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The Role of Citizen Science in the Research and Management of Invasive Lionfish across the Western Atlantic

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Abstract: Managing invasive Indo-Pacific lionfish (*Pterois volitans* and *P. miles*) in the Western Atlantic Ocean is beyond the capacity of natural resource organizations alone. In response, organizations have mobilized members of the public and citizen scientists to help. We used a structured survey to assess the activities and perceptions of 71 organizations that engage the public and citizen scientists in lionfish research and management throughout the invaded range of the Western Atlantic. Five case studies were also conducted that exemplified varied and multi-pronged approaches to engagement of the public and citizen scientists in lionfish control, monitoring, and knowledge-sharing. The public has been engaged to some extent in every approach, but organizations most frequently indicated engaging members of the public in raising awareness, promoting consumption, organized culling/removal, tournaments, and data collection. Sixty-five percent of organizations surveyed engaged the public in data collection, and data collection was ranked as the scientific research activity in which the public is most often involved. Most organizations indicated their data has contributed to scientific publications, management, and government agency research and/or policy. Collectively these findings demonstrate the conservation value of citizen scientists to assist organizational efforts to control, manage, and study a large-scale marine invasion.

Keywords: lionfish; citizen science; invasive; public; engagement; volunteers; management; conservation; control

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1. Introduction

The spatial scale of marine ecosystems, and the logistical difficulties and expenses of surveying them [1,2], limits our capacity to monitor the distributions of organisms in this environment. Consequently, invasive species and their impacts remain largely unrecorded [3] thereby challenging our capacity to control them and to mitigate their social, economic, and ecological impacts [4]. Many definitions of citizen science [5] exist. In addition, citizen science is referred to by a wide variety of other terms [6]; we prefer the use of "participatory science" as some members of our research group found "citizen" to potentially be exclusionary. We use "citizen science" in this paper because it was the term most commonly understood by our study's focus group participants and therefore used in

the survey. Most definitions describe citizen science as involving knowledge generation through participation of the public in research [6,7]. In the context of marine biological invasions, citizen scientists can allow for early detection [8–12] and can help monitor the structure, distribution, behavior, and dynamics of invasive populations [13,14]. Finally, citizen scientists can be engaged to support management of invasive species, particularly to the extent that this involves removals [15].

In the Western Atlantic Ocean, the Indo-Pacific lionfish (*Pterois volitans* and *P. miles*) has become one of the most successful biological invasions in the marine ecosystem to date [1,16]. Their establishment has been facilitated by opportunistic life history characteristics [17–19] and a generalist diet [20], and high population densities of lionfish have resulted in demonstrable effects on native species, fisheries, biodiversity, and ecosystem processes [21–26]. Management measures have been initiated [19,27] and there is evidence that negative impacts on local marine ecosystems may be mitigated through regular removals [28]. However, regional control of lionfish populations requires high rates of fishing mortality throughout their invaded range [23,27,29,30]. Moreover, much of the spawning stock population is on reefs beyond limits of diver removals [31,32]. Effective management of this invasion is clearly beyond the financial and human resource capacity of marine resource management agencies alone. While there is general agreement that complete eradication of lionfish will not be possible, population control via removal efforts can successfully reduce localized lionfish populations [28,33–35]. Lionfish control in these locations has been driven by grassroot community and organization efforts that, generally, (i) encourage removals by recreational divers [14,36,37] and (ii) promote lionfish consumption and development of commercial lionfish fisheries [38,39]. Meanwhile, research on lionfish biology and their population ecology has been enabled by sampling lionfish removed by volunteer divers [17,18,24,40,41].

The scale and inherent complexities of managing the lionfish invasion present researchers and practitioners with a wicked problem [42,43] as biological invasions require rapid management prior to comprehensive understanding of the invasion and its effects [44]. This is further complicated by the recognition that eradication is unlikely and there is no clear solution or endpoint [45]. Organizations across the lionfish invaded range have implemented diverse and localized management strategies [19,46] with management approaches that have sometimes been contradictory and controversial. For example, while market-based approaches to control invasives have been widely advocated, there are concerns that they could create incentives to maintain the invasive population [47]. Similarly, because the conservation goal of organizations that manage lionfish is for them to deplete the lionfish population, when successful, these efforts result in a decline in opportunities to see, remove, consume, and sell lionfish [48]. This could cause volunteer and citizen scientist engagement in these activities to in fact decrease [49].

To date, lionfish citizen science and removal efforts have been conducted largely by decentralized organizations and individuals throughout their invaded range. Some studies have described individual country or organization-specific initiatives involving citizen science and their contributions towards lionfish removals and control [50,51]. These represent a small sample of a myriad of efforts that have recently been organized around a general cause of helping governments and researchers to manage invasive lionfish populations. In this study, we assess the management approaches of organizations addressing the lionfish invasion across the invaded Western Atlantic range with the overarching objective to characterize engagement with the public and, specifically, citizen scientists for lionfish management. Specifically, we sought to understand: (i) the types of scientific activities and management approaches citizen scientists and the public engage in; (ii) the ways organizations engage the public and citizens scientists; (iii) the importance of citizen scientists for conducting lionfish management and research; (iv) if involvement of the public and citizen scientists affects the perceived impact of lionfish management programs; and (v) the limitations organizations face with regard to lionfish research and management.

2. Methods

2.1. Sampling

Our target sample included organizations and agencies involved in lionfish control based in areas across the invaded range (Figure 1), including the Caribbean island nations and territories, the United States (U.S.), Central America (here we include Belize), and South America. Regarding ethical approval, this study underwent Colorado State University's internal review process and was determined to be Not Human Subjects Research (Protocol #20-10495H, February 2021) because it assessed organizations rather than individuals. We employed two methods, a structured survey and semi-structured interviews with representatives of organizations and agencies.

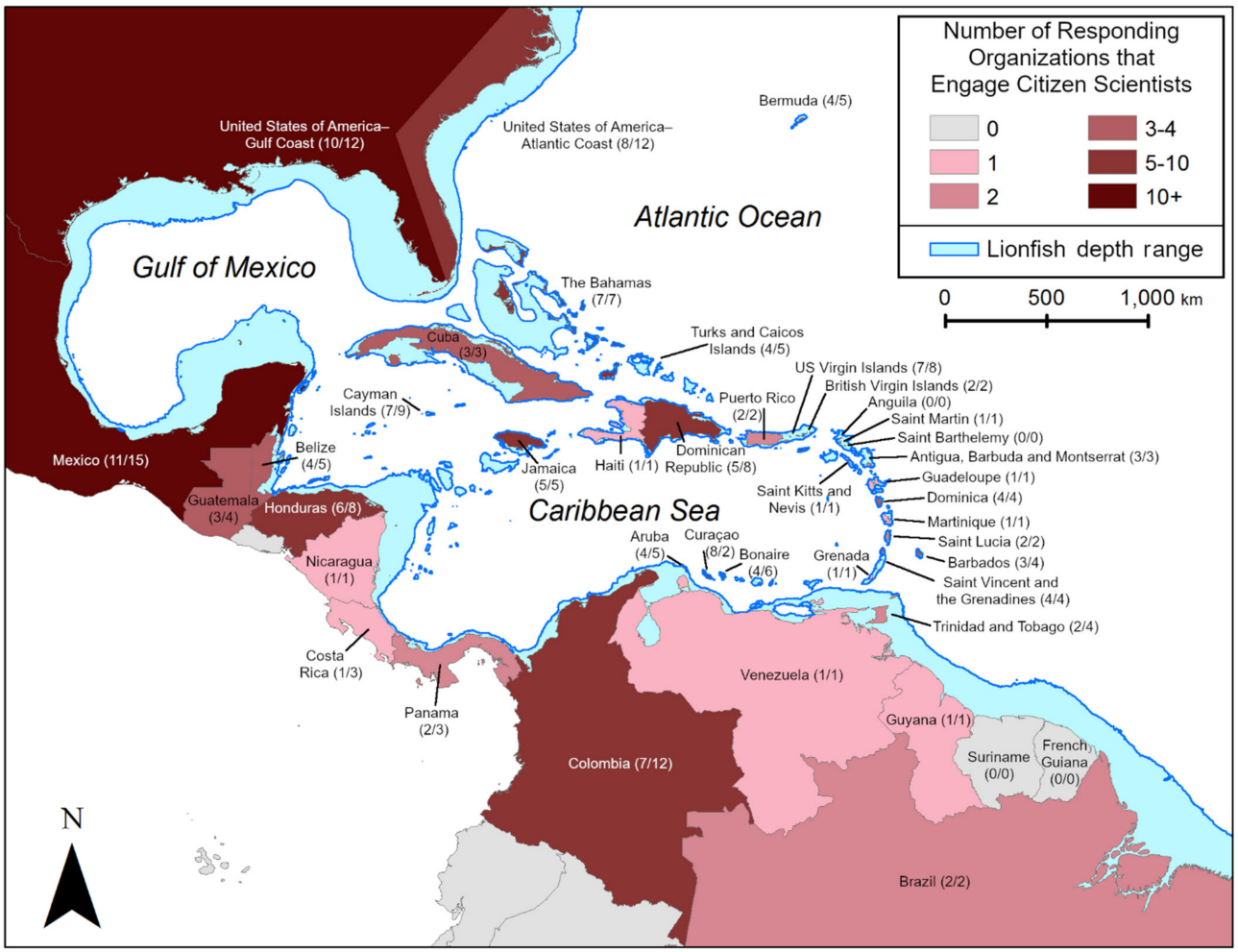

Figure 1. Map showing the lionfish invaded range and information about responding organizations. The number immediately after each location name is the number of organizations that responded to the survey, have worked in that location, and engage citizen scientists. The number after the slash (/) is the number of organizations total that have worked in each location and responded to the survey. Darker colors represent countries with more organizations that engage citizen scientists and lighter colors represent fewer organizations. Gray represents locations with no response. The lionfish depth range is defined as the ~300 m contour throughout the invaded range (North Carolina through Brazil). Lionfish are capable of occupying a range of habitats from 0.5 m to deeper than 300 m [34], and lionfish have been detected across the extent of this map as reported to the USGS Nonindigenous Aquatic Species database (https://nas.er.usgs.gov/viewer/omap.aspx?SpeciesID=963, accessed on 1 July 2021).

2.2. Survey Design and Administration

We distributed a structured survey in English (Supplementary Material S1—Survey) and Spanish by e-mail to a seed group, composed of individuals working for organizations and agencies who we identified, either through personal contacts, mailing lists, or the Gulf and Caribbean Fisheries Institute's conference proceedings (2008–2019) as having engaged citizen scientists or volunteers in lionfish-related activities. In addition, we posted an invitation to organizations who involve the public in lionfish research or management to contact us about taking the survey on the social media pages of organizations involved in marine conservation and lionfish control. We used snowball sampling to identify additional respondents [52]; at the end of the survey, each respondent was asked to recommend names of individuals in other organizations or agencies to participate.

The survey was sent to a total of 186 individuals, of whom 170 consisted of a seed group from the authors' contacts. Ten recipients were snowball contacts provided by our original seed group. One hundred and twelve recipients opened or started the online survey and 72 individuals completed the survey, resulting in a completion rate of 64%. We removed one respondent from our dataset as they were a duplicate, meaning that two people from the same organization completed the survey so only one of these responses was included in the final 71 responses used for data analysis. Forty-seven respondents completed the survey in English and 24 in Spanish. The median time respondents took to complete the survey was 25.7 min.

Respondents were asked to participate in the survey on behalf of their organization, with only one survey per organization accepted. The first draft of the survey was developed by the majority of authors using literature and personal knowledge of the study subject. An online focus group consisting of six lionfish practitioners provided verbal feedback on the overall survey design, objectives, and each survey item. Based on findings from the focus group, the survey was edited and piloted with five more conservation practitioners and researchers who have experience working on or researching lionfish control. The English language survey was available from March to June and the Spanish language during the month of June 2021. The Spanish language survey was translated from English by two bilingual authors (SJR and CBE) and piloted with ten Spanish native language speakers from six Spanish-speaking countries, two of whom were familiar with marine conservation issues. Following the initial release of the survey, every two-three weeks we summarized which organizations had completed the survey, retargeted sectors and geographic locations with gaps and sent reminder e-mails to existing contacts.

The structured survey was administered using Qualtrics. It included 25 items with open and closed-ended response items pertaining to organizations' lionfish management approaches, public participation, types of participation, citizen science, and the importance of citizen scientists to lionfish work. Management approaches were assessed through a choose-all-that-apply question which included a comprehensive list of approaches that were carefully collated through our focus group and pilot survey. Chosen approaches were then listed in later questions for ranking and indication of engagement with members of the public and citizen scientists. Seven-point Likert scale questions assessed the importance of citizen scientists to management and research efforts. Simple "yes" or "no" and choose-all-that-apply questions assessed whether the organization's research led to specific outcomes (i.e., inform policy) or engaged members of the public in specific activities (i.e., help with data analysis, help with study design). Finally, respondents indicated limitations to their lionfish work through a choose-all-that-apply question and then ranked their top 5 limitations.

During our focus group with practitioners, they indicated that citizen science was the term most widely used and understood. Our study design differentiated "members of the public" from "citizen scientists" through survey questions that asked about each separately and analyses that measured each separately. We considered "members of the public" to be individuals who are not part of a lionfish organization, but whose organizations might engage in their lionfish control activities. To avoid any misunderstanding by

respondents, we included the following definition of citizen science in the survey prior to questions specifically referencing citizen science: "volunteers and/or members of the public engaging in activities that generate information for research or management purposes. Note: sometimes "citizen science" is used interchangeably with "community science"".

2.3. Semi-Structured Interviews

To provide context for different management approaches and engagement with the public, we conducted semi-structured interviews with representatives from five organizations to create case studies [53]. Organizations were identified by authors as being representative of some of the most common types of lionfish management approaches (awareness raising, organized culling, tournaments, data collection) as well as voluntourism. Two interviews were conducted by P.K. using the online video platform, Zoom, and one was face to face. Written notes were taken throughout the interview and responses were summarized. The written summaries were then returned by e-mail to interviewees for review so interviewees could provide feedback concerning accuracy of their organization's case summary and the conclusions derived. Two case studies were reported by authors (F.A. and A.C.) of this paper who are or have been responsible for lionfish work conducted by the organization. Case studies included: (1) Organized culling efforts in the Flower Garden Banks National Marine Sanctuary (FGBNMS), managed by the U.S. National Oceanic and Atmospheric Administration (NOAA) Office of National Marine Sanctuaries, (2) A volunteer fishing derby series facilitated by the Reef Environmental Education Foundation (REEF), (3) A volunteer culling program facilitated by the Stichting Nationale Parken Bonaire (STINAPA Bonaire), (4) Voluntourism culling facilitated by the Reef Conservation International (ReefCI), and (5) Knowledge exchange and networking through the Lionfish University (LFU).

2.4. Analysis

Part of the survey asked participants to rank different approaches, which we then synthesized into scores. The average per capita ranking score (hereafter "ranking score") was calculated based on a ranking question in which respondents could label up to two approaches as "most impactful", up to two as "second most impactful" and up to two as "third most impactful". Each time an approach was listed as "most impactful", it received 3 points, those listed as second most impactful received 2 points, and third most received 1 point. The sum of those points was then divided by the number of organizations that implemented the approach and answered the question (two respondents did not answer the ranking question). Respondents could only rank approaches that their organizations have directly implemented (and therefore are familiar with), which they indicated in a previous survey question. In some cases, such as "lionfish cooking contests", this resulted in a very high ranking score because a small number of organizations indicated using the approach, but they ranked it as most impactful. In addition, these scores are based on perceptions. The survey question's exact wording was "Based on your organization's experience, which of its approaches to lionfish management appears to have been most impactful to helping control the lionfish invasion?". While our respondents' roles as scientists, leaders, and other integral members of their organizations suggest that they are knowledgeable about their organization's work and lionfish work, they did not necessarily have data or proof that an approach was or was not impactful.

One section of the survey asked whether the organization's research has contributed to peer-reviewed scientific publications, informed management, contributed to government agency research, or informed policy. Using Pearson's chi-square and Fisher's exact tests, we compared organizations that engage citizen scientists versus those that do not and their "yes" versus "no" responses to these four questions, excluding "don't know" responses.

3. Results

The 71 structured survey respondents collectively represent organizations whose work on lionfish management covers most of the tropical Western Atlantic (Figure 1). Seventeen organizations reported work in multiple locations. The only countries in the invaded Western Atlantic not represented in our study were Anguilla, French Guiana, Saint Barthelemy, and Suriname.

The individuals responding to the survey on behalf of their organization included senior-level representatives (45%) (for example, directors of an agency, owners of a business, senior scientists), program managers/coordinators (24%), scientists (17%) (including biologists and researchers), communication/outreach coordinators or extension agents (7%), and independent conservationists (3%). One student, a volunteer, and a conservation officer also contributed on behalf of their organizations. In other words, most of our respondents were individuals who had substantial knowledge of their organization.

Almost half of all organizations represented by respondents were non-governmental organizations/not for profits (47%), with the rest being government agencies (25%), for profits (17%), or "other" (11%). Almost half of all respondents (47%) reported that their organization's sector of involvement focused on marine protection. The rest of the organizations' sectors of involvement were: higher education (16%), public education/advocacy (11%), fishery-focused (7%), and tourism (6%). Approximately 13% of respondents noted "other" as a response sector. These organizations focused on: recreation, diver safety, technology and education, biodiversity protection including cultural, and research.

3.1. Approaches to Address the Lionfish Invasion

Organizations engaged in a wide variety of approaches to address the lionfish invasion, which were given ranking scores ranging from 0.04 to 3.0 (Table 1). Based on the ranking score, the approach perceived to have the greatest impact and was implemented by more than ten organizations was organized culling/removal (ranking score = 2.09). The approach with the second highest score and implemented by more than ten organizations was "public education, outreach or awareness raising" (ranking score = 1.84), followed by "tournaments/derbies" (ranking score = 1.72), "promoting consumption of lionfish (ranking score = 1.40), and "data collection" (ranking score = 1.33).

Table 1. Types of approaches directly implemented by organizations for lionfish control alongside their average per capita ranking score, the number of organizations who have used the approach, and the percent of organizations that have engaged the public or citizen scientists in the approach.

Approach	Percent of Organizations That Used Approach (n = 71) % (n)	Percent of Organizations Using Approach That Engaged the Public in Approach % (n)	Percent of Organizations Using Approach That Engaged Citizen Scientists in Approach % (n)	Average per Capita Ranking Score (n)
Lionfish removal				
Organized culling/Removal	60% (45)	71% (32, n = 45)	36% (16, n = 45)	2.09 (n = 43)
Tournaments/Derbies	41% (29)	90% (26, n = 29)	55% (16, n = 29)	1.72 (n = 29)
Culling by recreational fishers	35% (25)	76% (19, n = 25)	36% (9, n = 25)	1.20 (n = 25)
Gear testing (traps, rovers, spears, etc.)	28% (20)	40% (8, n = 20)	40% (8, n = 20)	0.70 (n = 20)
Education and awareness				
Public education, outreach or awareness raising	75% (53)	85% (45, n = 53)	24% (17, n = 53)	1.84 (n = 51)
Workshops/Seminars	51% (36)	42% (15, n = 36)	11% (8, n = 36)	0.86 (n = 35)
Training	42% (30)	73% (22, n = 30)	23% (7, n = 30)	0.90 (n = 29)

Table 1. *Cont.*

Approach	Percent of Organizations That Used Approach (n = 71) % (n)	Percent of Organizations Using Approach That Engaged the Public in Approach % (n)	Percent of Organizations Using Approach That Engaged Citizen Scientists in Approach % (n)	Average per Capita Ranking Score (n)
Promoting lionfish market development				
Promoting consumption of lionfish	62% (44)	86% (38, n = 44)	39% (17, n = 44)	1.40 (n = 43)
Working with restaurants or seafood markets/supermarkets	42% (30)	63% (19, n = 30)	27% (8, n = 30)	0.87 (n = 30)
Working with fishers	34% (24)	63% (15, n = 24)	21% (5, n = 24)	1.13 (n = 23)
Lionfish jewelry	21% (15)	80% (12, n = 15)	27% (4, n = 15)	0.57 (n = 14)
Working with wholesalers	20% (14)	79% (11, n = 14)	36% (5, n = 14)	0.36 (n = 14)
Working with fishmongers/seafood sellers	11% (8)	63% (5, n = 8)	50% (4, n = 8)	0.62 (n = 8)
Lionfish cooking contests	1% (1)	100% (1, n = 1)	0% (0)	3.00 (n = 1)
Information generation and sharing				
Data collection	63% (45)	53% (24, n = 45)	53% (24, n = 45)	1.33 (n = 43)
Knowledge management	38% (27)	56% (15, n = 27)	22% (6, n = 27)	0.96 (n = 26)
Networking	35% (25)	60% (15, n = 25)	24% (6, n = 25)	0.04 (n = 24)
Coordinated management and policy efforts				
Permitting or licensing	18% (13)	46% (6, n = 13)	17% (1, n = 6)	1.15 (n = 13)
Local or regional management/policy plan	6% (4)	50% (2, n = 4)	25% (1, n = 4)	2.25 (n = 4)
Volunteer and tourist engagement				
Volunteer program	32% (23)	61% (14, n = 23)	35% (8, n = 23)	0.35 (n = 23)
Adventure/Ecotourism	15% (11)	82% (9, n = 11)	18% (2, n = 11)	1.00 (n = 11)
Voluntourism	13% (9)	67% (6, n = 9)	67% (6, n = 9)	0.22 (n = 9)

Three themes emerged as most-commonly noted by respondents concerning why the approaches their organizations employed were most impactful. Many respondents indicated that approach(es) resulted in direct (in-water) control of lionfish populations. For example, one respondent wrote: "Being a marine sanctuary, removing the fish from the environment is the first step". Another common theme was that education/awareness-building approaches led to engagement and/or impact. One respondent explained that their approach(es) increased "awareness of the extent of the problem and how individuals can have a positive impact, changing attitudes regarding the consumption of lionfish". Support for supply chains and/or market-based solutions was the third most commonly noted theme. One respondent explained, "Promoting the consumption and in particular the restaurants interest in buying lionfish from the cullers provided an outlet for cullers to get rid of their catch and provided incentive to get out and cull regularly". While these were the most common themes, it was notable that several respondents emphasized the importance of understanding the local context for the reason that the approach(es) employed by their organizations were most impactful. One included a general theory of change. Finally, several respondents from organizations which collected data mentioned that such information was important for decision-making about effective management/control purposes.

3.2. Case Studies

The following case studies illustrate how citizen scientists and/or volunteers have been incorporated into different management approaches as well as lionfish research. Each case study demonstrates how implementation of specific management activities has been conducted on the ground. The NOAA Lionfish Invitational demonstrates cooperative efforts by volunteer divers and marine scientists to systematically assess the impact of the lionfish invasion on a remotely located MPA. Lionfish tournaments and outreach activities conducted by the REEF demonstrate how these activities can recruit volunteers

for large-scale removal efforts and data collection. In Bonaire, STINAPA exemplifies a national lionfish culling program that relies on local volunteer divers, thereby allowing MPA managers to maintain control over culling efforts. Work by ReefCI in Belize shows how tourist volunteers can be engaged to undertake regular, ongoing control efforts and data collection, amplifying the limited financial and manpower resources of marine management agencies, while LFU indicates the power of social networks to mobilize resources and facilitate exchange of knowledge.

3.2.1. NOAA FGBNMS Lionfish Invitational, U.S

Key Approaches: Volunteer Program and Organized Culling/Removal

The FGBNMS is a unique coral reef ecosystem located 100 nautical miles off the coast of Texas in the northwestern Gulf of Mexico. Recognizing the remote location of FGBNMS, NOAA partnered with several non-profit organizations and aquarium programs to permit and organize a series of chartered expeditions to undertake lionfish removals, and collect data on changes in reef health and lionfish populations over time. Since 2015, a total of six "FGBNMS Lionfish Invitational" research and removal expeditions have taken place, cumulatively engaging more than 150 volunteer divers and removing 2205 lionfish. The 30 volunteers joining each expedition are typically a mix of self-identified citizen scientists, professional and recreational spear fishers, and academic researchers, accompanied by NOAA marine scientists. Weather permitting, each expedition includes dives in seven different sites within FGBNMS. The lionfish removal dives are supplemented by fish survey dives to capture changes in lionfish density caused by the culling effort as well as changes in native fish populations over time. Data is also collected on catch per unit effort. Culled lionfish are measured for total and standard length on the dive vessel and are then brought to the NOAA FGBNMS lab where data is collected, using Texas A&M University student volunteers, on prey composition (via visual stomach analyses,) sex, weight, and age (via examination of otolith cross sections). Data collected has resulted in eight published articles and three scientific posters; one of which documented the oldest lionfish recorded in the Gulf of Mexico [54]. Lionfish removed during the expeditions have been used for demonstrations and dissections in schools and elsewhere, helping to raise awareness about the invasion and the threat it poses to local marine ecosystems.

3.2.2. REEF, USA

Key Approaches: Tournaments/Derbies and Data Collection

The REEF is a non-governmental organization established in 1990 in recognition of the potential to engage the diving community in understanding and protection of the marine environment. With a worldwide membership base of over 70,000 marine stewards and the world's largest database of sightings of marine life, REEF has been uniquely suited to play a leading role in lionfish invasion intervention. Data collected through REEF's various invasive lionfish-related activities, and with the support of volunteers and citizen scientists, have been disseminated in 38 peer-reviewed publications, manuals and reports, and numerous public and conference presentations. Here we will focus on REEF's role in the organization of lionfish derbies. The REEF has organized an annual lionfish derby series since 2009, offering cash prizes for teams capturing the most, smallest, and largest lionfish. The first lionfish derby was held in Abaco, Bahamas in 2009 and had 25 teams remove 1408 lionfish. Since then, REEF has hosted 57 derbies with more than 1777 participants and resulted in the direct removal of 28,544 lionfish. Festivals associated with the derbies engage the public with educational demonstrations and culinary tastings. In addition to the derbies it directly organizes, REEF also runs a Sanctioned Lionfish Derby Program, providing support in the form of logistical material, promotion, and in some cases, personnel assistance on derby day, to other organizations running lionfish derbies. This Sanctioned Derby program has supported 44 derbies, engaging nearly 800 participants, and resulted in the removal of over 21,500 lionfish. The COVID restrictions in 2020 and 2021 limited the derby series. Nevertheless, REEF ran two successful, socially distant

lionfish derbies in the Florida Keys, in September 2020 and April 2021. Both saw record numbers of registered participants and lionfish removed, indicating the continued interest and impact of these conservation events.

3.2.3. STINAPA Bonaire, Bonaire

Key Approaches: Training, Permitting/Licensing, Organized Culling/Removal, Volunteer Program, and Data Collection

The STINAPA Bonaire is a non-governmental, not for profit foundation commissioned by the island government to manage the country's two protected areas: the Bonaire National Marine Park (BNMP) and the Washington Slagbaai National Park (WSNP). Even before lionfish were first detected in the country, BNMP began working on a lionfish control plan and on raising awareness among dive operators, divers, and the general public. The BNMP also began to engage with the government regarding legislation to allow for removal of invasive lionfish via spearing, thus reversing a blanket prohibition on any spearing arising from designation of all Bonaire's waters as a no-take marine park. In 2011, 300 specialized spears known as E.L.F (Eliminating Lionfish) Tools were distributed to trained volunteer divers who were required to enter into a contract with BNMP whereby they agreed to provide data on date, time, location, and depth of capture of all lionfish removed. To help mitigate the costs incurred by volunteers engaging in lionfish removals, BNMP partnered with local dive shops, which provided the divers with free tank fills upon presentation of their lionfish removal badge and equipment (this was later discontinued as the invasion progressed). Any specimens removed were submitted to the CIEE Research Station Bonaire (CIEE RSB) for measurement and stomach contents examination, with all data collected in turn shared with the BNMP on a monthly basis. In 2013, the CIEE RSB developed a lionfish removal project at Klein Bonaire in partnership with STINAPA and a local dive operator. Volunteers recruited via the Bonaire Lionfish Hunters Facebook group paid USD20 to cover the cost of their tank fills and were allowed to keep any lionfish they caught after data was collected. Volunteers who participated regularly in these research trips to Klein Bonaire were selected by the BNMP to join additional removal events in the marine reserve where diving was otherwise prohibited.

3.2.4. ReefCI, Belize

Key Approaches: Voluntourism, Organized Culling/Removal, and Data Collection

A number of organizations across the Western Atlantic employ a "voluntourism" approach. Lionfish voluntourism refers to lionfish control programs facilitated by organizations that primarily involve volunteers who travel to the location in question for periods of approximately one week or more for the specific purpose of engaging in lionfish control activities. These are distinct from lionfish culling activities organized by dive operators for single or multiple dives as part of their normal operations. The extended duration of engagement allows these organizations to mobilize the labor needed to undertake the regular and ongoing removals required for effective control of invasive lionfish. As this type of sustained removal effort is generally beyond the financial and staffing capacity of MPA managers and local government agencies, volunteer engagement plays an important role. Moreover, as voluntourism participants typically are engaged for periods of several weeks, it is also possible to draw on them for advanced data collection. The ReefCI, a U.S.-registered not-for-profit organization, already had an ongoing, voluntourism-based marine conservation program underway in the Sapodilla Cayes Marine Reserve in Southern Belize when lionfish were first detected in the country in 2009. Recognizing the threat posed to native fish populations and local ecosystems, ReefCI added lionfish removal and data collection to its program, ramping up the intensity of this component as the invasion became more widespread. Between 2014 and 2019, ReefCI volunteers and staff removed 36,523 lionfish, representing the largest single lionfish removal program in the country. Volunteers receive training on lionfish biology and ecology and on the history and impacts of the invasion. Spears and lionfish containment devices are carried on almost every dive,

allowing for consistent removal of lionfish from the reserve. On average, 250–300 lionfish are removed each week. A subset is measured and dissected to record prey items and the remainder are served to ReefCI's guests during evening meals or provided to restaurants to encourage lionfish consumption. The tails and fins of speared lionfish are provided to artists (some of whom were trained by ReefCI) to make lionfish jewelry. The data collected is provided to the Belize Fisheries department and is also disseminated by ReefCI through its annual report and social media platform.

3.2.5. LFU, USA

Key Approaches: Public Education, Outreach or Awareness Raising, Knowledge Management, and Networking

The LFU is a volunteer-run social network dedicated to raising awareness and sharing knowledge and experience about invasive lionfish and the threat they pose. Active members include professional marine scientists (who participate in their personal capacity), policymakers, conservation practitioners, researchers, recreational divers, spear fishers, and others involved and/or interested in management of invasive lionfish. Legally constituted as a private not-for-profit entity, the LFU has a network of 57 volunteer "Field Reporters" located across the Western Atlantic and Mediterranean regions. These volunteers provide information and updates in their respective locations and help to mobilize data, contacts, and policy information to support lionfish management and research efforts undertaken by the many organizations with which LFU partners. While it does not independently engage in lionfish management activities, the LFU regularly supports other organizations through collaboration, promotion, mobilization of funding and volunteers, and dissemination of information and results via its website and social media channels. As part of its awareness raising and outreach, LFU has produced a number of informational videos and supported development, testing, and deployment of lionfish-specific traps. Another important initiative has been knowledge exchange with relevant stakeholders from the Mediterranean; most notably on experiences and lessons learned over the course of nearly three decades in the Western Atlantic with respect to invasive lionfish and their impact, along with options for managing the invasion. Researcher connections and data collection facilitated through the LFU network have contributed to a number of publications and research efforts.

3.3. Public Engagement

All but four organizations (N = 71) reported that they engage the public in at least one of the approaches they have directly implemented (Table 1). The approach in which the most organizations engaged members of the public was "public education, outreach or awareness raising" (n = 45), followed by "promoting consumption of lionfish" (n = 38), "organized culling/removal" (n = 32), "tournaments/derbies" (n = 26), and "data collection" (n = 24).

We found that organizations engaged members of the public in a wide variety of steps in the scientific research process (Figure 2). "Data collection" was by far the process reported by the most respondents (65%), and was also ranked as the activity most often carried out (n = 39), followed by "analysis of samples" (n = 14) and "help with data analysis" (n = 10). The only activity of all listed that was not ranked as "most often" carried out by participants was "development of hypotheses". This was also the activity least undertaken by organizations (n = 7). Approximately one quarter (27%) of organizations reported that their organization engaged in none of the listed activities.

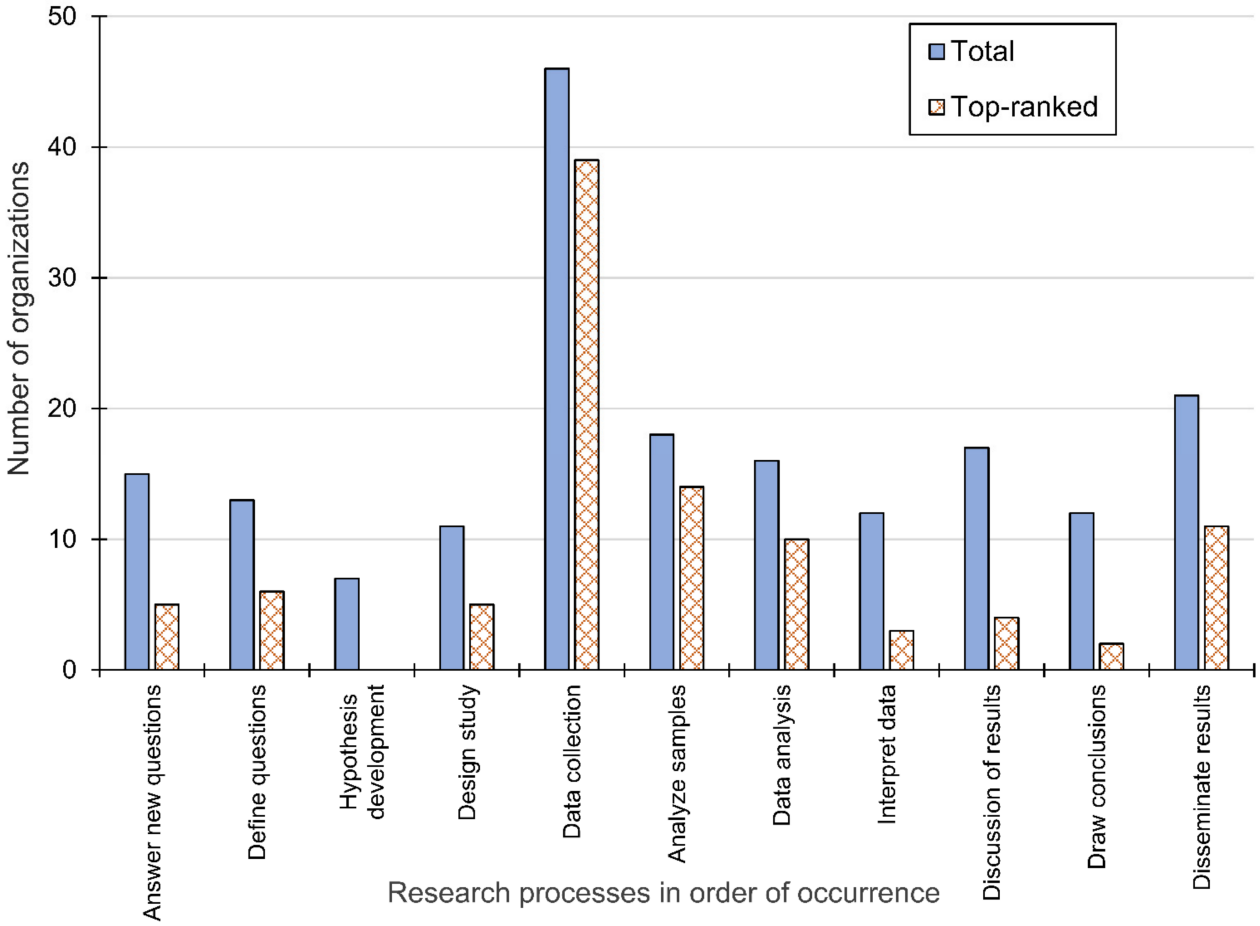

Figure 2. Research-related processes engaged in by members of the public. "Total" indicates if an organization involved members of the public in that process. "Top-ranked" indicates if the respondent from the organization ranked it as "most often" occurring. Each organization's respondent could place up to two processes in the "top-ranked" category.

3.4. Citizen Science

Sixty percent (n = 42) of all organizations surveyed reported that they involve citizen scientists (volunteers or members of the public engaged in activities that generated information explicitly for research or management purposes) in their programs. Of the organizations that engaged citizen scientists, nearly half (n = 20) were non-governmental organizations/not for profits, approximately a quarter (n = 11) were government, and six were for profits. Of these organizations involved in citizen science, 29 self-reported that they have worked in the Caribbean, eleven in Mexico, nine in Central America, 10 in the U.S.' Gulf of Mexico, eight in the U.S.' Atlantic coast, and three in South America.

The approach in which the most organizations engaged citizen scientists was "data collection" (n = 24), followed by "public education, outreach, and awareness" (n = 17), "promoting consumption of lionfish" (n = 17), "organized culling/removal" (n = 16), and "tournaments/derbies" (n = 16).

The majority of respondents (81%) of the 42 whose organizations engaged in citizen science indicated that their organization facilitated hands-on activities with citizen scientists. Respondents reported that most of the hands-on activities occurred "near site" (n = 45), meaning on a boat, dockside, or on shore. In-water was the second most common location (n= 23), and off site such as a hotel, lab, or classroom, was reportedly the least common location (n = 15).

3.5. Impact of Citizen Science

The majority of organizations who engaged citizen scientists reported that citizen scientists were moderately to extremely important to their scientific findings (69%), data collection (86%), and lionfish management efforts (83%), (Figures 3 and 4). Pearson's chi-square and Fisher's exact tests of independence showed no significant difference between organizations who engaged citizen scientists and those that did not and whether their data has contributed to peer-reviewed literature (71% versus 52%, χ^2 (1, n = 58) = 2.23, p = 0.14), informed management (85% versus 79%, (Fisher's) n = 58, p = 0.726), contributed to government agency research (81% versus 59%, χ^2 (1, n = 53) = 2.95, p = 0.09), or informed policy (67% versus 47%, χ^2 (1, n = 46) = 1.71, p = 0.19). While we excluded "don't know" responses from these analyses, the outcome with the most "don't know" responses (n = 25) corresponded with whether the organization's research informed policy, followed by whether data contributed to government research (n = 18), informed policy (n = 13), and informed management (n = 13). Fifty-three organizations responded that their data had contributed to at least one of those four outcomes.

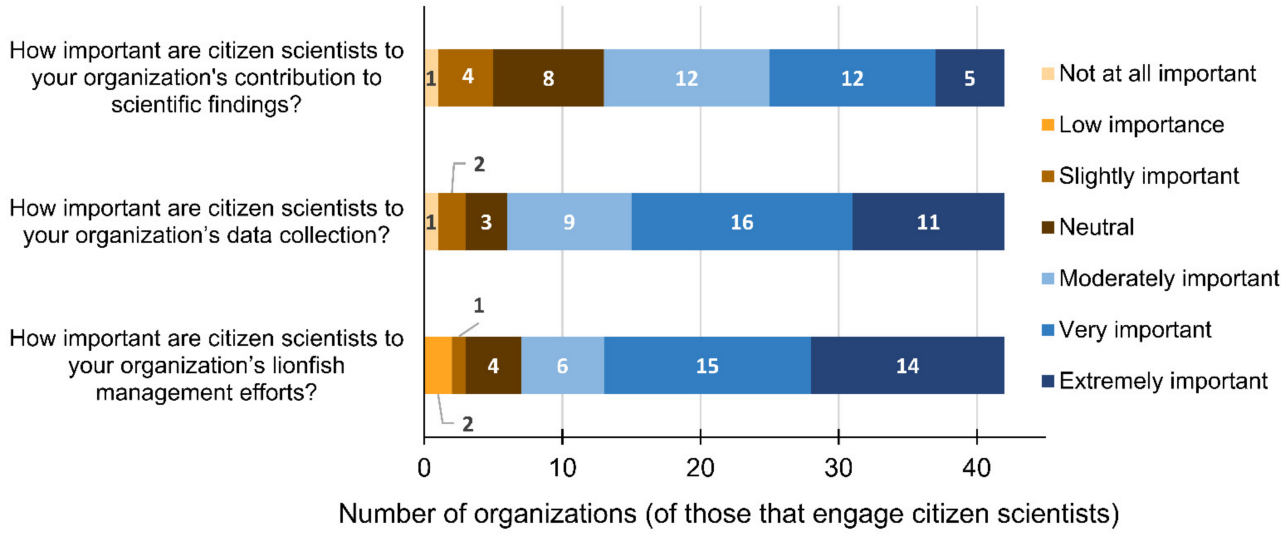

Figure 3. Importance of citizen scientists to research and management (n = 42). Counts for each category of a Likert scale from "Not at all important" to "Extremely important", in which organization representatives indicated how important citizen scientists are to contributing to scientific findings, data collection, and lionfish management efforts.

Notably, 60% of respondents indicated that their organizations would be unable to undertake their lionfish management work without use of citizen scientists. As shown in Figure 4, in comparison to organizations that could conduct their work without citizen scientists, a larger proportion of organizations that implement data collection stated that they would not be able to conduct their work without citizen scientists. The same was true for organizations that implement tournaments, organized culling/removal, and culling by recreational fishers.

3.6. Critical Obstacles

Funding was the top-ranked as well as the most commonly mentioned obstacle to lionfish research and management. Of all respondents who ranked a top obstacle (n = 63), 70% identified funding as their organization's greatest challenge. Limitations related to staffing (numbers of staff or staff time), was also identified as a major obstacle; it was listed second to funding as the most common challenge (n = 38),and was the most often named second-ranked challenge by 40% (n = 21) of respondents who listed a second challenge (n = 59). Access to gear (n = 19) (for example: boat, dive gear), while never identified as a first-ranked obstacle, was the third most commonly mentioned.

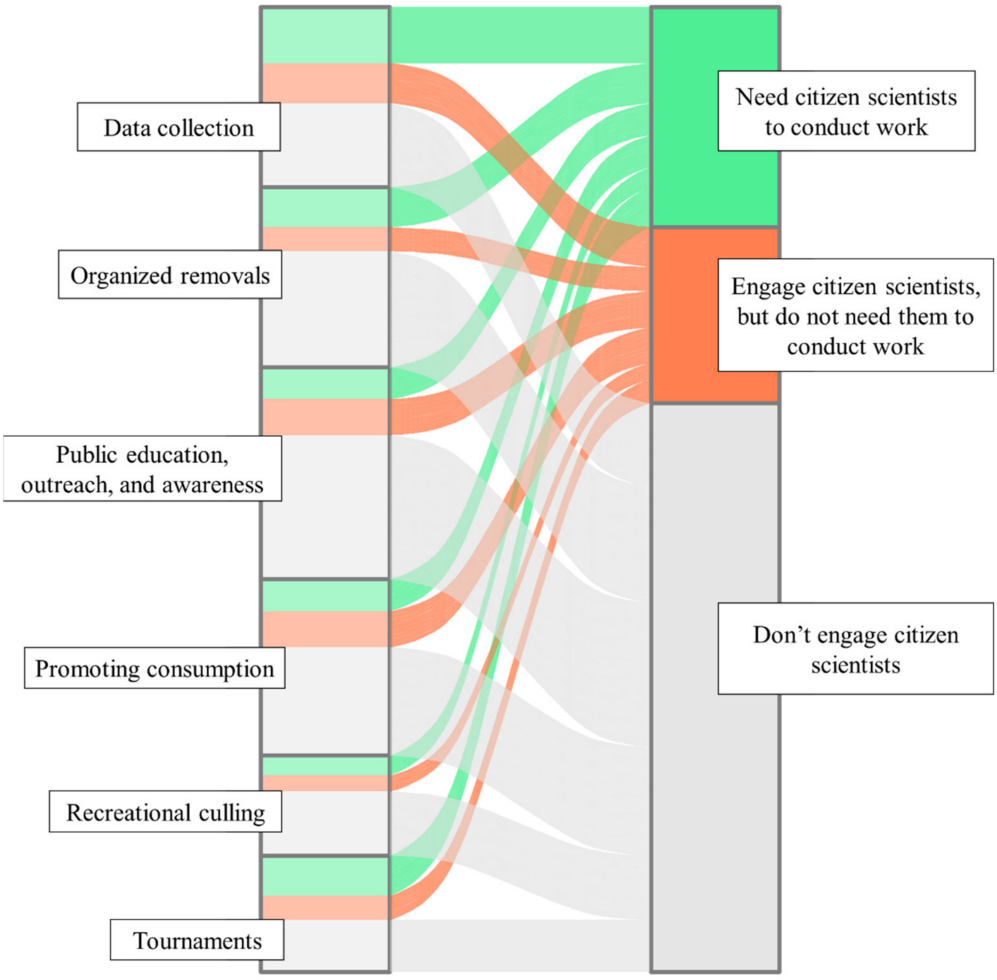

Figure 4. Alluvial plot demonstrating the perceived impact score of the six top-ranked directly implemented approaches for lionfish management and their proportionate connection to organizations' engagement of citizen scientists and whether the organization needs citizen scientists to carry out their work.

4. Discussion

4.1. Engagement

Citizen scientists provide significant contributions to lionfish research and management efforts across a broad spectrum of approaches, research processes, and types of organizations throughout the invaded range of the Western Atlantic. The majority of organizations that engage citizen scientists state that they could not do their work without them. In addition, most organizations engage the public in lionfish removals, which likely helps to mitigate the ecological impacts of lionfish [23,55]. Our findings show that not just members of the public, but citizen scientists specifically are engaged in every management approach. In other words, engagement of the public in lionfish control as well as involvement of citizen scientists in lionfish research play major roles in monitoring and managing the invasion.

4.2. Impact and Importance

Marine citizen scientists help provide cost-effective monitoring and early detection of invasive species across vast spatio-temporal scales [15,56]. For example, this was the case in the monitoring of the Asian shore crab (*Hemigrapsus sanguineus*) and the European green crab (*Carcinus maenas*) in the northeast U.S. [8]; detection of the European green crab's expansion into inland marine waters of Washington State [57]; the Harris mud crab

(*Rhithropoanopeus harrisii*) in Finnish waters [58]; and early detection of the expansion of European grass shrimp (*Palaemon adspersus*) in Prince Edward Island estuaries [59]. Through a project in the Mediterranean called "Is it Alien to you? Share it!!!" citizen scientists in Greece and Cyprus submitted 691 records of marine invasive and cryptogenic species and identified 3 new species in Greece [60]. With regard to the lionfish invasion more specifically, spearfishers serving as citizen scientists and citizen conservation practitioners are valuable resources for responding to the rapid invasion [51], and conservation volunteers support monitoring and control of marine invasive species [61]. Citizen science has also been used to identify areas vulnerable to impacts [45] and assess the effectiveness of culling efforts [36]. Our survey results and case studies also demonstrate the utility of citizen scientists in management through involvement in multiple management approaches and in both monitoring and removal capacities. This may explain why approaches with high ranking scores (indicating that approach was perceived as impactful) also involved citizen scientists the most.

We found that organizations reported engaging members of the public to some degree across the vast majority of research processes, but most often through data collection efforts. This is similar to findings on marine citizen science from around the world [5]. This type of engagement, consisting primarily of data collection, has been classified as a "contributory" model [62]. The recent research record on invasive lionfish demonstrates the value of these data collection efforts in producing scientific contributions as well as impacting management efforts. Data collected has helped document the spread and distribution of the W. Atlantic invasion [14,49,51]. As shown by our case study, REEF's existing volunteer fish survey project and invasive species early warning programs provided both marine managers and scientists with important data, supporting early detection and action to address the threat posed by invasive lionfish. Furthermore, lionfish citizen science data collection has contributed biological samples and data to produce research on their life history [17,18,40,63], control efforts [36,64], and management strategies [39]. Intense monitoring efforts also enabled the rapid detection of an ulcerative disease observed in the northern Gulf of Mexico lionfish [65] and provided data to document a subsequent recruitment failure and population crash [41,66].

Detections by citizen scientists are facilitating the monitoring of the lionfish invasion currently underway in the Mediterranean Sea [3,67,68]. In comparison to the Western Atlantic, the Mediterranean Sea is considered a hotspot for marine invasions due to the high level of shipping traffic and non-native species entering the sea via the Suez Canal [69]. Monitoring and early detection of invasive species by citizen scientists has recently increased in the Mediterranean, especially through the use of technological platforms such as Facebook and smartphones [60]. Given the magnitude of biological invasions in the Mediterranean Sea, as well as the recent increase in citizen science activity, engagement with citizen scientists in the region is likely an impactful strategy for monitoring and removal not just of lionfish but other invasive species as well.

4.3. The Nature of Engagement

"Collaborative" projects allow members of the public to participate in more steps of the scientific process, beyond data collection efforts while participants in "co-created" projects engage in all steps of a research project [7]. While organizations in our study did indicate that members of the public participate in collaborative projects, co-created projects appeared to be less common; for example, none of our respondents ranked development of research hypotheses highly. This finding presents an opportunity for organizations to actively engage the public and citizen scientists across more steps of the research process [70]. For invasive lionfish, citizen scientists have been involved throughout the entire research, development, and dissemination process of novel fishing gears, including remote operated vehicles and traps [41]. Involving citizen scientists in more steps of the research process, may have numerous benefits beyond sustained engagement [62]. For example, it may allow for enhancement of local scientific capacity [70]. Doing so has been found to be

instrumental in attaining citizen science programs' attitudinal, knowledge, and behavioral goals [71], and some scholars believe it essential to the future of citizen science in the natural sciences [33]. Similarly, from project inception, explicitly linking participants to projects which lead to policy or management impacts may lead to more sustained involvement in citizen science projects [72]. While we did not investigate the exact linkage between citizen scientists and final impacts, our results show that most organizations that engage citizen scientists have contributed their data to scientific publications, to government agency research, or used it to inform management, thus providing an opportunity to connect citizen scientists with outcomes.

Our results also show that lionfish citizen scientists are engaged in diverse approaches to management, such as actual removal of the invasive, providing direct conservation value to their work [62]. This likely increases longevity of engagement because they feel they are a part of the solution [15]. Importantly, lionfish management approaches and public engagement are typically context-specific and integrated with one another to create greater impact. Each of our case studies demonstrates how organizations accomplish multiple research and management objectives by implementing several approaches simultaneously and engaging citizen scientists in multiple objectives. As a result, lionfish citizen scientists and volunteers not only contribute to science, but are also often participants in integrated and solution-based management and outreach efforts: e.g., in-water lionfish control, human consumption campaigns [15]. This is not unique to lionfish-focused programs, as programs focused on invasive species, especially those with an edible invasive, are likely to take integrated approaches which can involve multiple stakeholders [47].

4.4. Challenges to Lionfish Research and Management

Funding was demonstrated to be the first and second greatest obstacles to lionfish research and management. In marine contexts, funding as an obstacle is unsurprising, considering the financial investment for necessary equipment (e.g., boats, scuba gear, certifications etc.) to conduct in-water research [73], which our study found to be the second most common location for citizen science hands-on activities. Funding is a difficulty for conservation efforts around the world [74], and will likely continue to be an obstacle. It is apparent that finding ways to sustain projects over time and space will be a priority. One promising avenue to address the funding obstacle is partnerships. Citizen science partnerships and collaborative efforts are important for funding lionfish programs' efforts [5]; for example, in-kind donations, such as access to dive equipment and charters, have played a role in lionfish research [49,75]. As shown in our case study on organized culling in Bonaire, STINAPA partnered with local dive shops which provided free tank fills to cullers. Voluntourism, as a growing sector, is another potential source of revenue [6] which can involve partnerships between private or public entities and marine conservation organizations. Collaborations with local NGOs/government, regional and international entities did not rank highly in our analysis of limitations; however, we were unable to tell from our data if this is due to the absence of those relationships. Co-creating more citizen science projects, which has been found to increase collaboration [5] may also hold promise to mitigate funding obstacles.

Our findings suggest several other opportunities for impactful lionfish research and management in the face of challenges, especially with regard to funding. For one, although voluntourism received an impact score of only two, voluntourism has become an important source of funding and a labor pool for conservation research efforts [6]. Therefore, in some cases, voluntourism may be necessary to fund programs. For example, our case study of ReefCI in Belize demonstrates that voluntourism plays a necessary role in helping to support lionfish research and management where it may otherwise have been financially infeasible. With appropriate training and supervision, voluntourists can offer a sustainable and consistent source of labor to facilitate lionfish management, keep lionfish populations in check, and restore native fish populations while protecting associated livelihoods. In other words, while some approaches received relatively low-ranking scores with regard to

"helping control the lionfish invasion", depending on the context, these approaches still may play an imperative role in accommodating funding challenges as well as facilitating other high impact activities. For example, REEF's derbies directly remove lionfish and concomitantly facilitate public education and promote the consumption of lionfish, thereby making the most of their investment with what appears to be one activity.

4.5. Study Limitations and Future Research

The work we present here has several limitations. This study relied upon our contacts to produce a seed group of potential respondents to the survey. While we attempted to reduce bias by asking respondents to identify other potential respondents, only 14% (n = 10) of the sample consisted of snowball references. Several factors may have impacted engagement with the survey and affected the response rate: (1) in some areas of the study region, access to the internet was limited and/or expensive; (2) we asked prospective respondents to use a computer to complete the survey as the survey design was not ideal for a respondent to undertake on a cellular phone; (3) the survey was offered in both English and Spanish languages but not offered in other languages spoken in the invaded range of the Western Atlantic; (4) the Spanish language survey was deployed for less time than the English language survey; (5) exogenous events in the study area, such as a large volcanic eruption in Saint Vincent and the Grenadines, and (6) at the time of survey administration, COVID-19 was impacting the study region, creating numerous hardships.

Considering the importance of funding to the organizations' conservation programs, as well the value of citizen scientists to conservation organizations, examining funding efforts and partnerships is a recommended topic for future research. This is just one element in the coupled human and natural system that could lead to insights and possibly improve citizen science programs. Overall, we see promise in understanding lionfish citizen science from a coupled human and natural systems perspective [9,49]. Increasing our understanding of system attributes, their interactions, and how they relate to citizen science could help organizations engage citizen scientists in more impactful ways. For example, understanding the feedback loops between ecosystem dynamics associated with effective culling and how that affects citizen scientists' motivations and duration of engagement would possibly allow citizen science program managers to increase and sustain participation over time. Considering the geographical scope of the invasion, another area for further research is the role of knowledge networks [76]. As demonstrated by the case of Lionfish University, such networks can be effective in bringing together diverse groups of stakeholders, including citizen scientists, and in brokering both knowledge exchange and active collaboration. In addition, research connecting biological outcomes (i.e., reduction in lionfish populations, increased native prey species abundance) to management approaches, perceived effectiveness, and engagement of citizen scientists would further clarify the role of citizen scientists in lionfish control efforts.

5. Conclusions

The geographic spread and ecological impacts of the W. Atlantic lionfish invasion has spurred the development of numerous conservation efforts, dedicated to this single issue. In this study, we surveyed 71 organizations working on lionfish across the invaded range. Our research emphasizes the importance of citizen scientists to organizations; the majority of organizations engaging citizen scientists noted they could not conduct their work without them. Collectively, our findings demonstrate the conservation value of citizen scientists and volunteers to organizations and the invasion at large. The data of the majority of organizations who engage citizen scientists contribute to peer-reviewed scientific publications, government agency research, and management efforts. Our findings suggest that citizen scientists are necessary for much of the data collected by organizations involved in lionfish management and research. In addition to data collection, citizen scientists participate to a lesser degree in other research processes, which are more collaborative and, in some cases, co-created.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/d13120673/s1: Supplementary Material S1 contains Survey.

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Informed Consent Statement: Informed consent was obtained from all respondents involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

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References

1. Côté, I.M.; Green, S.J.; Hixon, M.A. Predatory fish invaders: Insights from Indo-Pacific lionfish in the western Atlantic and Caribbean. *Biol. Conserv.* **2013**, *164*, 50–61. [CrossRef]
2. Danielsen, F.; Burgess, N.D.; Balmford, A.; Donald, P.F.; Funder, M.; Jones, J.P.G.; Alviola, P.; Balete, D.S.; Blomley, T.; Brashares, J.; et al. Local Participation in Natural Resource Monitoring: A Characterization of Approaches. *Conserv. Biol.* **2009**, *23*, 31–42. [CrossRef]
3. Azzurro, E.; Stancanelli, B.; Di Martino, V.; Bariche, M. Range expansion of the common lionfish Pterois miles (Bennett, 1828) in the Mediterranean Sea: An unwanted new guest for Italian waters. *BioInvasions Rec.* **2017**, *6*, 95–98. [CrossRef]
4. Crall, A.W.; Newman, G.J.; Jarnevich, C.S.; Stohlgren, T.J.; Waller, D.M.; Graham, J. Improving and integrating data on invasive species collected by citizen scientists. *Biol. Invasions* **2010**, *12*, 3419–3428. [CrossRef]
5. Kelly, R.; Fleming, A.; Pecl, G.T.; von Gönner, J.; Bonn, A. Citizen science and marine conservation: A global review. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190461. [CrossRef]
6. Eitzel, M.V.; Cappadonna, J.L.; Santos-Lang, C.; Duerr, R.E.; Virapongse, A.; West, S.E.; Kyba CC, M.; Bowser, A.; Cooper, C.B.; Sforzi, A.; et al. Citizen Science Terminology Matters: Exploring Key Terms. *Citiz. Sci. Theory Pract.* **2017**, *2*, 1–20. [CrossRef]
7. Follett, R.; Strezov, V. An Analysis of Citizen Science Based Research: Usage and Publication Patterns. *PLoS ONE* **2015**, *10*, e0143687. [CrossRef] [PubMed]
8. Delaney, D.G.; Sperling, C.D.; Adams, C.S.; Leung, B. Marine invasive species: Validation of citizen science and implications for national monitoring networks. *Biol. Invasions* **2008**, *10*, 117–128. [CrossRef]
9. Liu, J.; Dietz, T.; Carpenter, S.R.; Alberti, M.; Folke, C.; Moran, E.; Pell, A.N.; Deadman, P.; Kratz, T.; Lubchenco, J.; et al. Complexity of Coupled Human and Natural Systems. *Science* **2007**, *317*, 1513–1516. [CrossRef] [PubMed]
10. Mehta, S.V.; Haight, R.G.; Homans, F.R.; Polasky, S.; Venette, R.C. Optimal detection and control strategies for invasive species management. *Ecol. Econ.* **2007**, *61*, 237–245. [CrossRef]
11. Schofield, P.; Akins, L. Non-native marine fishes in Florida: Updated checklist, population status and early detection/rapid response. *BioInvasions Rec.* **2019**, *8*, 898–910. [CrossRef]
12. Sewell, J.; Parr, J. Citizen sentinels: The role of citizen scientists in reporting and monitoring invasive non-native species. In *Citizen Science for Coastal and Marine Conservation*; Routledge: Abingdon-on-Thames, UK, 2017.
13. Bodilis, P.; Louisy, P.; Draman, M.; Arceo, H.O.; Francour, P. Can citizen science survey non-indigenous fish species in the eastern Mediterranean Sea? *Environ. Manag.* **2014**, *53*, 172–180. [CrossRef] [PubMed]

14. López-Gómez, M.J.; Aguilar-Perera, A.; Perera-Chan, L. Mayan diver-fishers as citizen scientists: Detection and monitoring of the invasive red lionfish in the Parque Nacional Arrecife Alacranes, southern Gulf of Mexico. *Biol. Invasions* **2014**, *16*, 1351–1357. [CrossRef]
15. Encarnação, J.; Teodósio, M.A.; Morais, P. Citizen Science and Biological Invasions: A Review. *Front. Environ. Sci.* **2021**, *8*, 602980. [CrossRef]
16. Cure, K.; McIlwain, J.L.; Hixon, M.A. Habitat plasticity in native Pacific red lionfish Pterois volitans facilitates successful invasion of the Atlantic. *Mar. Ecol. Prog. Ser.* **2014**, *506*, 243–253. [CrossRef]
17. Fogg, A.Q.; Brown-Peterson, N.J.; Peterson, M.S. Reproductive life history characteristics of invasive red lionfish (*Pterois volitans*) in the northern Gulf of Mexico. *Bull. Mar. Sci.* **2017**, *93*, 791–813. [CrossRef]
18. Gardner, P.G.; Frazer, T.K.; Jacoby, C.A.; Yanong, R.P.E. Reproductive biology of invasive lionfish (*Pterois* spp.). *Front. Mar. Sci.* **2015**, *2*, 7. [CrossRef]
19. Morris, J.A.; Whitfield, P.E. *Biology, Ecology, Control and Management of the Invasive Indo-Pacific Lionfish: An Updated Integrated Assessment*; NOAA Technical Memorandum NOS NCCOS; NOAA/National Ocean Service/Center for Coastal Fisheries and Habitat Research: Beaufort, NC, USA, 2009.
20. Peake, J.; Bogdanoff, A.K.; Layman, C.A.; Castillo, B.; Reale-Munroe, K.; Chapman, J.; Dahl, K.; Patterson, W.F., III; Eddy, C.; Ellis, R.D.; et al. Feeding ecology of invasive lionfish (*Pterois volitans* and *Pterois miles*) in the temperate and tropical western Atlantic. *Biol. Invasions* **2018**, *20*, 2567–2597. [CrossRef]
21. Arias-González, J.E.; González-Gándara, C.; Luis Cabrera, J.; Christensen, V. Predicted impact of the invasive lionfish Pterois volitans on the food web of a Caribbean coral reef. *Environ. Res.* **2011**, *111*, 917–925. [CrossRef]
22. Ballew, N.G.; Bacheler, N.M.; Kellison, G.T.; Schueller, A.M. Invasive lionfish reduce native fish abundance on a regional scale. *Sci. Rep.* **2016**, *6*, 32169. [CrossRef]
23. Chagaris, D.; Binion-Rock, S.; Bogdanoff, A.; Dahl, K.; Granneman, J.; Harris, H.; Mohan, J.; Rudd, M.B.; Swenarton, M.K.; Ahrens, R.; et al. An Ecosystem-Based Approach to Evaluating Impacts and Management of Invasive Lionfish. *Fisheries* **2017**, *42*, 421–431. [CrossRef]
24. Dahl, K.A.; Patterson, W.F.; Snyder, R.A. Experimental assessment of lionfish removals to mitigate reef fish community shifts on northern Gulf of Mexico artificial reefs. *Mar. Ecol. Prog. Ser.* **2016**, *558*, 207–222. [CrossRef]
25. Green, S.J.; Akins, J.L.; Maljković, A.; Côté, I. Invasive Lionfish Drive Atlantic Coral Reef Fish Declines. *PLoS ONE* **2012**, *7*, e32596. [CrossRef]
26. Kindinger, T.L.; Albins, M.A. Consumptive and non-consumptive effects of an invasive marine predator on native coral-reef herbivores. *Biol. Invasions* **2017**, *19*, 131–146. [CrossRef]
27. Morris, J.A.; Shertzer, K.W.; Rice, J.A. A stage-based matrix population model of invasive lionfish with implications for control. *Biol. Invasions* **2011**, *13*, 7–12. [CrossRef]
28. Côté, I.M.; Akins, L.; Underwood, E.; Curtis-Quick, J.; Green, S.J. Setting the Record Straight on Invasive Lionfish Control: Culling Works. *PeerJ PrePrints* **2014**. [CrossRef]
29. Barbour, A.B.; Allen, M.S.; Frazer, T.K.; Sherman, K.D. Evaluating the Potential Efficacy of Invasive Lionfish (*Pterois volitans*) Removals. *PLoS ONE* **2011**, *6*, e19666. [CrossRef]
30. Johnston, M.W.; Purkis, S.J. A coordinated and sustained international strategy is required to turn the tide on the Atlantic lionfish invasion. *Mar. Ecol. Prog. Ser.* **2015**, *533*, 219–235. [CrossRef]
31. Andradi-Brown, D.A.; Grey, R.; Hendrix, A.; Hitchner, D.; Hunt, C.L.; Gress, E.; Madej, K.; Parry, R.L.; Régnier-McKellar, C.; Jones, O.P.; et al. Depth-dependent effects of culling-do mesophotic lionfish populations undermine current management? *R. Soc. Open Sci.* **2017**, *4*, 170027. [CrossRef]
32. Harris, H.E.; Patterson, W.F.; Ahrens, R.N.M.; Allen, M.S. Detection and removal efficiency of invasive lionfish in the northern Gulf of Mexico. *Fish. Res.* **2019**, *213*, 22–32. [CrossRef]
33. Frigerio, D.; Richter, A.; Per, E.; Pruse, B.; Vohland, K. Citizen science in the natural sciences. In *The Science of Citizen Science*; Vohland, K., Land-Zandstra, A., Ceccaroni, L., Lemmens, R., Perelló, J., Ponti, M., Samson, R., Wagenknecht, K., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 79–96. [CrossRef]
34. Gress, E.; Andradi-Brown, D.A.; Woodall, L.; Schofield, P.J.; Stanley, K.; Rogers, A.D. Lionfish (*Pterois* spp.) invade the upper-bathyal zone in the western Atlantic. *PeerJ* **2017**, *5*, e3683. [CrossRef]
35. López-Gómez, M.J.; Tuz-Sulum, A.; Perera-Chan, L.; Aguilar-Perera, A. Diver-fishermen volunteering provided reliable data on the lionfish invasion in the Alacranes reef national park, Mexico. In Proceedings of the 64th Gulf and Caribbean Fisheries Institute, Puerto Morelos, Mexico, 31 October–4 November 2011; Available online: http://aquaticcommons.org/21326/1/GCFI_64-19.pdf (accessed on 5 July 2021).
36. Green, S.J.; Underwood, E.B.; Akins, J.L. Mobilizing volunteers to sustain local suppression of a global marine invasion. *Conserv. Lett.* **2017**, *10*, 726–735. [CrossRef]
37. De León, R.; Vane, K.; Bertuol, P.; Chamberland, V.C.; Simal, F.; Imms, E.; Vermeij, M.J.A. Effectiveness of lionfish removal efforts in the southern Caribbean. *Endanger. Species Res.* **2013**, *22*, 175–182. [CrossRef]
38. Blakeway, R.D.; Jones, G.A.; Boekhoudt, B. Controlling lionfishes (*Pterois* spp.) with consumption: Survey data from Aruba demonstrate acceptance of non-native lionfishes on the menu and in seafood markets. *Fish. Manag. Ecol.* **2020**, *27*, 227–230. [CrossRef]

39. Chapman, J.K.; Anderson, L.G.; Gough, C.L.A.; Harris, A.R. Working up an appetite for lionfish: A market-based approach to manage the invasion of Pterois volitans in Belize. *Mar. Policy* **2016**, *73*, 256–262. [CrossRef]
40. Edwards, M.A.; Frazer, T.K.; Jacoby, C.A. Age and growth of invasive lionfish (*Pterois* spp.) in the Caribbean Sea, with implications for management. *Bull. Mar. Sci.* **2014**, *90*, 953–966. [CrossRef]
41. Harris, H.E.; Fogg, A.Q.; Gittings, S.R.; Ahrens, R.N.M.; Allen, M.S.; Iii, W.F.P. Testing the efficacy of lionfish traps in the northern Gulf of Mexico. *PLoS ONE* **2020**, *15*, e0230985. [CrossRef] [PubMed]
42. Conklin, J. *Dialogue Mapping: Building Shared Understanding of Wicked Problems*; Wiley: New York, NY, USA, 2005.
43. Woodford, D.J.; Richardson, D.M.; MacIsaac, H.J.; Mandrak, N.E.; van Wilgen, B.W.; Wilson, J.R.U.; Weyl, O.L.F. Confronting the wicked problem of managing biological invasions. *NeoBiota* **2016**, *8*, 63–86. [CrossRef]
44. Sims, C.; Finnoff, D.; Shogren, J.F. Bioeconomics of invasive species: Using real options theory to integrate ecology, economics, and risk management. *Food Secur.* **2016**, *8*, 61–70. [CrossRef]
45. Green, S.J.; Grosholz, E.D. Functional eradication as a framework for invasive species control. *Front. Ecol. Environ.* **2021**, *19*, 98–107. [CrossRef]
46. Del Carmen Carrillo-Flota, E.; Aguilar-Perera, A. Stakeholder perceptions of red lionfish (*Pterois volitans*) as a threat to the ecosystem and its potential for human consumption in Quintana Roo, Mexico. *Ocean Coast. Manag.* **2017**, *136*, 113–119. Available online: https://agris.fao.org/agris-search/search.do?recordID=US201700079091 (accessed on 5 July 2021). [CrossRef]
47. Nuñez, M.A.; Kuebbing, S.; Dimarco, R.D.; Simberloff, D. Invasive species: To eat or not to eat, that is the question. *Conserv. Lett.* **2012**, *5*, 334–341. [CrossRef]
48. Malpica-Cruz, L.; Fulton, S.; Quintana, A.; Zepeda-Domínguez, J.A.; Quiroga-García, B.; Tamayo, L.; Noh, J.Á.C.; Côté, I. Trying to collapse a population for conservation: Commercial trade of a marine invasive species by artisanal fishers. *Rev. Fish Biol. Fish.* **2021**, *31*, 667–683. [CrossRef]
49. Carballo, E.; Tobi, H. Citizen science regarding invasive lionfish in Dutch Caribbean MPAs: Drivers and barriers to participation. *Ocean Coast. Manag.* **2016**, *133*, 114–127. [CrossRef]
50. Morris, J. *Invasive Lionfish: A Guide to Control and Management*; Gulf and Caribbean Fisheries Institute Special Publication Series Number 1; Gulf and Caribbean Fisheries Institute: Marathon, FL, USA, 2012; p. 113. [CrossRef]
51. Scyphers, S.B.; Powers, S.P.; Akins, J.L.; Drymon, J.M.; Martin, C.W.; Schobernd, Z.H.; Schofield, P.J.; Shipp, R.L.; Switzer, T.S. The Role of Citizens in Detecting and Responding to a Rapid Marine Invasion. *Conserv. Lett.* **2015**, *8*, 242–250. Available online: https://conbio.onlinelibrary.wiley.com/doi/pdf/10.1111/conl.12127 (accessed on 5 July 2021). [CrossRef]
52. Bernard, H.R. *Research Methods in Anthropology: Qualitative and Quantitative Approaches*; Altamira Press: Walnut Creek, CA, USA, 2002.
53. Swanborn, P. *Case Study Research: What, Why and How?* 1st ed.; SAGE: Thousand Oaks, CA, USA, 2021. [CrossRef]
54. Blakeway, R.; Fogg, A.; Jones, G. Oldest Indo-Pacific Lionfish (*Pterois volitans/P. miles*) Recorded From the Northwestern Gulf of Mexico. *Gulf Caribb. Res.* **2021**, *32*, GCFI1–GCFI4. [CrossRef]
55. Côté, I.M.; Darling, E.S.; Malpica-Cruz, L.; Smith, N.S.; Green, S.J.; Curtis-Quick, J.; Layman, C. What Doesn't Kill You Makes You Wary? Effect of Repeated Culling on the Behaviour of an Invasive Predator. *PLoS ONE* **2014**, *9*, e94248. [CrossRef] [PubMed]
56. Earp, H.S.; Liconti, A. Science for the future: The use of citizen science in marine research and conservation. In *YOUMARES 9—The Oceans: Our Research, Our Future*; Jungblut, S., Liebich, V., Bode-Dalby, M., Eds.; Springer: Cham, Switzerland, 2019; pp. 1–19. [CrossRef]
57. Grason, E.W.; McDonald, P.S.; Adams, J.; Litle, K.; Apple, J.K.; Pleus, A. Citizen science program detects range expansion of the globally invasive European green crab in Washington State (USA). *Manag. Biol. Invasions* **2018**, *9*, 39–47. [CrossRef]
58. Lehtiniemi, M.; Outinen, O.; Puntila-Dodd, R. Citizen science provides added value in the monitoring for coastal non-indigenous species. *J. Environ. Manag.* **2020**, *267*, 110608. [CrossRef] [PubMed]
59. Pearson, J.M.N.; Kidd, J.A.; Knysh, K.M.; Van den Heuvel, M.R.; Gagnon, J.; Courtenay, S.C. Identification of native and non-native grass shrimps *Palaemon* spp. (Decapoda: *Palaemonidae*) by citizen science monitoring programs in Atlantic Canada. *J. Crustacean Biol.* **2019**, *39*, 189–192. [CrossRef]
60. Giovos, I.; Kleitou, P.; Poursanidis, D.; Batjakas, I.; Bernardi, G.; Crocetta, F.; Doumpas, N.; Kalogirou, S.; Kampouris, T.E.; Keramidas, I.; et al. Citizen-science for monitoring marine invasions and stimulating public engagement: A case project from the eastern Mediterranean. *Biol. Invasions* **2019**, *21*, 3707–3721. [CrossRef]
61. Anderson, L.G.; Chapman, J.K.; Escontela, D.; Gough, C.L.A. The role of conservation volunteers in the detection, monitoring and management of invasive alien lionfish. *Manag. Biol. Invasions* **2017**, *8*, 589–598. Available online: http://researchspace.bathspa.ac.uk/12869/1/12869.pdf (accessed on 5 July 2021). [CrossRef]
62. Ballard, H.L.; Phillips, T.B.; Robinson, L. Conservation outcomes of citizen science. In *Citizen Science*; Hecker, S., Haklay, M., Bowser, A., Makuch, Z., Vogel, J., Bonn, A., Eds.; UCL Press: London, UK, 2018; pp. 254–268. Available online: https://www.jstor.org/stable/j.ctv550cf2.25 (accessed on 5 July 2021).
63. Fogg, A.; Evans, J.; Peterson, M.; Brown-Peterson, N.; Hoffmayer, E.; Ingram, G.W. Comparison of Age and Growth Parameters of Invasive Red Lionfish (*Pterois volitans*) Across the Northern Gulf of Mexico. *Fish. Bull.* **2019**, *117*, 1–15. [CrossRef]
64. Malpica-Cruz, L.; Chaves, L.C.T.; Côté, I. Managing marine invasive species through public participation: Lionfish derbies as a case study. *Mar. Policy* **2016**, *74*, 158–164. [CrossRef]

65. Harris, H.E.; Fogg, A.Q.; Yanong, R.P.; Frasca, S., Jr.; Cody, T.; Waltzek, T.B.; Patterson, W.F. First Report of an Emerging Ulcerative Skin Disease in Invasive Lionfish: FA209/FA209, *9*/2018. *EDIS* **2018**, *5*, 1–7. [CrossRef]
66. Harris, H.E.; Fogg, A.Q.; Allen, M.S.; Ahrens, R.N.M.; Patterson, W.F. Precipitous Declines in Northern Gulf of Mexico Invasive Lionfish Populations Following the Emergence of an Ulcerative Skin Disease. *Sci. Rep.* **2020**, *10*, 1934. [CrossRef] [PubMed]
67. Savva, I.; Chartosia, N.; Antoniou, C.; Kleitou, P.; Georgiou, A.; Stern, N.; Hadjioannou, L.; Jimenez, C.; Andreou, V.; Hall-Spencer, J.M.; et al. They are here to stay: The biology and ecology of lionfish (*Pterois miles*) in the Mediterranean Sea. *J. Fish Biol.* **2020**, *97*, 148–162. [CrossRef] [PubMed]
68. Ulman, A.; Harris, H.E.; Doumpas, N.; Deniz Akbora, H.; Al Mabruk, S.A.A.; Azzurro, E.; Bariche, M.; Çiçek, B.A.; Deidun, A.; Demirel, N.; et al. 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.* **2021**, *8*, 413. [CrossRef]
69. Mannino, A.M.; Balistreri, P.; Deidun, A. The marine biodiversity of the Mediterranean Sea in a changing climate: The impact of biological invasions. *Mediterr. Identities Environ. Soc. Cult.* **2017**, 101–127. [CrossRef]
70. Hind, E.J.; Alexander, S.M.; Green, S.J.; Kritzer, J.P.; Sweet, M.J.; Johnson, A.E.; Amargós, F.P.; Smith, N.S.; Peterson, A.M. Fostering effective international collaboration for marine science in small island states. *Front. Mar. Sci.* **2015**, *2*, 86. [CrossRef]
71. Druschke, C.G.; Seltzer, C.E. Failures of Engagement: Lessons Learned from a Citizen Science Pilot Study. *Appl. Environ. Educ. Commun.* **2012**, *11*, 178–188. [CrossRef]
72. Thiel, M.; Penna-Diaz, M.A.; Luna-Jorquera, G.; Salas, S.; Sellanes, J.; Stotz, W. Citizen scientists and marine research: Volunteer participants, their contributions, and projection for the future. In *Oceanography and Marine Biology: An Annual Review*; Hughes, R.N., Hughes, D.J., Smith, I.P., Eds.; CRC Press: Boca Raton, FL, USA, 2014. [CrossRef]
73. Cigliano, J.A.; Meyer, R.; Ballard, H.L.; Freitag, A.; Phillips, T.B.; Wasser, A. Making marine and coastal citizen science matter. *Ocean Coast. Manag.* **2015**, *115*, 77–87. [CrossRef]
74. Sanders, M.J.; Miller, L.; Bhagwat, S.A.; Rogers, A. Conservation conversations: A typology of barriers to conservation success. *Oryx* **2021**, *55*, 245–254. [CrossRef]
75. Frazer, T.K.; Jacoby, C.A.; Edwards, M.A.; Barry, S.C.; Manfrino, C.M. Coping with the Lionfish Invasion: Can Targeted Removals Yield Beneficial Effects? *Rev. Fish. Sci.* **2012**, *20*, 185–191. [CrossRef]
76. Nesshöver, C.; Vandewalle, M.; Wittmer, H.; Balian, E.V.; Carmen, E.; Geijzendorffer, I.R.; Görg, C.; Jongman, R.; Livoreil, B.; Santamaria, L.; et al. The network of knowledge approach: Improving the science and society dialogue on biodiversity and ecosystem services in Europe. *Biodivers. Conserv.* **2016**, *25*, 1215–1233. [CrossRef]