2024-02

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Savva, I

10.1002/aqc.4104
Aquatic Conservation: Marine and Freshwater Ecosystems
Wiley

Received: 21 October 2023 | Revised: 30 December 2023 | Accepted: 26 January 2024
DOI: 10.1002/aqc.4104

RESEARCH ARTICLE

WILEY

An underwater clash of spears: Public engagement in Mediterranean lionfish control efforts

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Funding information
EU LIFE Programme financial instrument of the European Union – RELIONMED project, Grant/Award Number: LIFE16 NAT/CY/000832

Abstract

1. Invasive alien species pose a great challenge in conservation ecology. Rapid establishment of common lionfish (*Pterois miles*) in the eastern Mediterranean Sea and its ongoing westward expansion raises many questions about how to sustainably combat this invasion in the long term.
2. Drawing on experiences from the western Atlantic invasion, citizen scientists were engaged and demonstrated the efficiency of long-term coordinated removals for the first time in the Mediterranean Sea.
3. Findings reveal a sustained participation and interest throughout the coordinated removal events that encourage the organization of future events. Removal Action Teams were found effective at reducing lionfish numbers in small (less than half a hectare) areas of high conservation value, when removals were repeated systematically.
4. Single-day lionfish derbies, operated at greater spatial scales, succeeded in a 50% reduction in lionfish abundance while removing most large (>30 cm) individuals from an area after three consecutive events.
5. Given the recreational character of such activities, coordinated removals are useful options for management and conservation when guided by competent authorities and supported by citizens, as they promote marine environmental awareness and help develop a sense of stewardship among members of the public.

KEYWORDS
citizen science, Cyprus, invasive species management, lionfish derbies/tournaments, lionfish removals, Mediterranean Sea, *Pterois miles*

Ioannis Savva and Leda L. Cai are equal first authors.

1 | INTRODUCTION

Marine biological invasions constitute an emerging challenge in the context of global ecological change (Anton et al., 2019), with the potential of altering biodiversity patterns that often induce adverse impacts on social welfare (Mack et al., 2000; Tsirintanis et al., 2022). During recent decades, inclining trends in marine non-indigenous species (NIS) introductions have soared in the global ocean as a consequence of intensified anthropogenic footprint (Katsanevakis et al., 2014a; Ojaveer et al., 2018). On a planetary scale, Europe has the highest number of NIS (Tsiamis et al., 2018), where introductions ranged from six NIS per year in the 1970–1975 assessment period to 21 NIS per year in the latest assessment between 2012–2017 (Zenetos et al., 2022). Among the European Seas, the Mediterranean Sea, and especially the Levantine Basin, has by far the highest number of introductions due to the Suez Canal and intense shipping traffic (Katsanevakis et al., 2014a; Tsiamis et al., 2018; Zenetos et al., 2022), hence, rightfully entitled as a global NIS hotspot (Katsanevakis et al., 2014a).

A subset of the NIS species in the Mediterranean Sea is highly invasive (invasive alien species—IAS), negatively impacting biodiversity, human health and economies. When IAS are introduced into an area, their numbers are rarely controlled by native pathogenic organisms and predators (Giakoumi et al., 2019; Katsanevakis et al., 2014b), they become ubiquitous, can successfully outcompete similar functional groups of species and have negative effects on the recipient ecosystems (Earp et al., 2018; Edelist et al., 2013). Among the Osteichthyes, some prime examples of invasive species include *Fistularia commersonii*, *Siganus* spp., *Lagocephalus sceleratus*, *Plotosus lineatus* and *Parupeneus forsskali* (Tsirintanis et al., 2022). With the additional introduction, rapid colonization and establishment of *Pterois miles* (hereafter lionfish) in the eastern Mediterranean Sea (Azzurro et al., 2017; Kletou et al., 2016), a new alarming attention rose among scientists and stakeholders with widespread calls to tackle the invasion (Kleitou et al., 2021a), as adverse ecological impacts of this invasive fish are well documented in the western Atlantic (Côté & Smith, 2018).

To reduce the impacts of lionfish in the Mediterranean, the European Commission funded the project 'Preventing a LIONfish invasion in the MEDiterranean through early response and targeted Removal - RELIONMED' (LIFE16 NAT/CY/000832) that aimed to make Cyprus the first line of defence against the invasion (Kleitou et al., 2021a). After a year of research efforts to study its biological and ecological characteristics (Mouchlianitis et al., 2022; Savva et al., 2020), it became clear that lionfish adapted to the local conditions and quickly established growing populations that spread widely. A population suppression approach was adopted, also known as functional eradication (Green & Grosholz, 2021). The aim was to decrease lionfish abundance in target areas to levels that minimize adverse ecological impacts, which also satisfies the objectives of Descriptor 2 on NIS in the EU Marine Strategy Framework Directive (MSFD; Tsiamis et al., 2019).

striking positive effects on native biota and socio-economic indicators (Côté et al., 2014a; de León et al., 2013; Green et al., 2014; Green & Grosholz, 2021; Malpica-Cruz et al., 2017), especially when in close cooperation with the conservation sector (Quintana et al., 2023). Targeted removal efforts with spearfishing (Morris et al., 2012) pose a suitable potential fishery, unique for exploitation—at least within depths of recreational diving limits, that is, ∼30 m for SCUBA divers and ∼15–20 m for freediving spearfishers (Malpica-Cruz et al., 2016). However, such tactics require human and capital resources and can become an economic burden for competent authorities (Jardine & Sanchirico, 2018; Usseglio et al., 2017). A cost-effective way of removing lionfish is to engage the public in management. This approach not only fosters awareness among citizens (e.g., Giovos et al., 2019) but further encourages the commercialization of the species by utilizing the catches under a sustained supply and demand scheme (Chapman et al., 2016; Malpica-Cruz et al., 2021). These can be crucial steps in controlling invasive species and have been stressed as two of the top priorities identified by Giakoumi et al. (2019) to successfully manage NIS.

Public engagement campaigns or programs are widely renowned in the context of lionfish controlling efforts in the western Atlantic, guided by stakeholders such as NGOs, park managers, research institutions and fishermen unions (Malpica-Cruz et al., 2016). These often take the form of small, targeted removal events operated by trained volunteers (Ali et al., 2013; Frazer et al., 2012; Harms-Tuohy et al., 2018; Harris et al., 2019) or in large-scale tournaments/derbies that are open for participation to the wider public (Green et al., 2017; Malpica-Cruz et al., 2016; Morris et al., 2012). Specifically, the competitive structure of derbies often appeals to participants, to earn prizes and gain recognition by aiming for the most lionfish caught, the largest and/or smallest lionfish in size within a given timeframe. Both can be implemented in a strategic manner to attain the highest efficacy in clearing infested sites of exceptional ecological significance and at the same time optimizing limited management resources (Frazer et al., 2012; Green et al., 2017; Malpica-Cruz et al., 2016).

Drawing on published findings from the western Atlantic invasive lionfish range, the RELIONMED project formed lionfish Removal Action Teams (RATs), trained and equipped divers, as well as implemented lionfish removal events as an excellent replicability opportunity in the eastern Mediterranean region. Coordinated removal events ran for 3 years across Cyprus; the present study sought to investigate the outcome of these long-term efforts in regard to lionfish removal success and the societal effects of this citizen engagement activity. Our aim is to help inform managing authorities, and other bodies of interest, as the lionfish is spreading rapidly throughout the Mediterranean. Using both coordinated RAT surveys and Derby events, the study addresses five questions: (1) Was public participation in these events successful in terms of continuance intention and growth? (2) To what extent did RAT surveys suppress lionfish numbers? (3) Do recurrent derby events suppress lionfish numbers? (4) Which is the most effective diving removal effort? and (5) How many divers are sufficient for a thorough removal?

2 | MATERIALS AND METHODS

2.1 | Removal Action Teams assembly and Derby organization

The formation of RATs was initiated with the application, selection and registration of a maximum of 100 volunteer SCUBA divers certified with dive qualification from a known diving group or association. All the registered RAT members had to attend training workshops with sessions on lionfish and the invasion including its ecological impacts, biological remarks, edibility, safe handling and first-aid (Kleitou et al., 2021b). Following this, members became familiarized with a lionfish removal toolkit, which was handcrafted locally within the RELIONMED project, and consisted of sling spears, lionfish keepers (containers), puncture-resistant gloves and heat packs (reusable lionfish sting treatment). After the training, RAT excursions were scheduled at least on a monthly basis and RAT members were informed in advance for mobilization in priority areas for conservation, such as Natura 2000 sites and Marine Protected Areas (MPAs) with artificial reefs, or areas that were previously reported as lionfish hotspots.

Eight derbies with larger numbers of participant divers were implemented in a period of 2 years at the Natura 2000 areas of Kavo Gkreko (CY3000005), Nisia (CY3000006) and bordering sites. While most derbies were only for SCUBA divers, some derbies were mixed allowing the participation of free divers while one of the derbies that took place in a different area (Xylofagou) was exclusive for free divers. The public was informed about upcoming derby events through personal communication, news media and social media, including groups/pages created for the RELIONMED project. Derby participation was open to the public, and they could enter the competition by submitting their details, diving qualifications and health declaration forms at the assembly point. This was followed by a swift training session on the lionfish removal kit and lionfish safe handling procedures. Participants had to form small teams (two to three divers) before the competition, and they could only enter the water at allocated entry points. During the competition, the area was continuously patrolled by safety boats as well as monitored by staff on land at the entry points. Prizes were given for the most, the biggest and the smallest lionfish removed. In mixed derbies, prizes for SCUBA and free divers were separated. Refreshments and snacks were available throughout the entire duration of the competition and the awarding procedure. In most derbies, participants had the opportunity to taste different lionfish recipes prepared by chefs on the spot and the remaining lionfish were given to participants to consume.

For both types of coordinated lionfish removals, a permit was obtained from the Port & Marine Police and the Department of Fisheries and Marine Research (DFMR) of Cyprus. Removal efforts with SCUBA were allowed only in the presence of RELIONMED staff members with special permits.

2.2 | Data collection and curation

A standardized data sheet was developed to collect crucial information on certain lionfish removal variables right after divers exited the water (Table S1). Specifically, at the end of each of these events, RAT members or derby participants were asked for the maximum depth of their search effort, seawater temperature, bottom time and number of lionfish caught, seen and missed. The total catch of lionfish from each team was later validated directly from counting lionfish in the lionfish keepers and was corrected when mismatched.

The coordinated removal success in the social context was assessed in the demographic structure of the participants and the participation numbers. The catch characteristics of these events were evaluated by five main attributes including the (1) total number of lionfish removed, two standardized effort units on lionfish catch and misses: the (2) Catch per Unit of Effort (CPUE) and (3) Misses per Unit of Effort (MPUE). For both effort units, the bottom time (a proxy of lionfish search) and the number of divers involved were used for the calculation as shown below:

$$CPUE = \left(\frac{\#\ Lionfish\ Removed}{\#\ Divers\ Removing}\right) / Searching\ Time\ (h)$$

$$MPUE = \left(\frac{\#\ Lionfish\ Missed}{\#\ Divers\ Removing}\right) / Searching\ Time\ (h)$$

The area of search was not accounted for within the formula, since most divers were not capable of indicating the space covered during a dive. The fourth variable used in the study was (4) Catch Efficiency (%), which explains to what extent lionfish misses have affected the catch. The attribute was calculated as shown below:

$$Catch\ Efficiency\ (\%) = \left(\frac{\#\ Lionfish\ removed}{\#\ Lionfish\ seen}\right) * 100$$

To evaluate whether increased or reduced catches were attributed to the removal experience of the divers in the context of derbies, an attendance index was developed:

$$Attendance\ (\%) = \left(\frac{Cumulative\ attendance\ score}{Cumulative\ highest\ attendance\ score}\right) * 100$$

All derby participants including those who joined RAT memberships were given a score for each time they have attended any of the two types of removal events. The cumulative scores for each person at a given event in time were then divided by the highest attendance score achieved at the end of the project. In the context of RAT events, the lionfish removal familiarity was considered to all as equal, since most RAT members were frequent participants.

To evaluate the efficiency of removals, a 5th and the final metric was constructed by employing lionfish sightings as a proxy of lionfish abundance in targeted areas and standardized into Sightings per Unit of Effort (SPUE):

$$SPUE = \left(\frac{\#\ Lionfish\ Seen}{\#\ Divers\ Removing}\right) / Searching\ Time\,(h)$$

Aside from the temporal analysis, the SPUE was also fitted against removal pressure, which was defined as the number of removals exerted on a particular site at a given time. The removal pressure on derby sites subjected to removal efforts for the first time was set to zero, unless RAT efforts had previously cleared the area from lionfish. In this context, these sites were thus set at zero removal pressure from the preceding RAT survey. Subsequently, each time removal efforts took place at a particular site over the course of the derby events, the site was assigned to a higher score of removal pressure. In addition to SPUE, biomass composition retrieved from a sub-sample of lionfish from the derby events was further fitted in this respect to evaluate whether large lionfish disappear in sites subjected to higher removal pressure. The lionfish sub-sample consisted of the smallest and the largest lionfish individuals caught from across the participating teams.

To identify the maximum removal effort efficiency, a non-linear asymptotic regression was applied to model the plateau in which lionfish catches per hour are no longer benefited with additional divers within an optimal searching area of no more than half a hectare (an estimate of the likely area coverage of most of the featured diving sites during a single dive) over a continuous complex habitat:

$$Lionfish\ removed\ h^{-1} = plateau - (plateau - a) \times exp(-b \times \#\ of\ Divers)$$

where plateau is the maximum attainable lionfish removed h^{-1}, a is lionfish removed h^{-1} at zero number of divers and b is proportional to the relative rate of lionfish removed h^{-1} increase while the number of divers increases.

2.3 | Statistical analysis

Standard quantitative statistics were computed to characterize the demographic structure and compare ratios and distributions. To delineate the linear or non-linear temporal patterns in lionfish CPUE, MPUE and catch efficiency (%) for both types of coordinated removals, Generalized Additive (Mixed) Models (GAMs/GAMMs) were applied. Model fitting for each trend of interest was conducted with a set of different distribution families, and the one with the lowest Akaike's information criterion (AIC; Akaike, 1973) was selected as the most suitable model. All modelling framework was performed in R-studio v.4.2.2, and the level of significance α was adjusted to 0.05. GAMs were fitted with the 'mgcv' package in R-studio v.4.2.2, and model adequacy was visually inspected through residual plots. Graphics were produced via the package 'ggplot2', and maps were generated in QGIS v.3.16.4.

3 | RESULTS

3.1 | Demographic structure

At least 50% of the registered RAT members were actively attending most of the surveys. Overall, 113 SCUBA divers and 59 free divers participated in the derbies, with an average participation rate of 34 participants per derby. Both types of coordinated removals attracted many environmentally aware divers to tackle the lionfish issue. Most were either owners of diving centres or diving club members who experienced the lionfish threat and the stinging risk within confined environments during their frequent diving routes. Other divers registered in the lionfish derbies for the experience, the recreational perspective or even the incentive. Incentives in this case varied among individuals, with some aiming for the awards/prizes at the end of the competition, while others for consuming their lionfish catch.

The majority of the participants were men (Figure 1a,b), with most of the women joining in the derbies at the SCUBA category compared to the free diver entries (2-Proportion test, $\chi^2 = 7.62$, $p < 0.05$; Figure 1a,b). RAT members represented five districts (Limassol, Nicosia, Larnaca, Paphos and Famagusta) at unequal proportions ($\chi^2 = 8.56$, $p < 0.05$), with Paphos exhibiting the least number of registrations and Famagusta having the highest proportion of overseas members (Figure 1c). The participation structure for derby SCUBA entries was also found unequal both across districts ($\chi^2 = 31.18$, $p < 0.05$), and the locals-to-overseas composition was proportionally different in each of the districts ($\chi^2 = 21.24$, $p < 0.05$), with Paphos represented by a single entry from overseas (Figure 1d). For free diver derby entries, the participation composition mainly involved locals ($\chi^2 = 1.78$, $p > 0.05$), but the participant distribution across districts varied ($\chi^2 = 18.38$, $p < 0.05$; Figure 1d).

The age-density distribution of RAT members and the derby SCUBA entries was similar (Kernel density equality test, $p > 0.05$) and exhibited a bimodal shape, in which participants were represented by two distinct groups: below and above 40 years of age (Figure 1e,f). On the other hand, the derby free diver entries exhibited a positively skewed age–frequency distribution, towards younger participants (Figure 1f), which was significantly different from those in derby SCUBA entries (Kernel density equality test, $p < 0.05$) and RAT members (Kernel density equality test, $p < 0.05$).

3.2 | Coordinated removals—Removal Action Teams

The RAT surveys began in March 2019 and finalized in November 2021. About 122 individual dives were made along the Cyprus' coastline and overall, 3032 lionfish were removed through the RAT expeditions. At a district level, a few removal surveys were conducted in Paphos (Figure 2a,b), which were subjected to low and stable lionfish catches over time. A similar pattern was observed in Larnaca (Figure 2a,b), although some of the surveys had a higher CPUE,

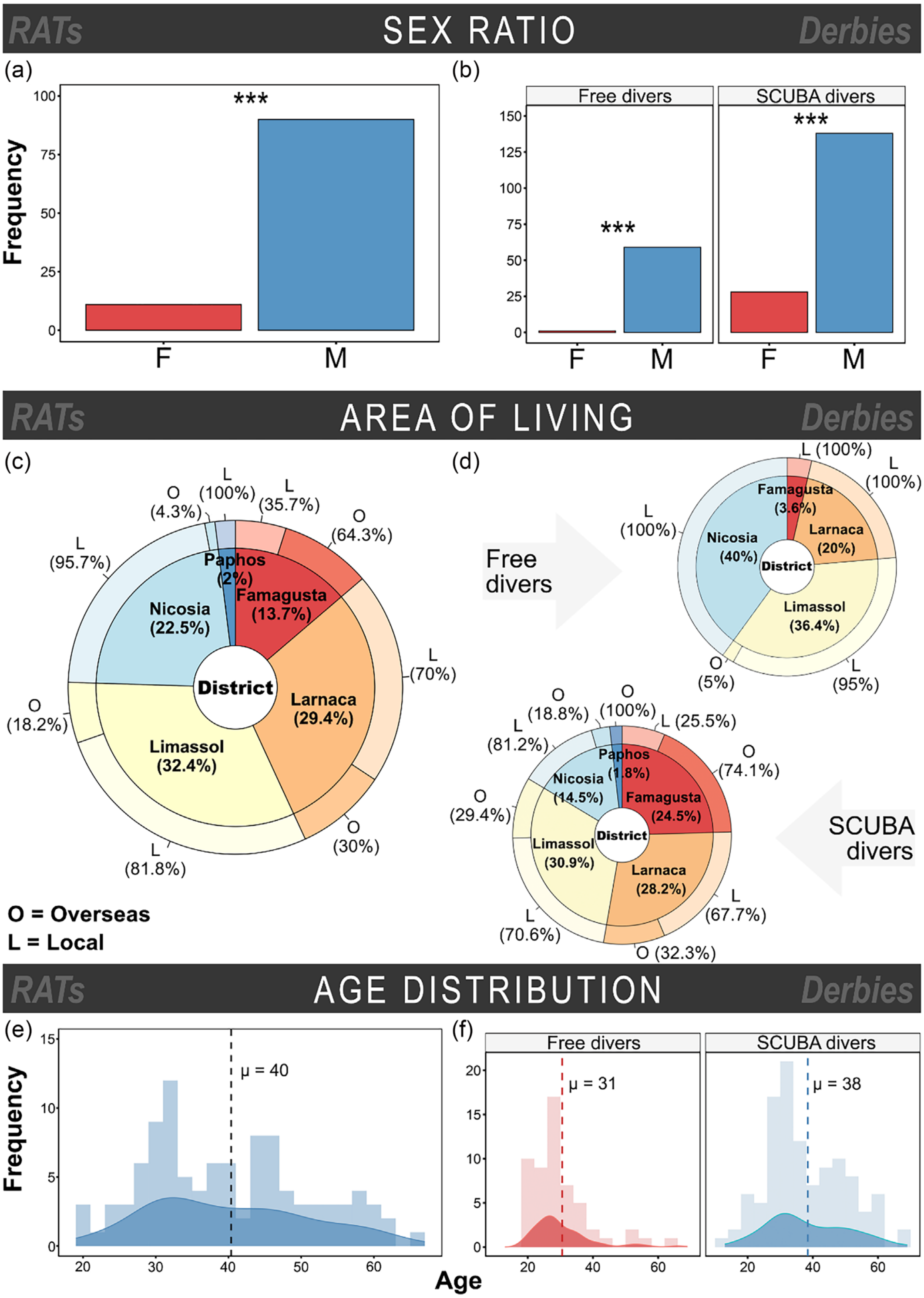

FIGURE 1 The demographic characteristics of Removal Action Team (RAT) members and derby participants. Note: μ corresponds to mean; significant difference is denoted with a triple asterisk where ****p* < 0.001.

represented by removal efforts at the Zenobia shipwreck. The increased MPUE and subsequently the decline of catch efficiency may also explain this stable CPUE trend. The greatest removal effort was imposed in the Famagusta district, mainly in the two Natura 2000 sites and within the MPA with artificial reefs at the Protaras/Paralimni area (Figure 2a). This implied the highest number of lionfish removed (Figure 2a), but not the highest catch yield in terms of CPUE (Figure 2b). Moreover, lionfish catches in Famagusta have shown an increase from 2019 to 2020 but dropped drastically by 2021, coinciding with an observed significant increase in MPUE and

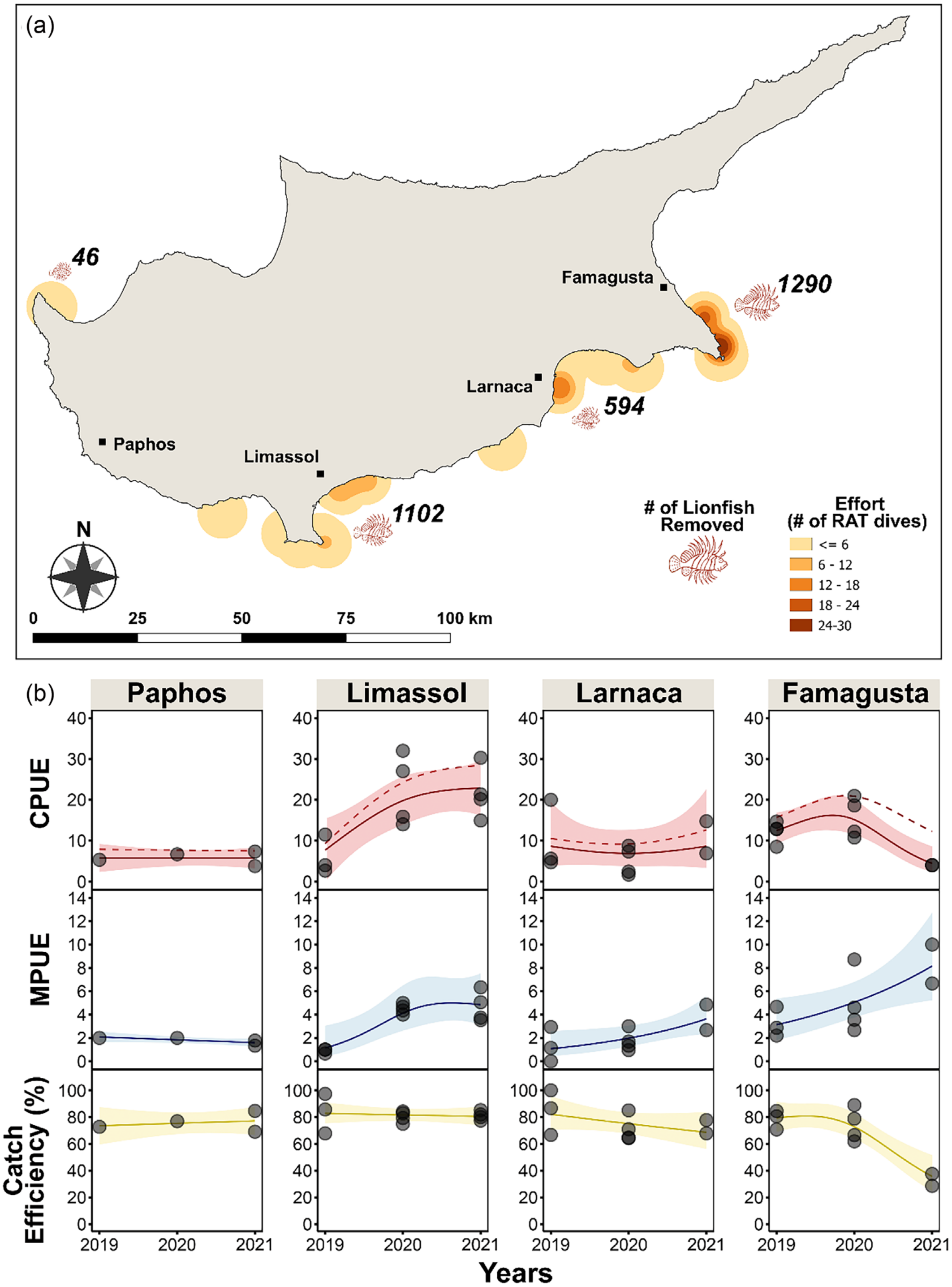

FIGURE 2 The RAT surveys between 2019 and 2021 for each district. (a) The heatmap denotes the RAT effort expressed in the number of surveys at a given area, while the lionfish size indicates the number of lionfish removed per district. (b) Linear and non-linear trends of Catch Per Unit Effort (CPUE), Misses Per Unit Effort (MPUE) and catch efficiency (%) are illustrated for each district. Note: Shaded bandwidth represents 95% confidence intervals; dashed CPUE lines express the SPUE; data points represent averaged seasons.

subsequently a significant decrease in catch efficiency (Figure 2b and Table 1). Limassol was second in the total amount of lionfish removed, with similar numbers to Famagusta despite having less removal effort by RAT members (Figure 2a). Furthermore, compared to the other districts, it demonstrated a completely different pattern in catches. Firstly, the recorded CPUE increased significantly over time (Figure 2b and Table 1). Secondly, while MPUE has also increased in 2020 and dropped again in 2021, it did not affect the catch efficiency over time (Figure 2b and Table 1). For all districts, the SPUE has shown to attain higher lionfish numbers; however, this did not change the overall pattern of the temporal trend (Figure 3b).

TABLE 1 Summary of the GAMs and GAMMs between the specified variables with or without random effects for a given activity.

Activity	Variables (Y∼X)	Random effect	Distribution family	*df* (smooth term)	*F* statistic or χ^2	*p*-value
RATs—Paphos	CPUE∼Years		Gaussian	1	0.000	1
RATs—Limassol	CPUE∼Years		Gaussian	1.54	6.141	**0.049**
RATs—Larnaca	CPUE∼Years		NB	1.323	0.347	0.788
RATs—Famagusta	CPUE∼Years		NB	1.885	10.920	**0.003**
RATs—Paphos	MPUE∼Year		Gaussian	1	2.400	0.261
RATs—Limassol	MPUE∼Year		Gaussian	1.844	21.72	**<0.001**
RATs—Larnaca	MPUE∼Year		NB	1	2.910	0.088
RATs—Famagusta	MPUE∼Year		NB	1	5.610	**0.018**
RATs—Paphos	CE (%)∼Year		Gaussian	1	0.152	0.734
RATs—Limassol	CE (%)∼Year		Gaussian	1	0.154	0.704
RATs—Larnaca	CE (%)∼Year		Gaussian	1	1.537	0.255
RATs—Famagusta	CE (%)∼Year		Gaussian	1.812	7.522	**0.021**
Derby	CPUE∼Months	Sites	NB	2.368	3.989	**0.038**
Derby	MPUE∼Months	Sites	Gamma	3.218	7.476	**0.001**
Derby	CE (%)∼Months	Sites	QPoisson	1	9.427	**0.005**
Derby	SPUE∼RP	Sites	NB	2.66	7.766	**0.002**

Note: Relationships were determined as significant (in bold) when the smoothing term was at $p < 0.05$ based on the approximate *F* statistic.
Abbreviations: CE, catch efficiency (%); NB, negative binomial; QPoisson, Quasi-Poisson; RP, Removal pressure.

3.3 | Coordinated removals—Derbies

Through these competitions, a total of 1732 lionfish were removed (Figures 3a–4b). Three of the derbies implemented during the summer and autumn of 2020 were more productive, removing between 350 and 400 lionfish from the targeted sites (Figure 3a). In terms of effort, lionfish CPUE relationship with time was significant, with catches increasing and then dropping towards the end of the derbies (Figure 3a and Table 1). Catches were not found to correlate with participants' attendance level (Spearman's correlation, $\rho = 0.05$, $S = 2759.2$, $p > 0.05$). An unexpected increase in the MPUE was also observed over time (Figure 3c and Table 1), which consequently reduced the lionfish catch efficiency (Figure 3d and Table 1).

The most frequently targeted sites were the Chapel, Cyclops and Kaliva at the Kavo Gkreko and Nisia regions, consequently, having the highest total number of lionfish removed from these events (Figure 4a). Other sites such as the Rita Inlet, Green Bay, Roman Harbour and Table Top were introduced in the expanded derby area at a later stage. In the absence of multiple removal efforts in all of the sites, no pairwise statistical comparison was performed, but it is noteworthy to emphasize that all the sites subjected to lionfish removals for the first time had a higher initial SPUE despite the expected variability observed between them (Figure 4b). Specifically, SPUE was influenced significantly by removal pressure, with SPUE decreasing by 50% and stabilizing after three consecutive removal events (Figure 4b and Table 1). This decline was followed by a shift in lionfish weight–density distribution towards smaller individuals (Figure 4c). Under this coordinated removal framework, a significant statistical difference was detected in CPUE between SCUBA and free divers (2-*t*-test, $df = 107$, $t = -2.33$, $p < 0.05$), with many amateur free divers demonstrating poor performance, while some experienced free divers excelled, as has been observed in Rita Inlet by a single free diver (Figure 4a) and two teams in the free divers' derby.

3.4 | Coordinated removals—Effort efficiency

The number of divers through the various lionfish removal events varied each time, with RAT groups ranging from two divers (only one diver removing lionfish) to more than 20 divers, usually participating in major culling events or derbies. Given most excursions focused on highly lionfish-invaded sites, it was found that 13 divers are enough to clear thoroughly an area of no more than half a hectare over continuous complex substrata (Figure 5). Even with nearly half the number of divers, removal efficiency decreases only by 15%. Should financial resources become limited, and 50% removal efficiency is deemed as the primary focus, then three to four divers are sufficient to achieve this goal. The same number of divers is thought suitable for optimal removal in unique cases, such as areas with artificial reefs surrounded by soft bottoms, where searching time is drastically reduced.

4 | DISCUSSION

Lionfish population suppression is an important element within an IAS regulatory framework, in which coordinated physical removals have continuously demonstrated their effectiveness towards achieving this

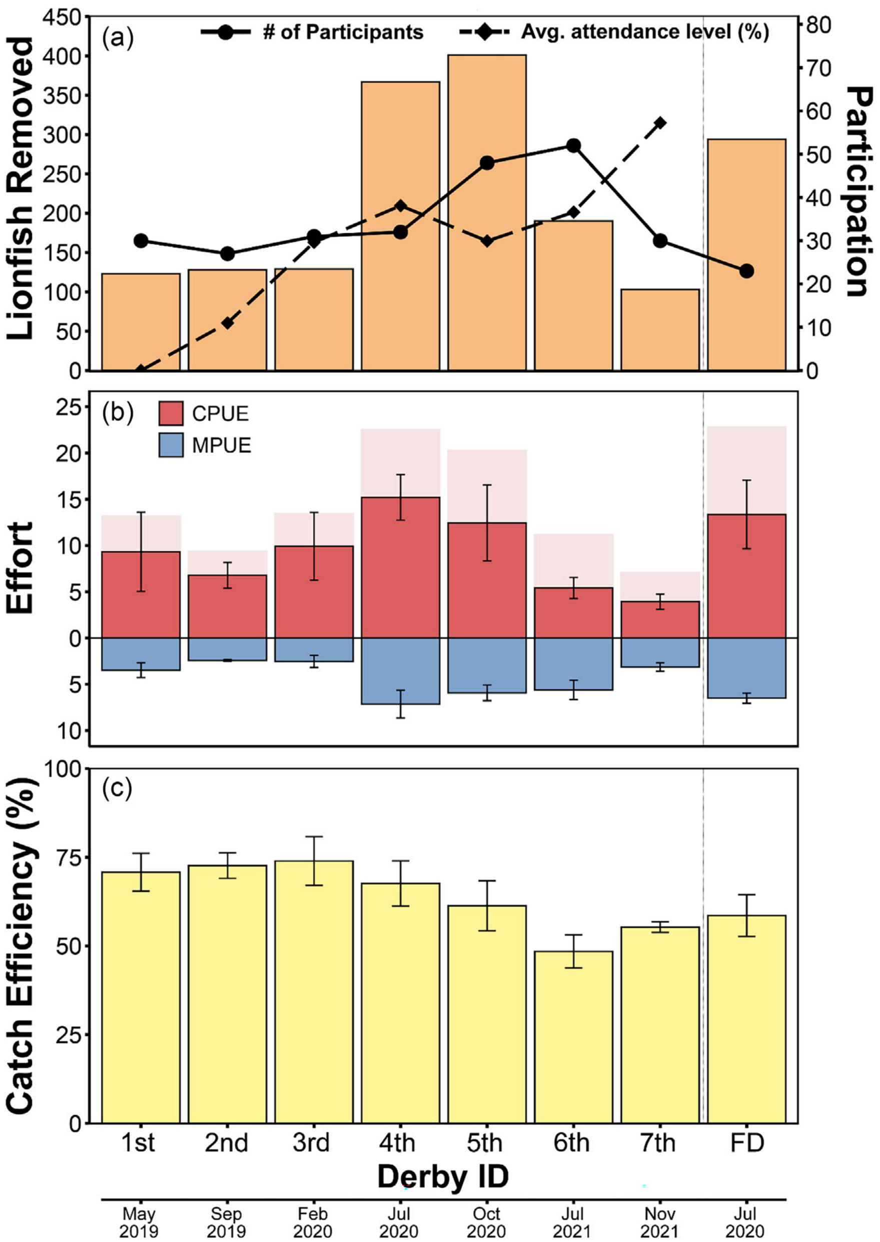

FIGURE 3 The lionfish removal efforts within the derby coordinated removal activity expressed in the number of (a) lionfish removed, participation variables, (b) effort units and (c) catch efficiency. Note: Error bars express the standard error; shaded Catch Per Unit Effort (CPUE) denotes the mean Sightings Per Unit Effort (SPUE); vertical grey line separates derbies implemented in Kavo Gkreko and Nisia regions from Xylofagou's free divers' (FD) event; the large temporal gap between the 5th and 6th derbies is attributed to COVID-19 lockdowns and subsequent safety measures.

goal. Our findings provide additional evidence for the Mediterranean invaded range and further highlight the importance of public engagement and the conservation value of citizen scientists (Clements et al., 2021; Green et al., 2017; Malpica-Cruz et al., 2016) to address this issue alongside long-term financially sustainable management (Chapman et al., 2016; Malpica-Cruz et al., 2021; Quintana et al., 2023).

Coordinated removals in Cyprus attracted participants of both genders of various ages and nationalities, distributed throughout Cyprus. Locals represented the majority of these, suggesting an encouraging interest in combating the lionfish invasion within their familiar diving sites. Most participants were marine stakeholders, while others were sea enthusiasts, both of which considered lionfish a marine environmental nuisance and a stinging risk hazard in renowned diving and bathing destinations. The high activity of RATs and the sustained high number of participants in each derby demonstrate the high success of the social dimension and indicate willingness to participate in future events. This is not surprising, since a targeted niche audience translates to active participation driven by the desire to have an impact in scientific efforts that lie within its personal interests, particularly when results are shared among the participants (Clements et al., 2021; Tiago, 2017). While many citizens are drawn to the environmental awareness aspect (Kleitou et al., 2021b) or the recreational activity element of such events (Green et al., 2017), others support the removal efforts voluntarily when personal recognition or rewards are provided, as both give a sense of achievement (Tiago, 2017).

The combined effort of both coordinated removal frameworks accomplished a total removal of 4764 lionfish within a 3-year time frame, which surpassed 12 times the number initially anticipated at

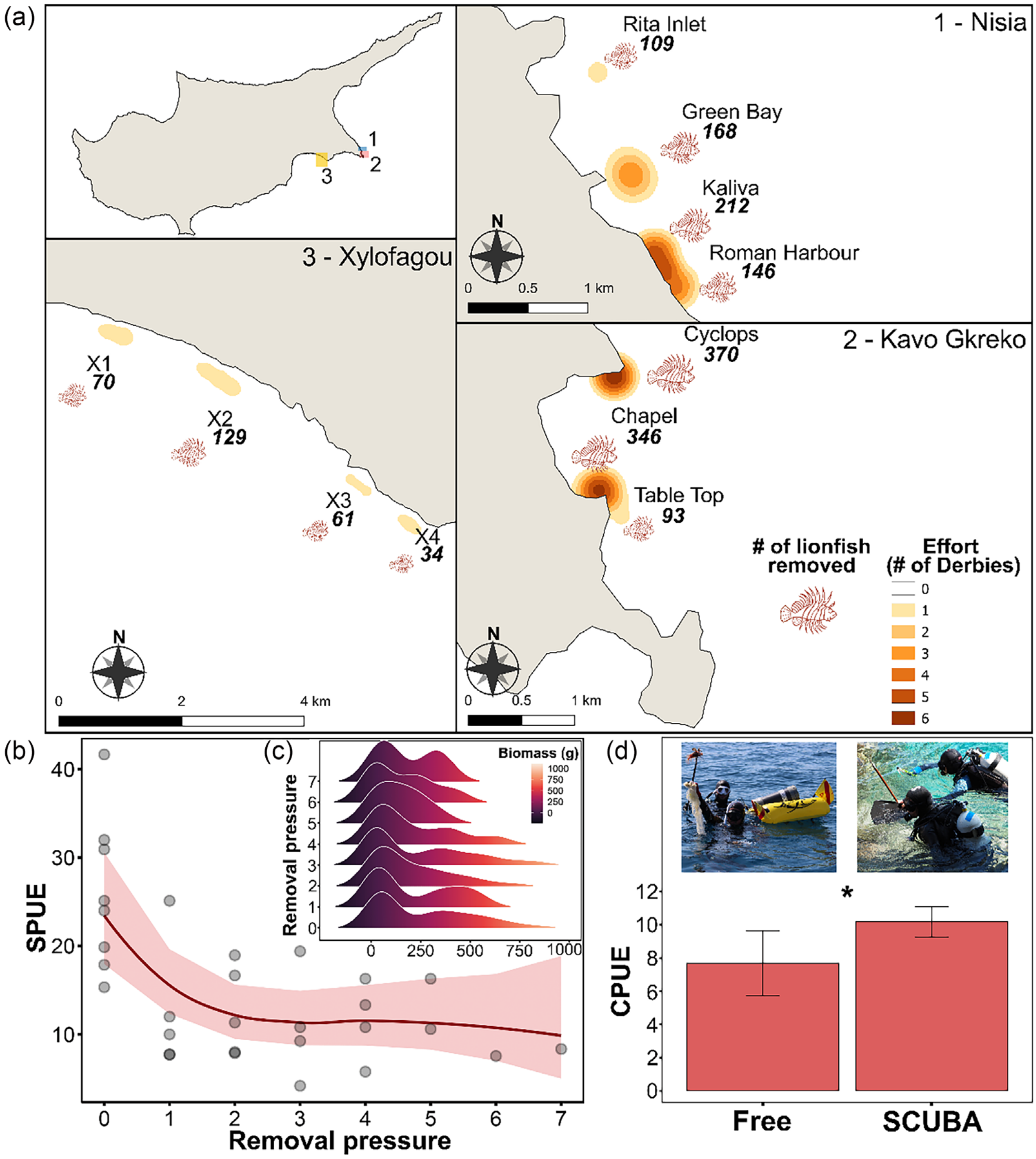

FIGURE 4 The site-specific results of the derby events (a). the Sightings Per Unit Effort (SPUE) and weight–density distribution as a result of removal pressure (b and c), and the catch results between the two categories of divers (d). The heatmap denotes the derby effort in associated sites, while lionfish size indicates the total number of lionfish removed per site. Note: Shaded bandwidth represents 95% confidence intervals; error bars express the standard error; significant difference is denoted with an asterisk where *$p < 0.05$.

the early stages of the RELIONMED project in late 2016. The resulting outcome draws a 2-fold interpretation. Firstly, the coordinated removals made possible the removal of lionfish from areas of high ecological importance, and secondly, lionfish numbers have rapidly increased both on a spatial and temporal scale, allowing more frequent encounters within the benthic environment of Cyprus (Savva et al., 2020). The observed lionfish population explosion allows for a quick recovery after removal events, but the catches have not been homogeneous across all the districts. This discrepancy may be driven by the removal frequency, and regional-specific characteristics, such as temperature, currents, habitat coverage and connectivity, as well as predator abundance. It has previously been shown that prevailing currents may prove beneficial in certain areas, substantially reducing the lionfish dispersion and larval settlement (Luiz et al., 2013), a plausible outcome in the Paphos district (Schilling et al., 2023). Furthermore, habitat complexity was also shown to drive lionfish aggregation behaviour for a number of reasons including, greater number and size diversity in refugia, prey species availability and greater potential for larval settlement (Hunt et al., 2019). Despite this being a prominent feature in Famagusta, the observed decline may in fact be associated with the frequent culling events established in the region since 2017 (Savva et al., 2020) and through the regular lionfish monitoring (Kleitou et al., submitted). Except for the Akrotiri peninsula's tip and its highly complex rocky reefs, Limassol's seafloor

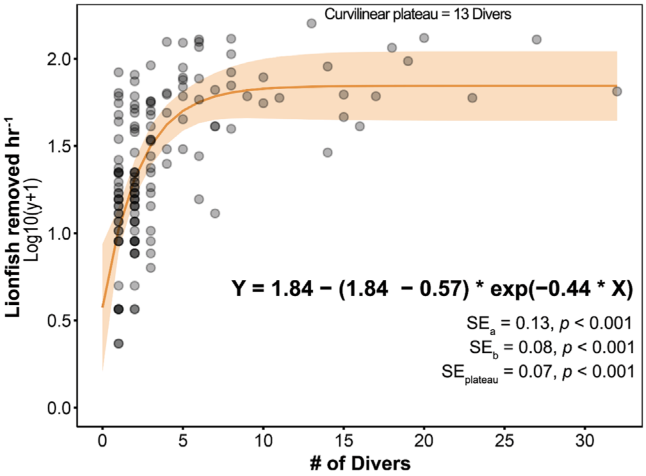

FIGURE 5 The asymptotic relationship between lionfish removed h^{-1} and the number of divers involved in each of the removal surveys. Note: S.E. and statistical significance are provided for all three models' parameters; shaded bandwidth represents 95% confidence intervals; the model is shown at log10(y + 1) scale for better visualization purposes.

is predominantly covered by seagrass meadows and soft substrata. With removals focused in two designated MPAs with artificial reefs installed in proximity, the vast majority of lionfish in the region are attracted to these complex patchy structures, forming hotspots of dense aggregations, as previously observed in the Caribbean (Tamburello & Côté, 2015), which further allow for higher detectability by divers. The exclusion of fishing activities in these MPAs together with the negative density-dependent movement exhibited by lionfish in highly complex patchy habitats (Smith et al., 2017; Tamburello & Côté, 2015) offered in a small surface area, may additionally explain the increased recolonization (Smith et al., 2017) and ultimately catch rate. In this respect, it is deemed necessary that removal frequency should be carefully revised for such unique seascapes in a dedicated study. Though this has not been the case in Larnaca with a similar seascape, where most RAT surveys were targeted in the Zenobia shipwreck, it is speculated that the combination of removals, lack of habitat connectivity (Kleitou et al., 2021b) and the presence of large groupers at the shipwreck may keep lionfish numbers and recruitment rates in control. The latter, however, must be interpreted with caution, as lionfish predation has only been recorded anecdotally in the Mediterranean (Crocetta et al., 2021; Ulman et al., 2021) while also, no predation links were established between native predators and lionfish densities on Caribbean reefs (Hackerott et al., 2013). Therefore, a substantial contribution to this field of research is highly recommended.

Results from the derby removals suggest that at a temporal scale, lionfish catches have shown an increase. This is likely attributed to the inclusion of sites at a later stage that previously remained inaccessible for removals (also see free divers' derby) and due to lionfish booming post the onset of the invasion (Savva et al., 2020). Soon after this peak, the catch yield dropped after all featured sites had been subjected to removals at least once, with divers reporting an exceptional evasion behaviour that affected the catch efficiency—also apparent in the RAT coordinated removals in Famagusta district. The intensive lionfish hunting pressure observed in the Famagusta district both from the RELIONMED's efforts and the increased lionfish hunt activity by recreational spearfishers possibly resulted in higher lionfish evasion rates. Considering that most lionfish exhibit strong site fidelity (Akins et al., 2014; Jud & Layman, 2012), unsuccessful lionfish catches in a given area could make lionfish wary towards divers, associating them with danger, and consequently becoming more difficult to catch in subsequent removal efforts (Ali et al., 2013; Côté et al., 2014b).

Focusing on the derby pressure, the overall effect of removals inflicted a 50% reduction in the lionfish numbers as consistently shown in previous studies with systematic culling (Alemu, 2016; Ali et al., 2013; Frazer et al., 2012; Green et al., 2017; Kleitou et al., 2021b; Smith et al., 2017). It should be highlighted that this does not represent a depletion level estimate that is required to alleviate predation effects (see Green et al., 2017), as the threshold limits of this concept have not been calibrated yet for the Mediterranean Sea or its distinct sub-divisions. In addition to the remarkable SPUE drop, the removals further shifted the weight–density distribution, by reducing most heavy lionfish individuals, the ones that consume more fish prey (Morris & Akins, 2009). Contrary to the SPUE, this morphometric shift was more prominent after four consequent derbies, assuming a strong habitat connectivity in a homogeneous rocky area (Tamburello & Côté, 2015). Overall, retraction of size–frequency distribution is a common sign of repeated removals that reduces the pressure on important native fish and has economic and ecological benefits (Frazer et al., 2012; Green et al., 2014), which is not surprising, as the largest lionfish in sight are often the ones targeted first by divers.

SCUBA divers were found to have a greater advantage in respect to lionfish search and catch yield at depth within highly complex artificial and natural habitats, which is commonly reported across a few studies (e.g., Malpica-Cruz et al., 2017; Malpica-Cruz et al., 2021). This is often why a few divers are required at lionfish-invaded sites, with at least 6–13 divers considered as optimal for ≥85% removal efficiency over a continuous complex habitat of no more than half a hectare; three to four divers can be as effective on sites with artificial structures surrounded by soft substratum. On the other hand, free divers are highly capable at covering larger spatial extent in shallow waters of less than 10 m depth, since searching can be conducted mostly on the surface. However, efficiency could be highly influenced by factors such as the individual-based experience, fitness, commitment and knowledge of the seascape, as well as the given density and concealment level of lionfish in the search area as has been speculated by similar studies (e.g., Jiménez et al., 2018, and therein). Such attributes have been a prime example in a few of the teams featured in this study, which makes them excellent cost-effective tools in combating lionfish, especially since recreational spearfishing is not illegal outside MPAs or any lionfish management framework. In spite of this liberty, recreational spearfishers are still limited by the EU Mediterranean Regulation (EU REG 1241//2019, 2006) and Annex III of the Cyprus Fishing Regulation (Fisheries Law N. 61(I)/2001; REG. 17B), where the maximum weight of caught fish allowed per day is 5 kg and an additional fish individual with any weight (Moutopoulos et al., 2021). Unless regulation is amended to treat IAS as exceptions, this type of stakeholders can only contribute little to the overall lionfish management strategy, by diminishing incentives to catch lionfish in the first place over the more preferable local fish, for example, groupers, seabreams and greater amberjacks.

4.1 | Towards conservation actions and future management

The lionfish invasion poses a great dilemma among marine stakeholders and underscores the challenges of how to cope with its nuisance effects. In the western Atlantic coast, physical removals by citizens and lionfish tournaments have become the most conventional and effective forms of lionfish control thus far, significantly reducing the lionfish abundance and shielding targeted locations from adverse effects (Côté & Smith, 2018). Results of the study herein do not deviate from the collective findings in this field of research, while the wider content facilitates a detailed technical know-how for implementing such strategies in an EU context with citizens acting as pivotal key players in an otherwise financially costly process.

Under the supervision of competent organizations and authorities, trained and highly competent licensed RATs have a great potential to frequently operate in areas of particular interest including ecologically sensitive seascapes, MPAs, artificial reefs and Natura 2000 areas. Lionfish tournaments/derbies, on the other hand, can be implemented less frequently (e.g., seasonally or biannually), but consecutively across a selection of lionfish spawning aggregation sites with spillover and larval subsidy effects on adjacent areas of conservation value. Legislation reforms concerning catches of invasive species by recreational spearfishers could passively benefit managers against the lionfish problem. In line with these strategies, the development of lionfish-based fishery could further prove crucial in the controlling efforts, foster market-based opportunities and enhance environmental awareness in local communities (Chapman et al., 2016; Malpica-Cruz et al., 2021; Quintana et al., 2023). Given the current commitment of the EU to manage established IAS under the forthcoming EU Biodiversity Strategy for 2030 (EC, 2022), the EU member states will be confronted to contemplate adaptive management strategies, some of which presented here are viable options.

AUTHOR CONTRIBUTIONS

Demetris Kletou and Periklis Kleitou contributed to funding acquisition. D. Kletou administered and supervised RELIONMED project and the RAT teams. Ioannis Savva and Leda L. Cai contributed equally to the initial manuscript drafting, including conceptualization, writeup, figure preparation, statistical framework, and GIS analysis. All authors contributed to the fieldwork, data collection, and organization of the events. All authors contributed to the manuscript's revisions and final draft preparation.

ACKNOWLEDGEMENTS

This work is dedicated to the loving memory of Rhys L. Williams, an overly devoted and our youngest RAT member who sadly passed away after the end of the RELIONMED project. We further express our deepest gratitude to all the individuals who participated in the Lionfish Removal events, including diving organizations and clubs, especially the BlueInstinct Freediving Centre, Nautilus C.M.A.S. Diving Club Limassol, Hippocampus Larnaca Sub Aqua Club, Cyprus Diving Centre, Scuba Tech Diving Centre, Ocean View Diving Cyprus and the Cyprus Spearfishers Clubs S.F.Y.K.K. and O.F.E.K. We are also most grateful to the Department of Fisheries and Marine Research of Cyprus for the permits and support of the project throughout its implementation. Lastly but not least, we sincerely appreciate the efforts made by the two reviewers for improving the quality of the manuscript through their insightful comments and suggestions. This work was supported by the EU LIFE Programme financial instrument of the European Union–RELIONMED project (grant agreement LIFE16 NAT/CY/000832).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data will be made available upon reasonable request.

CONSENT FOR PUBLICATION

All individuals listed as authors agreed to be listed and approve the submitted version of the manuscript.

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SUPPORTING INFORMATION

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How to cite this article: Savva, I., Cai, L.L., Kleitou, P., Hadjioannou, L., Jimenez, C., Karonias, A. et al. (2024). An underwater clash of spears: Public engagement in Mediterranean lionfish control efforts. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 34(2), e4104. https://doi.org/10.1002/aqc.4104