments Offer Concurrent Benefits

Lionfish tournament events (also called "derbies," "roundups," and "rodeos") coordinate concentrated organized removals. Tournaments consist of planned, competitive removal events, whereby divers compete to remove lionfish within a set time period. The top prize is typically awarded to the dive team that harvests the most lionfish during the tournament. There are usually categories for the largest and smallest lionfish as well, which may be won by less experienced spearfishers and encourage novices to participate in the competition. Based on our review, derbies have been organized in at least 25 Western Atlantic jurisdictions (Candelmo et al., 2022). Tournaments conducted in The Bahamas and Florida Keys showed reduced lionfish densities by >50% in an approximately 200 km^2 (Green et al., 2017). The largest tournament to date is the annual Emerald Coast Open tournament held in Destin, Florida. In 2019, 189 scuba divers competed for over $70,000 in prizes and removed over 14,000 lionfish in just two days.

Importantly, lionfish tournaments can concurrently achieve multiple objectives beyond the removals to help support research, education, and conservation awareness (Anderson et al., 2017). Researchers use these mass removal events to collect data on population structure, life history, and diet (e.g., Fogg et al., 2017). Indexes of abundance can be assessed by examining participants' catch-per-unit-effort (Harris et al., 2020b). To do so, tournament organizers need to collect data on fishing effort (e.g., number of divers and dives, total dive time) as well as harvester catches. Tournaments also attract out-of-town participants who contribute to the local economy. Trotta (2014) found that 47% of their participants were not residents of the community where the tournament was held. The tournaments and their associated public events (e.g., lionfish tastings, chef cook-offs, festivals) can help raise awareness and provide education about lionfish, as shown in Florida (Trotta, 2014) and Belize (Chapman et al., 2019). Priority public outreach messaging about lionfish consists of communicating that lionfish are (1) non-native, (2) environmentally destructive, and (3) safe and desirable to eat. Finally tournaments can serve as a platform for marine and environmental conservation education about other priority issues, such as invasive species more generally, overfishing, marine litter, and climate change.

Sustaining organized lionfish removal events year after year can be challenging. In some cases, historic, high profile annual events

have been discontinued (e.g. Guy Harvey Lionfish Safari, NE Florida Lionfish Blast). This can be the result of lack of interest, dilution of participation due to excessive frequency (e.g., weekly), loss of financial support, and difficulties with planning around unpredictable weather. In the state of Florida, the Florida Fish and Wildlife Conservation Commission (FWC) has provided financial and logistical support for tournaments since 2014 (FWC, 2018). The number of lionfish tournaments in the state peaked in 2015 with 40 FWC-supported events in 2015 (ibid). This has gradually declined to only eight in 2021. Part of the decline may be attributed to the consolidation of tournaments into less frequent but larger events. For example, the aforementioned Emerald Coast Event, which offers considerable prizes as well as novel events and additional ways to participate beyond the two-day event that are less dependent on favorable weather conditions.

Community and Stakeholders Should Be Engaged to Facilitate Lionfish Management

Stakeholder participation involves the inclusion of diverse resource user groups in the management and planning process. For lionfish management, this has included volunteers, citizen scientists, fishers, seafood wholesalers and retailers, chefs, students and local citizens. Stakeholder participation in lionfish research has been particularly effective for facilitating monitoring and control efforts for collecting specimens, reporting observations, and the dissemination of information (Clements et al., 2021). For example, in Bonaire, culled lionfish were used to study their invasion ecology, and partnerships were formed between the management agency (Stichting Nationale Parken Bonaire), a research facility (CIEE Research Station, Bonaire), dive operators, and volunteer divers (Ali, 2017). Stakeholder engagement can range from the use of informal partnerships, such as allowing or promoting culling and derbies, to formal strategic planning. Belize's 2019-2023 National Lionfish Management Strategy used a formal planning process built on the concept of coupled human and natural systems (Chapman et al., 2019) to develop recommendations for lionfish management. Social and ecological indicators were assessed and reviewed during community meetings, and monitoring these indicators enables adaptive management (Allen and Garmestani, 2015). To mitigate potential risks of noncompliance and poaching, Belize's Lionfish Working Group also implemented specialized training programs for tourist divers (Chapman et al., 2019). Additionally, local divers and diving organizations enable consistent monitoring and removal efforts. For example, the Caribbean Oceanic Restoration and Education (CORE) Foundation in the U.S. Virgin Islands helped to develop the territory's Caribbean Lionfish Response Program and has conducted regular (generally weekly) lionfish removals since 2009.

Opportunities Exist to Develop Commercial Lionfish Fisheries

Commercial lionfish fisheries offer a potential market-based solution to control densities (Morris et al., 2012; Noll and Davis, 2020), improve food security, and diversify fisher catches and livelihoods (Chapman et al., 2016). These removals may be of greatest value in regions where governments have not pursued control efforts (Graham and Fanning, 2017). Lionfish meat is considered high-quality (Morris et al., 2011; Blakeway et al., 2019; Noll and Davis, 2020), and annual commercial spearfishing landings of lionfish for food in the U.S. northern Gulf of Mexico have been as high as 20,000 kg (Harris et al., 2020a). Current ex-vessel prices of lionfish in the United States are approximately $10–$14 USD per kg, which compares to high-end reef fish prices (Simnitt et al., 2020). Prices in Belize and the Cayman Islands are also similar to high-end reef fish. In these areas, prices have increased over time, mostly due to public awareness campaigns, which communicated that lionfish are a safe-to-eat, tasty, and an environmentally-friendly seafood product (Morris et al., 2011; Chapman et al., 2016; Blakeway et al., 2019).

Lionfish byproducts, e.g., leather from lionfish skin or jewelry made from lionfish fins and spines (Karp et al., 2015; Mulgrew, 2020), could increase their dock-side price and incentivize their harvest. For example, a lionfish jewelry women's group supported income generation, social wellbeing, and skill acquisition among women in Belize's artisanal fishing communities (Karp et al., 2015; Guerrero, 2020). Live captured lionfish can be sold in the aquarium industry and some jurisdictions have implemented moratoriums on the import of live lionfish to encourage local harvest and to reduce the introduction of new genetic material (e.g., Florida, USA). Innovative harvest technologies may also offer opportunities to maximize fisheries resources (Harris et al., 2021). Lionfish have been observed as deep as 300 m (Gress et al., 2017) and experimental harvest gear such as lionfish traps could enable commercial harvest of these populations when their catch efficiencies make them economically viable (Harris et al., 2020b).

There are also reasonable concerns for developing markets for an invasive species,. First, short-term economic dependence could result from a burgeoning lionfish harvest (Nuñez et al., 2012; Pasko & Goldberg, 2014). For spearfishing lionfish, however, their harvest may simply augment current fishing activity. Levels of removal are comparatively small, but so is the capital investment in harvest gear (i.e., short pole spears and a lionfish container), making continued harvest pressure likely. Strong communication between managers and fishers is recommended to prevent overcapitalization and ensure that objectives are shared (i.e., mitigating lionfish impacts and improving fisheries resources). Although harvest control rules (e.g., bag limits, size limits, or seasons) are clearly not recommended for lionfish given the goal to reduce their impacts, an ideal fishery would achieve an "optimum lionfish yield," with quantitative targets that allow managers to adapt policy strategies to achieve functional control of lionfish without losing the supplemental economic and socio-ecological benefits of harvesting them (Chagaris et al., 2017; Chagaris et al., 2020; Bogdanoff et al., 2021; Green and Grosholz, 2021).

Policy Support for Management

Policy Adaptation Enables Effective Lionfish Management

Lionfish management plans have been developed throughout the Western Atlantic region across a variety of scales (Graham and Fanning, 2017). In the U.S., for example, response specific plans exist

for national parks (McCreedy et al., 2012) and national marine sanctuaries (Johnston et al., 2015), in addition to the overall U.S. National Plan (Invasive Lionfish Control Ad-hoc Committee of the Aquatic Nuisance Species Task Force, 2014). Forecasting potential undesirable consequences is essential to effective policy development (Levin et al., 2012). In the case of permitting spearing while using scuba in areas, policymakers must consider non-compliance with resource regulations and the opportunistic take of protected species (Solomon et al., 2015). Policy changes to allow scuba divers to spear lionfish with special permits have been adopted in Bermuda, Cayman Islands, the Turks and Caicos Islands, Saba, St. Eustatius, St. Lucia, Aruba and Bonaire, as well as Cyprus, Israel and the Egyptian Mediterranean (Candelmo et al., 2022).

Invasive Species Policy and Management Should Be Regionally Coordinated

The vast and connected nature of oceans makes managing marine biological invasions exceptionally challenging (Simberloff, 2000; Bax et al., 2001; Thresher and Kuris, 2004). Regional strategies should include measures to detect, monitor, and control populations (Mehta et al., 2007; Burgiel, 2014). The 24th General Meeting of the International Coral Reef Initiative (ICRI) created an *Ad Hoc* Committee to develop a strategic plan for the control of lionfish (Gómez Lozano et al., 2013). The resulting Regional Lionfish Management Strategy served as the framework for governments and other stakeholders to use when creating their national lionfish management plans (Gómez Lozano et al., 2013). The objectives were to: (1) facilitate collaboration between stakeholders for coordinated efforts across political and geographic boundaries; (2) encourage coordinated research and monitoring; (3) encourage governments to review and amend relevant legislation and, if necessary, develop new regulations and policies to control lionfish; (4) control invasive lionfish populations where possible, and; (5) provide education and outreach mechanisms to generate public support and foster stewardship in invasive lionfish programs (Morris et al., 2012; Gómez Lozano et al., 2013). Similarly, the Florida FWC sponsored a "Lionfish Summit" in 2013 as well as a follow-up summit five years later in 2018. The goals of these summits were to: (1) assess the efficacy of current research, management, control, and outreach efforts; (2) prioritize areas for future lionfish control, and; (3) improve collaborations amongst multiple agencies and geographic locations (FWC, 2018). The results of these summits were used by the agency to help to address regulatory barriers for lionfish fisheries; inform resource allocations by the state of Florida for research, education and outreach; and direct future research and technology development (e.g., lionfish-specific traps and other novel gear types).

CURRENT EASTERN MEDITERRANEAN LIONFISH MANAGEMENT

Some areas have begun limited management efforts to control lionfish. For example, in Turkey permission has so far been provided to allow single-day scuba removal events. In Israel, a permit was issued as a pilot study to a single diving center for culling lionfish with scuba diving and pole spears. In the Egyptian Mediterranean, 70 scuba divers were issued spearfishing permits. Overall, however, targeted control efforts in the Mediterranean remain limited. Currently, national and European laws prohibit spearfishing with scuba in much of the Eastern Mediterranean. Although such regulations were developed for conservation purposes, they also inhibit removals of invasive species including lionfish. Lionfish removals by scuba divers are currently prohibited in Greece, Turkey, Lebanon, Tunisia, Algeria, and Israel (Candelmo et al., 2022).

Cyprus has initiated official policy changes for lionfish management and is the only locality currently undertaking substantial targeted removal efforts (Candelmo et al., 2022). On its northern coasts, permits to spear lionfish were granted in 2017 from regional authorities to conduct a pilot program allowing scuba divers to spear lionfish under co-management of the Underwater Research and Imaging Center and Deep Dive Diving Center. Culling has occurred at least once a week, changes in lionfish abundance are being monitored, and the program has removed over 35,000 lionfish between June 2018 and August 2021 (Çiçek, unpubl. Data). In 2017, authorities also permitted a hunters federation to organize lionfish derbies for freedivers and scuba divers and over 3,800 lionfish were removed from the four tournaments to date. Additionally, a recently proposed by-law to authorize individuals and other dive operators to apply for permits to harvest lionfish with scuba is awaiting parliamentary approval. On the southern coasts of Cyprus, governmental authorities issued a permit in 2018 to the RELIONMED EU LIFE project to train scuba divers to remove lionfish for the purposes of research and control. The permit allows project researchers and 100 members of "Removal Action Teams" to remove lionfish with scuba and pole spears. These divers were trained on hunting and handling safety and first aid for stings, taught the ecology and history of the lionfish invasion, and received lionfish spearfishing equipment—including pole spears, containment units, puncture-resistant gloves, and heat packs to treat stings. The removal events were supervised and monitored by scientists, and have provided data for assessing the efficiency of controlling lionfish in Cyprus (Kleitou et al., 2019; Kleitou et al., 2021a; Kleitou et al., 2021b). To date, over 5,500 lionfish have been removed in about 40 targeted removal events hosted by RELIONMED, including eight tournaments.

SYNTHESIS OF MANAGEMENT RECOMMENDATIONS

Biological invasions are notoriously difficult to manage. Critical examination of current management may be needed following an unprecedented event like a biological invasion (Kleitou et al., 2021b); however, delayed management response can result in protracted ecological and economic impacts the invasion (Hewitt et al., 2009; Kleitou et al., 2021c). With invasive

lionfish in the Mediterranean, for example, policy examination required three years before new policies were implemented in Israel (Stern and Rothman, 2019a; Stern and Rothman, 2019b). The situation is complicated by the fact that nations like Israel and Egypt border two seas—the Mediterranean where lionfish are invasive and the Red Sea where lionfish and other *Pterois* species are native protected species that cannot be fished or traded. Lessons from Western Atlantic indicate lionfish abundances increase rapidly following detection and can reach peak levels two years (Linardich et al., 2021), highlighting the need for rapid action.

This review synthesizes lessons from several decades of lionfish management in the Western Atlantic to provide actionable, policy-relevant management recommendations. Broadly, our review suggests that invasive lionfish managers should support sustained lionfish removals with participatory approaches and cooperative management. Crucially, these strategies require strong communication between government managers, stakeholder organizations, and individuals. To facilitate this, we summarize our recommendations with an illustrated infographic (**Figure 2**). Illustrative examples of these lessons and key considerations for these recommendations are provided in **Table 1**.

Policy Changes to Permit Lionfish Removal

Policy makers are better able to manage the impacts of lionfish *via* evidence-based decisions and coordinated responses. Given limited resources, it is important to identify and/or prioritize removal efforts spatially and temporally. These may include highly visited tourist areas, marine protected areas, and nursery and spawning aggregation sites for commercially and ecologically important fishes that are impacted by lionfish (Akins, 2012; Linardich et al., 2021).

Effective adaptive management must consider the unintended consequences of policy changes (Levin et al., 2012). In the case of permitting lionfish removals with the use of scuba and spear gear, policymakers must balance the potential for non-compliance and the take of protected species (Solomon et al., 2015). In the Mediterranean, groupers are largely overfished and thus there is reasonable apprehension for permitting spearfishing using scuba. At the same time, lionfish primarily consume native taxa (D'Agostino et al., 2020) and compete with native Mediterranean groupers, so providing lionfish control would likely benefit the groupers and ecosystem health. This issue of potential non-compliance was similarly faced by Western Atlantic states that enacted policies permitting lionfish removals with scuba in areas where spearfishing on scuba was otherwise prohibited. The risk of abuse was mitigated by (1) gear restrictions that mandated use of short pole spears (e.g., less than 1 m in length), which are largely ineffective in harvesting most other fishes, and (2) pursuing a participatory approach by working with scuba divers, local stakeholders and organizations. These participatory management approaches for lionfish removals, monitoring, and research appear to have largely resulted in cumulative positive social, economic, and ecological effects (Reed, 2008; Clements et al., 2021). In the Mediterranean, lionfish management in Cyprus [e.g., The Underwater Research and Imaging Center (URIC) and RELIONMED projects] has demonstrated similar successes for awareness programs, control, monitoring and data collection (Kleitou et al., 2019; Kleitou et al., 2021a).

Support for Commercial and Recreational Lionfish Fisheries to Sustain Removal

Opportunities exist to develop commercial and recreational lionfish fisheries throughout their invaded ranges (Simnitt et al., 2020). Commercial lionfish fisheries can help diversify fishing livelihoods and control lionfish populations (Chapman et al., 2019; Bogdanoff et al., 2021). The development of these fisheries will require a high enough ex-vessel price to incentivize commercial fishing effort. Innovation for lionfish by-products (e.g., extraction of fish oils, collagen, jewelry, leather, etc.) and harvest gear offers additional means to add value to their market price, which further support economic harvest. The development of recreational lionfish fisheries has been largely successful. To promote these, managers can leverage social incentives (which may vary based on culture) including recognition and camaraderie with other divers; competition between fishers; inspiring marine conservation; consumption of lionfish; and, where appropriate, incentives and awards for competitive removal tournaments. Indeed, many dedicated lionfish harvesters are not motivated by profit, but rather by conservation concerns, enjoyment of the activity, and finding purpose in their hobby (Frey and Jegen, 2002).

Participatory and Regional Coordination to Align and Evaluate Removal Efforts

Regional collaboration to address the Mediterranean lionfish invasion should include synthesis of research and action plans among the marine managers working on the issue. These efforts can be assisted with organized summits (in person, online, or hybrid) for lionfish researchers and managers to share experiences, set and prioritize research and management objectives (FWC, 2018), and develop regional management plans (Anderson et al., 2017; Graham & Fanning, 2017; FWC, 2018). Scientific workshops are also beginning to emerge in the Mediterranean. For example, Turkey's UNDP MARIAS Project organized an East-West lionfish knowledge exchange workshop in late 2020, Cyprus's RELIONMED Project hosted a lionfish workshop in early 2022, and a joint pufferfish-lionfish international conference is planned in Turkey in May 2022. Such workshops provide opportunities to communicate and collaborate on research initiatives, and strengthen regional ties which can benefit future regional management directives. We see opportunities for continuing and expanding regional management coordination in the Mediterranean Sea. For example, the General Fisheries Commission for the Mediterranean (GFCM) can make binding recommendations and enforce compliance in its 23 contracting parties from the Mediterranean, EU, and Black Sea. In the most recent Eastern Mediterranean Working group meeting (May 2021), the GFCM

FIGURE 2 | Infographic summary of recommended and failed approaches for invasive lionfish management.

determined that lionfish will be listed as a priority invasive species to study. Also in 2021, a regional online GFCM repository was developed to help coordinate fisheries and aquaculture legislation in the Mediterranean and facilitate access to the multi-lingual data for fishers, policy makers, researchers, and the general public. Such work provides the foundation for multi-national coordination in fisheries and invasive species management.

TABLE 1 | A summary of recommended actions for lionfish control in the Mediterranean Sea using examples and key considerations from management in the Western Atlantic Ocean.

Recommended action		Illustrative example(s)	Key considerations that were managed
Do	Allow harvest *via* scuba and pole spears	Culling managed by stakeholder groups.	Potential for noncompliance and abuse mitigated by gear use restrictions and working with stakeholder groups
Do	Recreational tournaments	Emerald Coast Open Lionfish tournament has removed 10-20k lionfish per year	Resources are needed to conduct event
Do	Lionfish hunting tourism	Florida Keys; Bahamas; Belize; Lionfish tournaments	Novice divers need training
Do	Participatory management	Belize Lionfish Working Group; REEF tournaments and surveys; Cyprus Underwater Research and Imaging Centre; Cyprus RELIONMED	Managers and scientists must communicate and work with stakeholders and organizations
Do	Commercial fishery removals	Markets for lionfish in Belize and Florida, jewelry small businesses in Belize, Aruba.	Price must be high enough to incentivize harvest; Overfishing will decrease catch efficiencies; Potential for economic dependencies
Do	Coordinate regional management	GCFI lionfish working group efforts; GFCM fisheries management	Logistical complexities and possible tensions across geopolitical boundaries
Don't	Rely on "bounty" programs	Belize; Mississippi (USA)	Insufficient resources inhibit long-term solution; Better return on public investment can be achieved through developing self-sustaining incentives and programs
Don't	"Train" native predators	Sharks and moray eels in the U.S. Virgin Islands	Increases aggressive behavior towards divers

AUTHOR CONTRIBUTIONS

AU and HH contributed to the conception and design of the study. AU, FA, HH, SRG, and AF led the writing of the manuscript. AF prepared the map figure. All authors participated in the contribution of data, the drafting and revising of the manuscript, the final article revisions and approved the submitted version.

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REFERENCES

Akins, J. L. (2012). "Control Strategies: Tools and Techniques for Local Control," in *Invasive Lionfish: A Guide to Control and Management. Gulf Caribb. Fish. Inst*. Ed. J. A. Morris Jr. (Marathon, Florida: Special Publication), 24 – 47.

Akins, J. L., Morris, J. A., and Green, S. J. (2014). *In Situ* Tagging Technique for Fishes Provides Insight Into Growth and Movement of Invasive Lionfish. *Ecol. Evol.* 4, 3768–3777. doi: 10.1002/ece3.1171

Albins, M. A., and Hixon, M. A. (2008). Invasive Indo-Pacific Lionfish *Pterois volitans* and *Pterois miles* Reduce Recruitment of Atlantic Coral-Reef Fishes. *Mar. Ecol. Prog. Ser.* 367, 233–238. doi: 10.3354/meps07620

Albins, M. A., and Lyons, P. J. (2012). Invasive Red Lionfish *Pterois volitans* Blow Directed Jets of Water at Prey Fish. *Mar. Ecol. Prog. Ser.* 448, 1–5. doi: 10.3354/meps09580

Ali, F. Z. (2017). *The Ecological and Socio-Economic Impacts of the Lionfish Invasion in the Southern Caribbean. Dissertation* (Southampton, United Kingdom: University of Southampton).

Ali, F. Z., Collins, K., and Peachey, R. (2013). The Role of Volunteer Divers in Lionfish Research and Control in the Caribbean. *In Joint Int. Sci. Diving S.*, 7.

Allen, C., and Garmestani, A. (2015). "Adaptive Management," in *Adaptive Management of Social-Ecological Systems*. Eds. C. Allen and A. Garmestani (Dordrecht: Springer). doi: 10.1007/978-94-017-9682-8_1

Anderson, L., Chapman, J., Escontrela, D., and Gough, C. (2017). The Role of Conservation Volunteers in the Detection, Monitoring and Management of Invasive Alien Lionfish. *Manage. Biol. Invasions* 8, 589–598. doi: 10.3391/mbi.2017.8.4.14

Andradi-Brown, D. A. (2019). "Invasive Lionfish (*Pterois volitans* and *P. Miles*): Distribution, Impact, and Management,". *Mesophotic Coral Ecosystems. Springer Cham* 12, 931–941. doi: 10.1007/978-3-319-92735-0_48

Azzurro, E., Stancanelli, B., Di Martino, V., and Bariche, M. (2017). Range Expansion of the Common Lionfish *Pterois miles* (Bennett 1828) in the Mediterranean Sea: An Unwanted New Guest for Italian Waters. *BioInvasions Rec.* 6 (2), 95–98. doi: 10.3391/bir.2017.6.2.01

Bariche, M., Kleitou, P., Kalogirou, S., and Bernardi, G. (2017). Genetics Reveal the Identity and Origin of the Lionfish Invasion in the Mediterranean Sea. *Sci. Rep.* 7 (1), 6782. doi: 10.1038/s41598-017-07326-1.

Bariche, M., Torres, M., and Azzurro, E. (2013). The Presence of the Invasive Lionfish *Pterois miles* in the Mediterranean Sea. *Med. Mar. Sci.* 14 (2), 292–294. doi: 10.12681/mms.428.

Bax, N., Carlton, J., Mathews, A., Haedrich, R., Howarth, F., Purcell, J., et al (2001). The Control of Biological Invasions in the World's Oceans. *Cons. Biol.* 15, 1234 – 1246. doi: 10.1111/j.1523-1739.2001.99487.x

Biggs, C. (2009). "Invasion Of The Western Atlantic And Caribbean Oceans," in *Ebook. 1st Ed. Fish 423-Invasion Ecology*. Available at: http://

depts.washington.edu/oldenlab/wordpress/wp-content/uploads/2013/03/Pterois- volitans_Biggs.pdf.

Blakeway, R., Jones, G., and Boekhoudt, B. (2019). Controlling Lionfishes (*Pterois* Spp) With Consumption: Survey Data From Aruba Demonstrate Acceptance of Non-Native Lionfishes on the Menu and in Seafood Markets. *Fish. Manage. Ecol.* 27, 227-230. doi: 10.1111/fme.12404

Bogdanoff, A. K., Shertzer, K. W., Layman, C. A., Chapman, J. K., Fruitema, M. L., Solomon, J., et al. (2021). Optimum Lionfish Yield: A Non-Traditional Management Concept for Invasive Lionfish (*Pterois* Spp.) Fisheries. *Biol. Invasions* 23 (3), 1–16. doi: 10.1007/s10530-020-02398-z

Burgiel, S. W. (2014). From Global to Local: Integrating Policy Frameworks for the Prevention and Management of Invasive Species. *: Invasive Species Globalized World. Ecological Social Legal Perspect. Policy. Univ. Press Scholarship- Chicago Scholarship*, 283. doi: 10.7208/chicago/9780226166216.003.0013

Candelmo, A. C., Ulman, A., Ali, F. A., Gittings, S. R., Huber, S. R., Magno, L. E., et al. (2022). Information on Marine Management Policies for Invasive Lionfish in the Western Atlantic Ocean and Mediterranean Sea. *Dryad Data Repository*. doi: 10.5061/dryad.z08kprrf7

Carballo-Cárdenas, E. C., and Tobi, H. (2016). Citizen Science Regarding Invasive Lionfish in Dutch Caribbean MPAs: Drivers and Barriers to Participation. *Ocean Coast. Manage.* 133, 114–127. doi: 10.1016/j.ocecoaman.2016.09.014

Chagaris, D., Binion-Rock, S., Bogdanoff, A., Dahl, K., Granneman, J., Harris, H. E., et al. (2017). An Ecosystem-Based Approach to Evaluating Impacts and Management of Invasive Lionfish. *Fisheries* 42, 421–431. doi: 10.1080/03632415.2017.1340273

Chagaris, D. D., Patterson, W. F. I., and Allen, M. S. (2020). Relative Effects of Multiple Stressors on Reef Food Webs in the Northern Gulf of Mexico Revealed *via* Ecosystem Modeling. *Front. Mar. Sci.* 7. doi: 10.3389/FMARS.2020.00513

Chapman, J. K., Anderson, L., Fruitema, M. L., Solomon, J., Green, S., Bogdanoff, A., et al. (2019). "Belize National Lionfish Management Strategy 2019-2023," in *Blue Ventures Conservation*, (London, UK: Blue Ventures Conservation, London), 102.

Chapman, J. K., Anderson, L. G., Gough, C. L., and Harris, A. R. (2016). Working Up an Appetite for Lionfish: A Market-Based Approach to Manage the Invasion of *Pterois volitans* in Belize. *Mar. Pol.* 73, 256–262. doi: 10.1016/j.marpol.2016.07.023

Clements, K. R., Karp, P., Harris, H. E., Ali, F., Candelmo, A., Rodríguez, S. J., et al. (2021). The Role of Citizen Science in the Research and Management of Invasive Lionfish Across the Western Atlantic. *Diversity* 13, 673. doi: 10.3390/d13120673

Côté, I. M., Akins, L., Underwood, E., Curtis-Quick, J., and Green, S. J. (2014). Setting the Record Straight on Invasive Lionfish Control: Culling Works. *PeerJ PrePrints* 2, e398v1. doi: 10.7287/peerj.preprints.398v1

Côté, I. M., and Smith, N. S. (2018). The Lionfish *Pterois* Sp. Invasion: Has the Worst-Case Scenario Come to Pass? *J. Fish Biol.* 92, 660–689. doi: 10.1111/jfb.13544

Cure, K., Benkwitt, C. E., Kindinger, T. L., Pickering, E. A., Pusack, T. J., McIlwan, J. L., et al. (2012). Comparative Behavior of Red Lionfish *Pterois volitans* on Native Pacific Versus Invaded Atlantic Coral Reefs. *Mar. Ecol. Prog. Ser.* 467, 181–192. doi: 10.3354/meps09942

D'Agostino, D., Jimenez, C., Reader, T., Hadjioannou, L., Heyworth, S., Aplikioti, M., et al. (2020). Behavioural Traits and Feeding Ecology of Mediterranean Lionfish and Naiveté of Native Species to Lionfish Predation. *Mar. Ecol. Prog. Ser.* 638, 123–135. doi: 10.3354/meps13256

Dahl, K. A., and Patterson, W. F. (2014). Habitat-Specific Density and Diet of Rapidly Expanding Invasive Red Lionfish, *Pterois volitans*, Populations in the Northern Gulf of Mexico. *PloS One* 9, e105852. doi: 10.1371/journal.pone.0105852

Dahl, K. A., Patterson, W. F.III, and Snyder, R. A. (2016). Experimental Assessment of Lionfish Removals to Mitigate Reef Fish Community Shifts on Northern Gulf of Mexico Artificial Reefs. *Mar. Ecol. Prog. Ser.* 558, 207–221. doi: 10.3354/meps11898

Darling, E., Green, S., O'Leary, J., and Côté, I. (2011). Indo-Pacific Lionfish are Larger and More Abundant on Invaded Reefs: A Comparison of Kenyan and Bahamian Lionfish Populations. *Biol. Invasions* 13, 2045–2051. doi: 10.1007/s10530-011-0020-0

Davis, A. C. D., Akins, L., Pollock, C., Lundgren, I., Johnston, M. A., Castillo, B., et al. (2021). Multiple Drivers of Invasive Lionfish Culling Efficiency in Marine Protected Areas. *Cons. Sci. Practce* 3(11), e541. doi: 10.1111/csp2.541

de León, R., Vane, K., Bertuol, P., and Chamberland, V. C. (2013). Effectiveness of Lionfish Removal Efforts in the Southern Caribbean. *Endanger. Species Res.* 22, 175–182. doi: 10.3354/esr00542

Dragičević, B., Ugarković, P., Krželj, M., Zurub, D., and Dulčić, J. (2021). New Record of *Pterois* Cf. *miles* (Actinopterygii: Scorpaeniformes: Scorpaenidae) From the Eastern Middle Adriatic Sea (Croatian Waters): Northward Expansion. *Acta Ichthyol. Pisca.* 51 (4), 379–383. 10.3897/aiep.51.75811

Fishelson, L. (1975). Ethology and Reproduction of Pteroid Fishes Found in the Gulf of Aqaba (Red Sea), Especially *Dendrochirus brachypterus* (Cuvier), (Pteroidae, Teleostei). *Publ Stat. Zool Napoli* 39, 635–656.

Florida Fish and Wildlife Conservation Commission (2018) *2018 Lionfish Summit Workshop Report*. Available at: https://content.govdelivery.com/accounts/FLFFWCC/bulletins/2567671.

Fogg, A. Q., Brown-Peterson, N. J., and Peterson, M. S. (2017). Reproductive Life History Characteristics of Invasive Red Lionfish (*Pterois volitans*) in the Northern Gulf of Mexico. *Bull. Mar. Sci.* 93, 791–813. doi: 10.5343/bms.2016.1095

Fogg, A. Q., Ruiz, C. F., Curran, S. S., and Bullard, S. A. (2016). Parasites From the Red Lionfish, *Pterois volitans* From the Gulf of Mexico. *Gulf Caribb. Res.* 27, 1–5. doi: 10.18785/gcr.2701.07

Frazer, T. K., Jacoby, C. A., Edwards, M. A., Barry, S. C., and Manfrino, C. M. (2012). Coping With the Lionfish Invasion: Can Targeted Removals Yield Beneficial Effects? *Rev. Fish. Sci.* 20 (4), 185–191. doi: 10.1080/10641262.2012.700655

Frey, B. S., and Jegen, R. (2002). Motivation Crowding Theory. *J. Econ. Surv.* 15 (5), 589–611. doi: 10.1111/1467-6419.00150

Galil, B. S., Boero, F., Campbell, M. L., Carlton, J. T., Cook, E., Fraschetti, S., et al. (2015). 'Double Trouble': The Expansion of the Suez Canal and Marine Bioinvasions in the Mediterranean Sea. *Biol. Inv.* 17, 973–976. doi: 10.1007/s10530-014-0778-y

Galil, B. S., Marchini, A., and Occhipinti-Ambrogi, A. (2018). "Mare Nostrum, Mare Quod Invaditur—The History of Bioinvasions in the Mediterranean Sea," in *Histories of Bioinvasions in the Mediterranean*. Eds. A. Queiroz and S. Pooley (Cham: Springer), 21–49. doi: 10.1007/978-3-319-74986-0_2

Gómez Lozano, R., Anderson, L., Akins, J. L., Buddo, D. S. A, García-Moliner, G., Gourdin, F., et al. (2013). Regional Strategy for the Control of Invasive Lionfish in the Wider Caribbean. *International Coral Reef Initiative* 1, 31.

Graham, R. E., and Fanning, L. M. (2017). A Comparison of Eight Country Plans for the Invasive Indo-Pacific Lionfish in the Wider Caribbean. *Glob. Ecol. Cons.* 12, 253–262. doi: 10.1016/j.gecco.2017.12.001

Green, S. J., Dilley, E. R., Benkwitt, C. E., Davis, A. C. D., Ingeman, K. E., Kindinger, T. L., et al. (2019). Trait-Mediated Foraging Drives Patterns of Selective Predation by Native and Invasive Coral-Reef Fishes. *Ecosphere* 10 (6), e02752. doi: 10.1002/ecs2.2752

Green, S. J., and Grosholz, E. D. (2021). Functional Eradication as a Framework for Invasive Species Control. *Front. Ecol. Environ.* 19, 98–107. doi: 10.1002/fee.2277

Green, S. J., Underwood, E. B., and Akins, J. L. (2017). Mobilizing Volunteers to Sustain Local Suppression of a Global Marine Invasion. *Cons. Lett.* 10 (6), 726–735. doi: 10.1111/conl.12426

Gress, E., Andradi-Brown, D. A., Woodall, L., Schofield, P. J., Stanley, K., and Rogers, A. D. (2017). Lionfish (*Pterois* spp.) Invade the Upper-Bathyal Zone in the Western Atlantic. *PeerJ* 5, e3683. doi: 10.7717/peerj.3683

Guerrero, C. (2020). *'Belioness: Factors Influencing the Performance of a Community-Based Social Enterprise Established by a Non-Governmental Organization'* (Canterbury: MSc thesis. University of Kent).

Harms-Tuohy, C. A., Appeldoorn, R. S., and Craig, M. T. (2018). The Effectiveness of Small-Scale Lionfish Removals as a Management Strategy: Effort, Impacts and the Response of Native Prey and Piscivores. *Manage. Biol. Inv.* 9(2), 149–162. doi: 10.3391/mbi.2018.9.2.08

Harris, H. E., Fogg, A. Q., Allen, M. S., Ahrens, R. N. M., and Patterson, W. F. (2020a). Precipitous Declines in Northern Gulf of Mexico Invasive Lionfish Populations Following the Emergence of an Ulcerative Skin Disease. *Sci. Rep.* 10, 1–17. doi: 10.1038/s41598-020-58886-8

Harris, H. E., Fogg, A. Q., Gittings, S. R., Ahrens, R. N. M., Allen, M. S., and Patterson, III W.F. (2020b). Testing the Efficacy of Lionfish Traps in the Northern Gulf of Mexico. *PloS One* 15 (8), e0230985. doi: 10.1371/journal.pone.0230985

Harris, H. E., Fogg, A. Q., Yanong, R. P. E., Frasca, S., Cody, T., Waltzek, T. B., et al. (2018). "First Report of an Emerging Ulcerative Skin Disease in Invasive Lionfish. UF/IFAS Ext," in *Electron. Data Inf. Source*. Gainesville, Florida: University of Florida, vol. FA209, 1–7. Available at: http://edis.ifas.ufl.edu/fa209.

Harris, H. E., Patterson, W. F.III, Ahrens, R. N. M., and Allen, M. S. (2019). Detection and Removal Efficiency of Invasive Lionfish in the Northern Gulf of Mexico. *Fish. Res.* 213, 22–32. doi: 10.1016/j.fishres.2019.01.002

Harris, H. E., Whalen, B. K., Gude, A. G., and Allen, M. S. (2021). Testing a Bite-Shortened Hook to Minimize Fish Handling in a Recreational Fishery. *Fisheries* 46 (7), 1–8. doi: 10.1002/fsh.10608

Hewitt, C. L., Everett, R. A., and Parker, N. (2009). "Examples of Current International, Regional and National Regulatory Frameworks for Preventing and Managing Marine Bioinvasions," in *Biological Invasions in Marine Ecosystems*. Eds. G. Rilov and G. A. Crooks (Heidelberg: Springer), 335–352. doi: 10.1007/978-3-540-79236-9_19

Invasive Lionfish Control Ad-hoc Committee of the Aquatic Nuisance Species Task Force (2014) *National Invasive Lionfish Prevention and Management Plan*. Available at: https://www.fws.gov/anstaskforce/Meetings/2014_May/NILPMP_5_2014_Final_Draft.pdf.

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

Johnston, M. W., and Purkis, S. J. (2014). Are Lionfish Set for a Mediterranean Invasion? Modelling Explains Why This Is Unlikely to Occur. *Mar. Pollut. Bull.* 88 (1-2), 138–147. doi: 10.1016/j.marpolbul.2014.09.013

Johnston, M., and Purkis, S. J. (2015). A Coordinated and Sustained International Strategy Is Required to Turn the Tide on the Atlantic Lionfish Invasion. *Mar. Ecol. Prog. Ser.* 533, 219–235. doi: 10.3354/meps11399

Karp, P., Fruitema, M., Chapman, J., Curtis-Quick, J., Spencer, E., and Saul-Demers, N. (2015). Incentivizing Lionfish Removal Through Development of Markets for Jewelry: Preliminary Experience From Belize, the Bahamas and St. Vincent and the Grenadines. *Gulf Caribb. Fish. Inst.* 68, 208–210.

Kilgo, J. M. (2014). *Lionfish Response Management Plan, U.S. Virgin Islands Update*. United States Virgin Islands: NOAA Coral Reef Information System, 79.

Kimball, M. E., Miller, J. M., Whitfield, P. E., and Hare, J. A. (2004). Thermal Tolerance and Potential Distribution of Invasive Lionfish (*Pterois volitans*/Miles Complex) on the East Coast of the United States. *Mar. Ecol. Prog. Ser.* 283, 269–278. doi: 10.3354/meps283269

Kleitou, P., Crocetta, F., Giakoumi, S., Giovos, I., Hall-Spencer, J. M., Kalogirou, S., et al. (2021b). Fishery Reforms for the Management of Non-Indigenous Species. *J. Environ. Manage.* 280, 111690. doi: 10.1016/j.jenvman.2020.111690

Kleitou, P., Hall-Spencer, J., Rees, S., Sfenthourakis, S., Demetriou, A., Chartosia, N., et al. (2019). *Tackling the Lionfish Invasion in the Mediterranean. The EU-LIFE RELIONMED Project: Progress and Results. 1st Mediterranean Symposium on the Non-Indigenous Species* (Antalya, Turkey).

Kleitou, P., Hall-Spencer, J. M., Savva, I., Kletou, D., Hadjistylli, M., Azzurro, E., et al. (2021c). The Case of Lionfish (*Pterois miles*) in the Mediterranean Sea Demonstrates Limitations in EU Legislation to Address Marine Biological Invasions. *J. Mar. Sci. Engin.* 9 (3), 1–16. doi: 10.3390/jmse9030325 325

Kleitou, P., Rees, S., Cecconi, F., Kletou, D., Savva, I., Cai, L. L., et al. (2021a). Regular Monitoring and Targeted Removals can Control Lionfish in Mediterranean Marine Protected Areas. *Aquat. Cons.* 31 (10), 2870–2882. doi: 10.1002/aqc.3669

Kletou, D., Hall-Spencer, J. M., and Kleitou, P. (2016). A Lionfish (*Pterois miles*) Invasion has Begun in the Mediterranean Sea. *Mar. Biodivers. Res.* 9(46), 1–7. doi: 10.1186/s41200-016-0065-y

Kulbicki, M., Beets, J., Chabanet, P., Cure, K., Darling, E., Floeter,, et al. (2012). Distributions of Indo-Pacific Lionfishes Pterois Spp. In Their Native Ranges: Implications for the Atlantic Invasion. *Mar. Ecol. Prog. Ser.* 446, 189–205. doi: 10.3354/meps09442

Levin, K., Cashore, B., Bernstein, S., and Auld, G. (2012). Overcoming the Tragedy of Super Wicked Problems: Constraining Our Future Selves to Ameliorate Global Climate Change. *Policy Sci.* 45 (2), 123–152. doi: 10.1007/s11077-012-9151-0

Linardich, C., Brookson, C. B., and Green, S. J. (2021). Trait-Based Vulnerability Reveals Hotspots of Potential Impact for a Global Marine Invader. *Glob. Change Biol.* 27, 4322– 4338. doi: 10.1111/gcb.15732

Luiz, O., Marceniuk, A., Santos, W., Rocha, L., Floeter, S., Buck, C., et al. (2021). Multiple Lionfish (*Pterois* Spp.) New Occurrences Along the Brazilian Coast Confirm the Invasion Pathway Into the Southwestern Atlantic. *Biol. Invasions* 23, (10), 3013-3019. doi: 10.1007/s10530-021-02575-8

Malpica-Cruz, L., Chaves, L. C., and Côté, I. M. (2016). Managing Marine Invasive Species Through Public Participation: Lionfish Derbies as a Case Study. *Mar. Pol.* 74, 158–164. doi: 10.1016/j.marpol.2016.09.027

Mavruk, S., Bengil, F., Yeldan, H., Manasirli, M., and Avşar, D. (2017). The Trend of Lessepsian Fish Populations With an Emphasis on Temperature Variations in Iskenderun Bay, the Northeastern Mediterranean. *Fish. Oceanogr.* 26, 542–554. doi: 10.1111/fog.12215

McCreedy, C., Toline, C. A., and McDonough, V. (2012). "Lionfish Response Plan: A Systematic Approach to Managing Impacts From the Lionfish, an Invasive Species," in *Units of the National Park System*. (Fort Collins Colorado:Natural Resource Rep. NPS/NRSS/WRD/NRR— 2012/497. Natl. Park Service), 99.

Mehta, S., Haight, R., Homans, F., Polasky, S., and Venette, R. (2007). Optimal Detection and Control Strategies for Invasive Management. *Ecol. Econ.* 61, 237–245. doi: 10.1016/j.ecolecon.2006.10.024

Morris, J. A. Jr, and Akins, J. L. (2009). Feeding Ecology of Invasive Lionfish (*Pterois volitans*) in the Bahamian Archipelago. *Environ. Biol. Fish.* 86, 389–398. doi: 10.1007/s10641-009-9538-8

Morris, J. A., Akins, J. L., Green, S. J., Buddo, D. S. A., and Lozano, R. G. (2012). *Invasive Lionfish: A Guide to Control and Management*. Ed. J. A. Morris (Marathon, Florida: Gulf Caribb. Fish. Inst. Special Publication), 113.

Morris, J. A., Thomas, A., Rhyne, A. L., Breen, N., Akins, L., and Nash, B. (2011). Nutritional Properties of the Invasive Lionfish: A Delicious and Nutritious Approach for Controlling the Invasion. *Bioflux* 4 (1), 21–26.

Mulgrew, B. (2020). *Putting the Cat Back in the Bag: Turning the Invasive Lionfish Scourge Into a Conservation Opportunity*. (UC San Diego: Center for Marine Biodiversity and Conservation). Available at: https://escholarship.org/uc/item/9k7915x0.

Noll, S., and Davis, B. (2020). The Invasive Species Diet: The Ethics of Eating Lionfish as a Wildlife Management Strategy. *Ethics Pol. Environ.* 23, 1–16. doi: 10.1080/21550085.2020.1848189

Nuñez, M. A., Kuebbing, S., Dimarco, R. D., and Simberloff, D. (2012). Invasive Species: To Eat or Not to Eat, That is the Question. *Cons. Lett.* 5, 334–341. doi: 10.1111/j.1755-263X.2012.00250.x

Pasko, S, and Goldberg, J. (2014). Review Of Harvest Incentives To Control Invasive Species. Manage. *Biol. Invasions*. 5 (3), 263. doi: 0.3391/mbi.2014.5.3.10

Peake, J., Bogdanoff, A. K., Layman, C. A., Castillo, B., Reale-Munroe, K., Chapman, J., et al. (2018). Feeding Ecology of Invasive Lionfish (*Pterois volitans* and *Pterois miles*) in the Temperate and Tropical Western Atlantic. *Biol. Inv.* 20 (9), 2567–2597. doi: 10.1007/s10530-018-1720-5

Peiffer, F., Bejarano, S., Palavicini de Witte, G., and Wild, C. (2017). Ongoing Removals of Invasive Lionfish in Honduras and Their Effect on Native Caribbean Prey Fishes. *PeerJ* 5, e3818. doi: 10.7717/peerj.3818

Pusack, T. J., Benkwitt, C. E., Cure, K., and Kindinger, T. L. (2016). Invasive Red Lionfish (*Pterois volitans*) Grow Faster in the Atlantic Ocean Than in Their Native Pacific Range. *Environ. Biol. Fish.* 99 (6), 571–579. doi: 10.1007/s10641-016-0499-4

Reed, M. S. (2008). Stakeholder Participation for Environmental Management: A Literature Review. *Biol. Cons.* 141 (10), 2417–2431. doi: 10.1016/j.biocon.2008.07.014

Samaha, C., Zu Dohna, H., and Bariche, M. (2016). Analysis of Red Sea Fish Species' Introductions Into the Mediterranean Reveals Shifts in Introduction Patterns. *J. Biogeog.* 43 (9), 1797–1807. doi: 10.1111/jbi.12793

Savva, I., Chartosia, N., Antoniou, C., Kleitou, P., Georgiou, A., Stern, N., et al. (2020). They Are Here to Stay: The Biology and Ecology of Lionfish (*Pterois*

miles) in the Mediterranean Sea. *J. Fish Biol.* 97, 148– 162. doi: 10.1111/jfb.14340

Schofield, P. J. (2009). Geographic Extent and Chronology of the Invasion of Non-Native Lionfish (*Pterois volitans* [Linnaeus 1758] and *P. miles* [Bennett 1828]) in the Western North Atlantic and Caribbean Sea. *Aquat. Invasions* 4 (3), 473–479. doi: 10.3391/ai.2009.4.3.5

Sikkel, P. C., Tuttle, L. J., Cure, K., Coile, A. M., and Hixon, M. A. (2014). Low Susceptibility of Invasive Red Lionfish (*Pterois volitans*) to a Generalist Ectoparasite in Both its Introduced and Native Ranges. *PloS One* 9, e95854. doi: 10.1371/journal.pone.0095854

Simberloff, D. (2000). No Reserve Is an Island. Marine Reserves and Non-Indigenous Species. *Bull. Mar. Sci.* 66 (3), 567–580.

Simnitt, S., House, L., Larkin, S. L., Tookes, J. S., and Yandle, T. (2020). Using Markets to Control Invasive Species: Lionfish in the US Virgin Islands. *Mar. Res. Econ.* 35 (4), 319–341. doi: 10.1086/710254

Solomon, J., Gavin, M. C., and Gore, M. L. (2015). Detecting and Understanding Non-Compliance With Conservation Rules. *Biol. Cons.* 189 (4), 1–4. doi: 10.1016/j.biocon.2015.04.028

Stern, N., Jimenez, C., Huseyinoglu, M. F., Andreou, V., Hadjioannou, L., Petrou, A., et al. (2019). Constructing the Genetic Population Demography of the Invasive Lionfish *Pterois miles* in the Levant Basin, Eastern Mediterranean. *Mitochondrial DNA Part A* 30 (2), 249–255. doi: 10.1080/24701394.2018.1482284

Stern, N., and Rothman, S. B. S. (2019a). Divide and Conserve the Simultaneously Protected and Invasive Species. *Aquat. Conserv: Mar Freshw Ecosyst.* 29, 161–162. doi: 10.1002/aqc.2950

Stern, N., and Rothman, S. B. S. (2019b). "Iron Lion Zion: The Successful, Albeit Lingered, Invasion of the Lionfish in the Israeli Mediterranean Sea," in *Lionfish Invasion and Its Management in the Mediterranean Sea*, vol. 49 . Eds. M. F. Hüseyinoğlu and B. Öztürk (Istanbul, Turkey: Turkish Marine Research Foundation (TUDAV) , 121.

Sutherland, W. J., Barnard, P., Broad, S., Clout, M., Connor, B., Côté, I. M., et al. (2017). A 2017 Horizon Scan of Emerging Issues for Global Conservation and Biological Diversity. *Trends Ecol. Evol.* 32, 31–40. doi: 10.1016/j.tree.2016.11.005

Thresher, R. E., and Kuris, A. M. (2004). Options for Managing Invasive Marine Species. *Biol. Invasions* 6 (3), 295–300. doi: 10.1023/B:BINV.0000034598.28718.2e

Trotta, K. A. (2014). *Socioeconomics of the Lionfish Derby Fishery. Master's Thesis.* (Broward County, Florida: Nova Southeastern University. NSUWorks, Oceanographic Center). Available at: https://nsuworks.nova.edu/occ_stuetd/21.

Tuttle, L. J., Sikkel, P. C., Cure, K., and Hixon, M. A. (2017). Parasite-Mediated Enemy Release and Low Biotic Resistance May Facilitate Invasion of Atlantic Coral Reefs by Pacific Red Lionfish (*Pterois volitans*). *Biol. Invasions* 19, 563–575. doi: 10.1007/s10530-016-1342-8

Ulman, A., Harris, H. E., Doumpas, N., Deniz Akbora, H., Al Mabruk, S. A. A., Azzurro, E., et al. (2021). Low Pufferfish and Lionfish Predation in Their Native and Invaded Ranges Suggests Human Control Mechanisms may be Necessary to Control Their Mediterranean Abundances. *Front. Mar. Sci.* 8(868). doi: 10.3389/fmars.2021.670413

Ulman, A., Tunçer, S., Tuney Kizilkaya, I., Alford, P., and Zilifli, I. (2020). The Lionfish Expansion in the Aegean Sea in Turkey: A Looming Potential Ecological Disaster. *Reg. Stud. Mar. Sci.* 36, 101271. doi: 10.1016/j.rsma.2020.101271

Valdivia, A., Bruno, J. F., Cox, C. E., Hackerott, S., and Green, S. J. (2014). Re-Examining the Relationship Between Invasive Lionfish and Native Grouper in the Caribbean. *PeerJ* 2 (4), e348, 1–16. doi: 10.7717/peerj.348

Watkins, H. V., Yan, H. F., Dunic, J. C., and Côté, I. M. (2021). Research Biases Create Overrepresented "Poster Children" of Marine Invasion Ecology. *Cons. Letters.* 14, e12802. doi: 10.1111/conl.12802

Zenetos, A., and Galanidi, M. (2020). Mediterranean Non Indigenous Species at the Start of the 2020s: Recent Changes. *Mar. Biodivers. Rec.* 13 (10), 1-17. doi: 10.1186/s41200-020-00191-4

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