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Management of Non-Indigenous Species in the Mediterranean Sea with an Emphasis on Lionfish (Pterois miles)

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MANAGEMENT OF NON-INDIGENOUS SPECIES IN THE MEDITERRANEAN SEA WITH AN EMPHASIS ON LIONFISH (*PTEROIS MILES*)

by

PERIKLIS KLEITOU

A thesis submitted to the University of Plymouth

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Acknowledgments

Many people made this journey possible, and for that I am deeply grateful. Family and friends were always supportive and never held grudges despite I often offered so little in return. I owe a lot, to my wife and mother of my new-born who had to endure my absence and sacrifice important life moments for my academic choices, to my best friends who were always supportive and compassionate, and to my parents and siblings who are always there giving me strength and ease any obstacles. There are no proper words to convey my deep appreciation to all of them.

I am thankful to the many colleagues who contributed to activities of this project, supported field activities, data analyses, interpretation and brainstorming that produced impactful ideas. I would like to particularly express my appreciation to my team at MER Lab, especially, my brother Demetris Kletou who is always there, sharing burdens and supporting each step of my personal progress, and Ioannis Savva, Leda L. Cai, Ioannis Giovos, Charalampos Antoniou, Francesco Cecconi, Christina Michail, and Giorgos Constantinou who are always on my side. They say that "alone, we can do so little but together, we can do so much".

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Finally, I am deeply appreciated to all divers and volunteers who supported citizen science monitoring data and participated in removal activities of lionfish. Their passion for conservation is remarkable and example for others.

I want to dedicate this PhD thesis to the memory of Rhys Williams who passed away last year at the age of 21. Rhys was an enthusiastic SCUBA diver/conservationist who contributed significantly to citizen-science monitoring, joined scientific dives, and participated and motivated others to participate in conservation activities of this project. He became a friend, and for all his contribution, I am thankful. He will be missed, and he will be remembered.

Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Doctoral College Quality Sub-Committee.

Work submitted for this research degree at the University of Plymouth has not formed part of any other degree either at the University of Plymouth or at another establishment.

Most Chapters of this PhD project were financially supported by the LIFE Programme – Nature and Biodiversity (European Commission) (Reference: LIFE16 NAT/CY/000832). Chapter 4 was funded by MAVA Foundation through the Regional Activity Centre for Specially Protected Areas (SPA/RAC) (Contract No 01 / SPA/RAC_2020). Chapter 2 was a result of both projects. The projects were carried out in collaboration with the Marine and Environmental Research (MER) Lab from Cyprus.

Relevant scientific workshops, seminars and conferences were regularly attended at which work was often presented. I physically presented the project at four conferences/symposia in five countries, and virtually at two. In addition, I presented the project in workshops or seminars organised as part of at least six different projects. I contributed to at least six more presentations of other colleagues at international conferences. Chapters 1, 3, 4, 5, 6 have already been published in peer-reviewed journals. Chapter 5 included as Appendix a peer-reviewed Risk Assessment document that was submitted to the European Commission to evaluate inclusion of lionfish in the Union List of invasive alien species (EU Regulation no.1143/2014). In addition, knowledge and guidelines from lionfish management attempts were transferred in a technical report that supplements the research outputs as Appendix and which was published as a regional (Mediterranean) management guide for lionfish, endorsed by the

Prince of Monaco Albert II. The guide was registered with a unique Digital Object Identified (DOI) and an International Standard Book Number (ISBN). Chapter 2 is currently under review by a peer-reviewed journal. Furthermore, I led or contributed to the publication of at least 25 scientific articles related to non-indigenous species during the PhD project. Interviews about the project and its results were given in numerous television and online media channels such as The Guardian and The Telegraph and disseminated by hundreds. Regional and local authorities consulted the results of the study. All the above mentioned highlight the pathways by which this PhD project will have impact on decisions to manage invasive species (particularly lionfish) in the Mediterranean Sea.

Publications that led to research outputs of this project are shown below while a list of other relevant publications published during the period of study is given at the end of this document.

List of publications (related to the Chapters / research outputs)

Section 3. Chapter 1

Kleitou, P., Savva, I., Kletou, D., Hall-Spencer, J. M., Antoniou, C., Christodoulides, Y., ... & Rees, S. (2019). Invasive lionfish in the Mediterranean: Low public awareness yet high stakeholder concerns. *Marine Policy*, *104*, 66-74. https://doi.org/10.1016/j.marpol.2019.02.052

Section 5. Chapter 3

Kleitou, P., Rees, S., Cecconi, F., Kletou, D., Savva, I., Cai, L. L., & Hall-Spencer, J. M. (2021). Regular monitoring and targeted removals can control lionfish in Mediterranean Marine Protected Areas. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *31*(10), 2870-2882. https://doi.org/10.1002/aqc.3669

Section 6. Chapter 4

Kleitou, P., Moutopoulos, D. K., Giovos, I., Kletou, D., Savva, I., Cai, L. L., ... & Rees, S. (2022). Conflicting interests and growing importance of non-indigenous species in commercial and recreational fisheries of the Mediterranean Sea. *Fisheries Management and Ecology*, *29*(2), 169-182. https://doi.org/10.1111/fme.12531

Section 7. Chapter 5

Kleitou, P., Hall-Spencer, J. M., Savva, I., Kletou, D., Hadjistylli, M., Azzurro, E., ... & Rees, S. E. (2021). The case of lionfish (Pterois miles) in the Mediterranean Sea demonstrates limitations in EU legislation to address marine biological invasions. *Journal of Marine Science and Engineering*, *9*(3), 325. https://doi.org/10.3390/jmse9030325

Section 8. Chapter 6

Kleitou, P., Crocetta, F., Giakoumi, S., Giovos, I., Hall-Spencer, J. M., Kalogirou, S., ... & Rees, S. (2021). Fishery reforms for the management of non-indigenous species. *Journal of Environmental Management*, *280*, 111690. https://doi.org/10.1016/j.jenvman.2020.111690

Appendix 11.5. Supplementary report

Kleitou, P., Hall-Spencer, J., Rees, S., & Kletou, D. (2022*). Guide to Lionfish Management in the Mediterranean.* University of Plymouth, 1-62. https://doi.org/10.24382/KYCK-J558

Presentations at international conferences

1. Kleitou, P., Hall-Spencer, J., Kletou, D., Hadjioannou, L., Savva, I., & Kletou, D., … & Rees, S. (2022). Challenges and recommendations for the lionfish

management in the Mediterranean Sea. 22nd *International Conference on Aquatic Invasive Species, ICAIS. Oostende, Belgium.*

2. Kleitou, P., Rees, S., Savva, I., Cai, L., Hall-Spencer, J., Hadjioannou, L., ... & Kletou, D. (2022). Experiences with the invasive lionfish highlight the threats and challenges of invasive species management in the Marine Protected Areas of the Mediterranean Sea. *1st Thalassa Scientific Conference in Cyprus. Larnaca, Cyprus.*

3. Kleitou, P., & Hall-Spencer, J., Rees. S., Kleitou, D. (2021). Invasive species in the Marine Protected Areas: Time for measures. *The 2020 Forum of Marine Protected Areas in the Mediterranean (MPA Forum) (online). Monaco.*

4. Kleitou, P., & Hall-Spencer, J. (2020). Lionfish invasion of the Mediterranean Sea. *The Mediterranean: scientific expertise for decision-makers, MED2020 (online). France.*

5. Kleitou, P., Hall-Spencer, J., Rees, S., Sfenthourakis, S., Demetriou, A., Chartosia, N., ... & Kletou, D. (2019). Tackling the lionfish invasion in the Mediterranean. the EU-LIFE RELIONMED Project: progress and results. *Proceedings of the 1st Mediterranean Symposium on the Non-Indigenous Species, Antalya, Turkey.*

6. Kleitou, P., Hall-Spencer, J., Kletou, D., Savva, I., Antoniou, C., Jimenez, C. Hadjioannou, L., Rees, S. (2019). Targeted removals of invasive species from Marine Protected Areas. *42nd CIESM Congress. Cascais, Portugal.*

7. Kleitou, P., Hall-Spencer, J., Kletou, D., Antoniou, C., Chartosia, N., Hadjioannou, L., … & Rees, S. (2019). Management of Invasive Species in Marine Protected Areas: The case of lionfish in eastern Mediterranean. *54th European Marine Biology Symposium. Dublin, Ireland.*

Word count of main body (Sections 1-9) of thesis is 58,317.

Signed 

Date 11/05/2023

Abstract

Management of non-indigenous species in the Mediterranean Sea with an emphasis on lionfish (*Pterois miles)*

Periklis Kleitou

The 21st century faces a global challenge; understanding the ecosystem changes and regulating fish resources is essential to provide food for humankind and to preserve the oceans. Marine ecosystems are being increasingly altered because of global, regional, and anthropogenic stressors such as climate change, Non-Indigenous Species (NIS), pollution, fisheries, eutrophication, and habitat loss. In an era of escalating transformations of marine ecosystems, the Mediterranean Sea is recognized as a hotspot of global biotic and abiotic changes. In recent decades, human-mediated introductions of NIS have notably reshaped the marine ecological structures and processes of the region. The Suez Canal (constructed in 1869 and subsequently expanded) has established a permanent sea-level waterway connecting Red Sea with the Mediterranean Sea. Lack of preventive measures and climate change allow more thermophilic NIS of Indo-Pacific origin to find their niche in the Mediterranean Sea.

Over 750 multicellular NIS have established viable populations in the region and a complete halt of their spread is impossible. Non-indigenous species have become members of a complex system of interactions between economy, society, and environment, affecting the livelihoods of local communities. Managers are faced with a complex task of navigating the changing conditions. They must find ways to utilize the potential benefits that some NIS may provide, while simultaneously protecting ecosystems from the harmful impacts that some invasive species can induce.

This PhD started in 2018 at a moment when the Mediterranean Sea was experiencing the lionfish (*Pterois miles)* expansion in one of the fastest population expansions ever

recorded for marine invasive species. With a documented invasion history in the Western Atlantic, and proven possible management measures, the lionfish invasion in the Mediterranean Sea offered a critical opportunity for research and acquisition of fundamental knowledge about management possibilities during escalating invasion stages.

With an emphasis on lionfish, this PhD employed social (surveys and questionnaires) and ecological research methods (visual *census* surveys) to provide novel knowledge on four management action priorities for NIS and guide a holistic management in the region. The priority management actions were (i) Education and public awareness (Chapters 1, 3, and 4), (ii) Rehabilitation of the environment (Chapter 2), (iii) Commercial and recreational utilization (Chapters 2 and 4), and (iv) Targeted removal of the species (Chapters 2 and 3).

Considering the identified gaps in public awareness and knowledge about lionfish and NIS in the Mediterranean Sea (Action 1), questionnaire surveys conducted in Chapter 1 revealed high awareness of stakeholders about lionfish and its impacts but limited public awareness and support for new fisheries from lionfish. The Chapter analysed stakeholder motivations, the guided the implementation of communication initiatives aiming at involving the local communities in lionfish management. Chapter 4 revealed lack of knowledge and awareness of fishers regarding the origin of many common NIS, and divergent perceptions on the ecological impacts that were correlated with the price of the species in the market. There is potential here for collaborative and communicative management processes to harmonize divergent views amongst fishers. The goal would be to mutually agree management measures that can support livelihoods and restore the ecosystem.

Rehabilitation of the environment (Action 2) and development of a healthy functioning ecosystem has the potential to control the distribution and abundances of introduced species. Two experiments that conducted visual *census* surveys in Chapter 2 demonstrated that recent fishery restrictions in a Marine Protected Area (MPA) of Cyprus likely benefited the spatial and temporal expansion of lionfish populations. Additional management measures, such as selective fishing and targeted removals, to offset invasive species spread would help MPAs recovery processes especially in the early years of MPAs' designation and contribute to their conservation objective.

The decreased lionfish densities in fished areas compared to strictly MPA zones (no fishing) found in Chapter 2 demonstrated the potential contribution of fisheries (commercial and recreational utilization – Action 3) to regulate NIS populations. Chapter 4 used fishery-dependent data and questionnaire surveys to demonstrate the emerging and important contribution of NIS catches in Cyprus fisheries, both in terms of volume and value. The Chapter has shown that recreational fishers avoided common NIS and even easy targets, such as lionfish. Recreational fishers are potentially driven by motivations beyond economic gain, such as traditional norms for larger and 'trophy' fish which are often keystone top-predators within marine ecosystems. Conversely, targeting of NIS by commercial fishers was largely driven by the price and their familiarity with the species. By reforming both recreational and commercial fisheries to adapt to NIS and launching market campaigns to address motivational factors, it could be possible to mitigate the negative impacts of NIS and generate greater profits and yields for local communities.

Chapters 2 and 3 demonstrated the efficiency of targeted removals (Action 4) with volunteers in controlling lionfish populations from priority sites. Social and environmental benefits from the execution of such events outweigh the economic costs, as demonstrated by their potential to incentivize lionfish fisheries, collect biological and ecological data, enhance public knowledge, awareness, secure support, and promote cooperative efforts.

Chapters 5-6 used the knowledge from Chapters 1-4 to guide reforms in the management and policy frameworks of NIS in the Mediterranean Sea and ameliorate the impacts of established NIS. Chapter 5 documented challenges encountered with a proposal to include lionfish in the European Union List of Invasive Alien Species (IAS) (EC/1143/2014) and provided recommendations on the basic IAS Regulation and the Delegated Regulation on risk assessments (EC/2018/968) that could be applied to improve relevance, coverage, effectiveness, and management of marine IAS at a European and regional level. To move beyond current problematic management approaches that do not adapt to the presence of non-indigenous species, Chapter 6 proposed major fishery reforms and an Ecosystem Based Fisheries Management framework that could direct a concerted and harmonized holistic approach against NIS to limit the socioeconomic and ecological impacts. Finally, results were summarized and a comprehensive tailored-made guide for the management of lionfish in the Mediterranean region was also developed and supplemented the major outputs of the PhD as Appendix. The guide provides information about key topics for the management of lionfish such as targeted lionfish removals, development of markets, outreach and communication activities, research and monitoring, and regional cooperation.

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1. Introduction

1.1. The Mediterranean Sea

The Mediterranean Sea is the largest (2,500,000 km^2) and deepest (5,267 m maximum depth) enclosed sea on Earth; connected with the Atlantic Ocean through the Strait of Gibraltar in the west, with the smaller enclosed Black Sea through the Bosporus Strait in the northeast, and with the Red Sea and Indian Ocean through the Suez Canal in the southeast (Figure 1.1). With a lower productive capacity compared to most of other oceanic zones, the region is characterized by oligotrophic to ultra-oligotrophic waters but enriched by regional features such as temporal thermoclines, wind conditions, currents and river discharges, and municipal sewage (Bas, 2009). Nutrients are entering the region mainly through the Straits of Gibraltar and Bosporus (Kletou & Hall-Spencer, 2012). A shallow ridge at 400 m depth between Tunisia and Sicily separates the region into the western (0.85 million km^2) and eastern (1.65 million km^2) sub-region.

With a semi-enclosed-and-locked configuration affected by physical, oceanic, and atmospheric processes (Bas, 2009), the Mediterranean Sea is characterised by well-defined mosaics of contrasting ecosystems. Evaporation exceeds precipitation and river run off, especially at the eastern sub-region, causing the salinity to increase from west to east (Figure 1.1). The sea surface temperature shows high seasonality and important gradient from west to east and north to south (Figure 1.1). Shelf waters cover about 20% compared with approximately 7.6% of the global estimates. The southern region is characterised by narrower and steeper shelves compared to the more extended shelves of the north coasts, apart from few exceptions (i.e. narrow shelves in Turkish coasts, Aegean Sea, Ligurian, and northern Alboran Sea) (Pinardi *et al.*, 2006; Coll *et al.*, 2010). Remarkably, deeper waters (i.e. from 300-500 m to the bottom) demonstrate high homogeneity with relatively constant temperature and high salinity (Emig & Geistdoerfer, 2005).

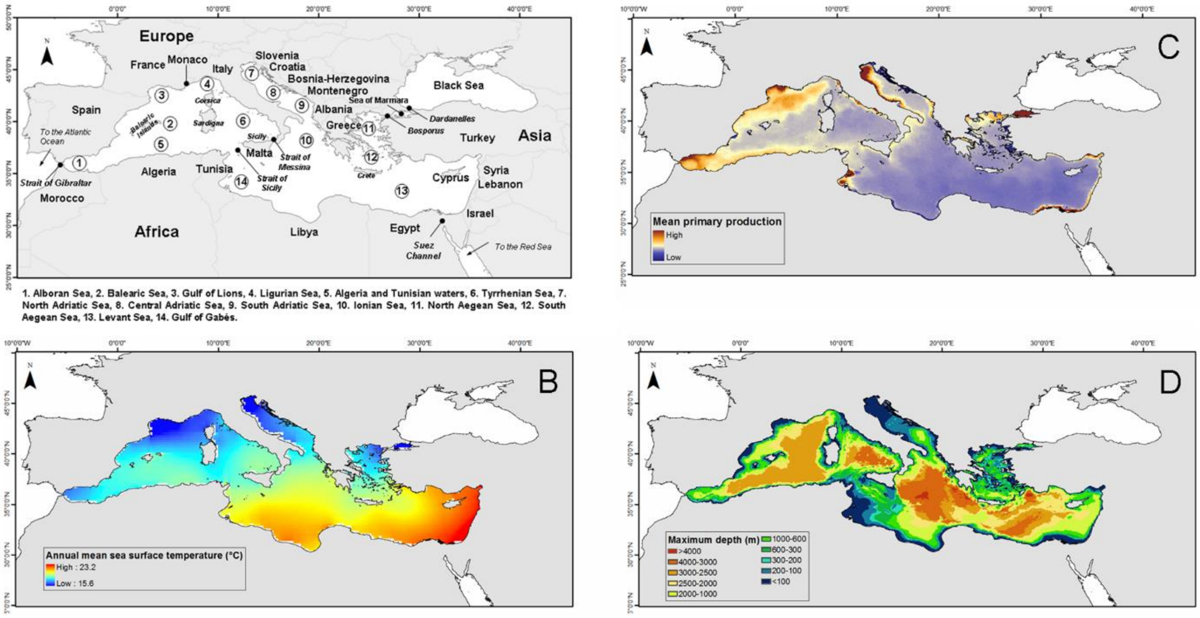

Figure 1.1. Maps of the Mediterranean Sea; **A:** Labelled countries of the Mediterranean and connections with other Seas, **B:** Annual surface temperature; **C:** Mean primary production; **D:** Maximum depth. Source: (Coll *et al.*, 2010).

Despite covering approximately 0.7% of the world ocean surface, the Mediterranean Sea offers favourable climate and ecological niches to cold, temperate and subtropical biota contributing to the co-occurrence of over 17,000 species equivalent to approximately 7% of world's marine biodiversity (Boudouresque, 2004; Coll *et al.*, 2010). This exceptional ecosystem richness has offered valuable ecosystem services which support human wellbeing for millennia (Sardá, 2013; Theodoropoulou, 2019). Such ecosystem services are linked, among others, to trading, tourism, cultural heritage, aquaculture and fisheries (Sardá, 2013).

In recent decades, high demand for its ecosystem services, intensification of economic activities, and rise of modern facilities and infrastructures are strongly deteriorating the natural capacity of the Mediterranean ecosystems (Liquete *et al.*, 2016). The region has been facing abrupt physical and ecosystem changes (Conversi *et al.*, 2010) and characterised ‘under siege’ due to multiple human pressures (Coll *et al.*, 2012). These include overfishing, eutrophication, habitat loss, and climate change, all of which are impairing the function, structure, and integrity of the Mediterranean ecosystems (Claudet & Fraschetti, 2010; Coll *et al.*, 2010; Lacoue-Labarthe *et al.*, 2016). Indicatively, it has been estimated that over 60% of the commercial stocks are fished at unsustainable levels in the region, the second highest record reported at a global level after the Southeast Pacific (FAO, 2022). A recent analysis in 21 Levantine (Eastern Mediterranean) fishery stocks found that 17 of them (90%) were exploited outside safe biological limits, 10 of which are in critical condition (Demirel *et al.*, 2020).

Synergistic effects of those pressures coupled with the intensification of human activities, increased global marine trade, and enlargement of the Suez Canal, have rapidly increased the human-mediated translocation of Non-Indigenous Species (NIS) beyond their native ranges, and notably reshaped the ecological structures and processes of the Mediterranean Sea (Galil *et al.*, 2018a; Galil *et al.*, 2019).

1.2. The Mediterranean under escalating tropicalization

In an era of climate change and escalating transformations in ecological settings, the Mediterranean Sea is recognized as a hotspot of global biotic and abiotic changes (Moullec *et al.*, 2019). The number of Non-Indigenous Species (NIS) has been accelerating without saturation signs and is now far greater than in any other world region; reaching approximately 1000 multicellular species with over 750 classified as established (Zenetos *et al.*, 2022). Established non-indigenous species increased by 40% in 11 years (Zenetos *et al.*, 2022).

Non-indigenous species are spreading at an unprecedented rate and tropical species are increasing in abundance and expanding westwards and/or northwards while indigenous species are declining (Givan *et al.*, 2018; Azzurro *et al.*, 2019b). The changes occur significantly faster compared to other regions where tropicalization of catch occurs (increasing dominance of warm-water species) (Last *et al.*, 2011; Cheung *et al.*, 2013). The Mediterranean Sea is considered as the most invaded sea worldwide (Edelist *et al.*, 2013; Giakoumi *et al.*, 2019b)

Major introduction pathways for the NIS in the region are shipping (transfer via biofouling and ballast waters), Suez Canal, aquaculture, and aquarium releases. The Suez Canal opened in 1869 to connect the Red Sea with the Mediterranean Sea and reduce the travel distance between Europe and Asian colonies. Since then, the Canal has been repeatedly expanded to favour shipping trade. Its dimensions increased from 8 m deep with an initial cross section area of 304 m^2 to 24 m deep with a cross section of 5200 m^2 in 2015 (Galil *et al.*, 2017a). Its presence established a permanent sea-level waterway favouring introductions from the warmer Red Sea to the Mediterranean Sea. Today, it is responsible for about half of the NIS introductions in the Mediterranean Sea but together with climate change and the lack of preventing measures is expected to allow more thermophilic species of Indo-Pacific origin to find their niche in the area; exacerbating the effects on the local biological communities (Galil *et al.*, 2017).

A fraction of the introduced NIS — termed as 'invasive alien species (IAS)' — is causing adverse impacts on the recipient ecosystems, posing major threats to the biodiversity, ecological processes, and ecosystem services (Chaffin *et al.*, 2016; de Castro *et al.*, 2017; Geburzi & McCarthy, 2018). The social and ecological impacts of invasive species have been translated to tremendous economic losses and management costs (reviewed in Christophe *et al.*, 2020; Diagne *et al.*, 2020).. In the eastern Mediterranean, for example, the NIS goldband goatfish *Upeneus moluccensis* replaced the native red goatfish *Mullus barbatus* and the NIS rabbitfishes *Siganus rivulatus* and

S. luridus outcompeted the native herbivorous fish *Sarpa salpa* and transformed algae-dominated rocky habitats to "barrens" (Sala *et al.*, 2011; Vergés *et al.*, 2014). The chlorophyte algae *Caulerpa taxifolia* and *C. cylindracea* have caused devastating impacts to native algal assemblages and seagrass beds across the entire Mediterranean Sea (Streftaris & Zenetos, 2006).

Invasive alien species often cause direct negative economic consequences to the Mediterranean industries. Nuisance species such as the various pufferfishes (Family: Tetraodontidae), the striped eel catfish *Plotosus lineatus*, and the nomad jellyfish *Rhopilema nomadica* strongly interfere with or alter fishery activities by damaging gears and fishery catches (EastMed, 2010; Kalogirou, 2013; Galanidi *et al.*, 2018). *Rhopilema nomadica* outbreaks also cause significant costs to power plants by clogging intake pipes and to the tourism industry as they can release venomous stinging cells (Galil, 2007; Ghermandi *et al.*, 2015). It was estimated that the pufferfish *Lagocephalus sceleratus* damages to the artisanal gear of small-scale fishers, of Turkey alone, is approximately € 2 million per year (Ünal *et al.*, 2015), while an outbreak of jellyfish *Rhopilema nomadica* in Israel can cost an annual monetary loss of €1.8–6.2 million (Ghermandi *et al.*, 2015).

Nevertheless, other NIS can provide benefits to humans by introducing novelty, replacing lost ecological functions, adding redundancy that strengthens resilience, and providing ecosystem services (Chaffin *et al.*, 2016). In parallel, many NIS have become targets for local fisheries of the region, often helping to stabilize local fisheries catch (Michailidis *et al.*, 2019; van Rijn *et al.*, 2019; Saygu *et al.*, 2020).

Amongst the NIS introduced in the Mediterranean Sea, the recent invasion by lionfish *Pterois miles* (Bennett, 1828) raised strong concerns as it had a documented invasion in the Western Atlantic where it demonstrated one of the fastest and most ecologically harmful fish invasions ever recorded (Albins & Hixon, 2013; Roy *et al.*, 2015). Today, it is among the most documented invasive species globally. A bibliometric search in Scopus, using the term "Lionfish" was made on 19 February 2023 and identified a total of 569 references (Figure 1.2). The number of studies related to lionfish increased exponentially in the early 2010s when lionfish reached its highest densities in the Western Atlantic (Ballew *et al.*, 2016) (Figure 1.2).

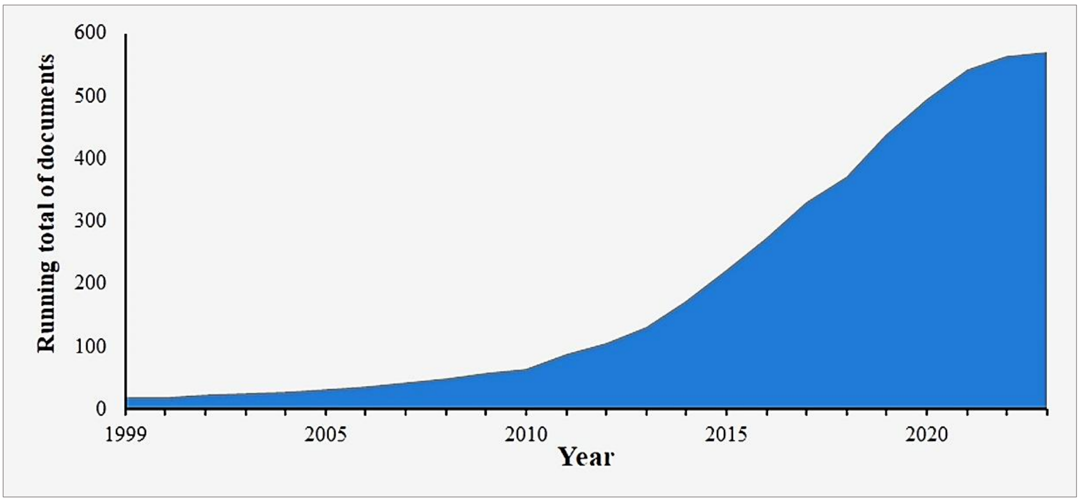

Figure 1.2. Number of documents published in Scopus, extracted using the term "Lionfish" on 19 February 2023.

1.3. The lionfish invasion – a threat to ecosystem communities and functions

1.3.1. Lionfish distribution and future expansion in the Mediterranean Sea

Pterois miles native range is restricted to the Indian Ocean (Kulbicki *et al.*, 2012), specifically from the Red Sea all the way down to the eastern South Africa, in Arabian Sea, Persian Gulf, Gulf of Oman, Laccadive Sea, Bay of Bengal, Andaman Sea and Indonesian region. Around Indonesia, *P. miles* population overlaps with its congeneric *P. volitans* and *P. russelii. Pterois miles* can be easily distinguished from sister species (11 species are described in the *Pterois* genus) apart from *P. volitans*, which looks very similar and distinguished primarily through small variations in meristic counts (one lower count of dorsal and anal fin rays in *P. miles*) (Schultz, 1986); although not always reliably as counts can overlap between the two species. The taxonomic distinction of *P. miles* and *P. volitans* is supported by reciprocal monophyly in phylogenetic trees as well as clear difference in maximum intraspecific and minimum interspecific sequence divergence (Freshwater *et al.*, 2009).

Both of these two lionfish species (*Pterois miles* and *P. volitans*) were introduced in the North-western Atlantic in late 1980s and expanded throughout the region, northwards along the east coast of the USA reaching as far as Rhode Island, eastwards to Bermuda, and southwards throughout the Gulf of Mexico, Central America, South America, Caribbean and Brazil (Goodbody-Gringley *et al.*, 2019). Due to their external similarities, distinguishing the two species becomes highly uncertain in the absence of genetic analyses. During the last years, genetic analyses suggested that *P. volitans* is the most ubiquitous species in the invaded Western Atlantic region (Hamner *et al.*, 2007; Freshwater *et al.*, 2009; Betancur-R *et al.*, 2011). Until recently, it was believed that *Pterois miles* dispersal was limited to the US coasts and that their population didn’t cross across the Florida Strait (Freshwater *et al.*, 2009). However, more recently, it has been shown using genetic barcoding that the species has now extended its distribution into the Caribbean basin and Mexico; albeit in low numbers (Guzmán-Méndez *et al.*, 2017). Morphological characters, life cycle, habits, and dispersal potential of this species are very similar to those of *Pterois volitans*, and this is the reason that many studies treated both species as a single one (i.e. *Pterois* complex). Sequence data from one mtDNA gene and two nuclear introns indicated that *P. volitans* specimens of the western Atlantic might even be hybrids between the Indian Ocean *P. miles* and a Pacific lineage encompassing *P. lunulata/russelii*; raising the need for further investigation (Wilcox *et al.*, 2018).

Lionfish (*Pterois miles*) was recorded in the Mediterranean Sea in 1991 off Israeli coasts (Golani & Sonin, 1992) but most likely in a non-successful invasion attempt since no other individual was reported until around two decades later. In 2012, two lionfish were recorded off Lebanon (Bariche *et al.*, 2013) indicating a 'new invasion event' (Bariche *et al.*, 2017). The lionfish rapidly spread and established in the entire Levantine Sea, southern and central Aegean Sea, Greek Ionian Sea, and reached Tunisia and Italy (Kletou *et al.*, 2016; Azzurro *et al.*, 2017; Giovos *et al.*, 2018b; Dimitriadis *et al.*, 2020) (Figure 1.3), demonstrating one of the fastest fish invasions ever reported in the Mediterranean Sea (Poursanidis et al., 2020).

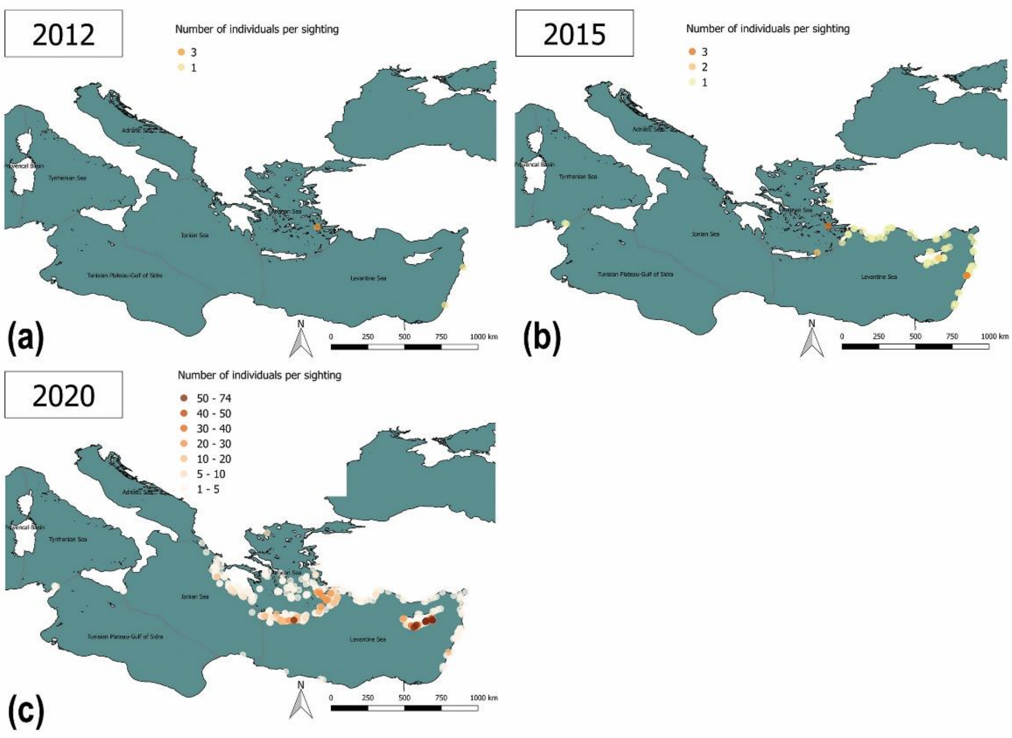

Figure 1.3. Number of individuals observed per sighting for (a) 2012, (b) 2015, and (c) 2015. Source: Kleitou *et al.* (2021b)

All lionfish genetic studies conducted in the Mediterranean populations have identified only *Pterois miles* to be present (Bariche *et al.*, 2017; Dimitriou *et al.*, 2019; Stern *et al.*, 2019; Vavasis *et al.*, 2019). Records of *Pterois volitans* in Turkey were reported but these were only based on meristic/morphometric measurements or just underwater observations (Gürlek *et al.*, 2016; Gökoğlu *et al.*, 2017; Turan *et al.*, 2017) and given their similarity and potential overlapping morphometric/meristic characteristics with *Pterois miles* (mentioned before); their presence is rather questionable and likely erroneous (Çinar *et al.*, 2021).

The expected future distribution of lionfish in the Mediterranean Sea is debatable. Remote sensing and dispersion modelling have been carried out and shown that lionfish current habitat suitability is clearly limited to the Central and Eastern Mediterranean in areas where lionfish have already been recorded (Poursanidis, 2016; D’Amen & Azzurro, 2020; Poursanidis *et al.*, 2020). However, previous research has shown that tropical invaders may spread far beyond their native niches and that Species Distribution Modelling (SDM) may underestimate the potential spread of invasive species (Parravicini *et al.*, 2015). Indeed, Poursanidis (2016) SDM failed to predict lionfish invasion in current lionfish hotspot areas such as Cyprus. Lionfish invasion proved that the species might be able to expand its climatic niche (i.e. environmentally shift beyond their climatic limits in their native ranges) while there is still a high degree of niche unfilling (i.e. the presence of favourable climate in the invaded domain not yet occupied by the species) which prospects a likely spread of lionfish beyond the prediction of current SDMs (Poursanidis *et al.*, 2020). Based on Maximum Entropy (MaxEnt) model, Loya-Cancino *et al.* (2023) predicted that lionfish will be able to find suitable regions up to Spain, Portugal and France, and that climate change scenarios could enable them to spread in the entire Mediterranean Sea.

In contrast to the previous modelling studies which have used a large set of environmental marine layers and predictors for prediction, Dimitriadis *et al.* (2020) used the minimum 15.3°C winter isotherm as the sole limiting factor for the lionfish geographical expansion which was found to constrain the expansion of lionfish in the Western Atlantic (Whitfield *et al.*, 2014). With the assumption that lionfish will expand in the areas higher than 15.3°C, Dimitriadis *et al.* (2020) found that *P. miles* could substantially expand in the Mediterranean Sea, except the coolest northernmost regions, under future climatic scenarios (Figure 1.4). Indeed, a reduction in the range expansion of the species across the Mediterranean Sea was observed since 2020-2021 and its distribution, hitherto, has been restricted east of Italy and Tunisia. Further studies incorporating physiology studies into species distribution models (e.g. Gamliel *et al.* (2020) could potentially improve the predictions of lionfish dispersal under current conditions and climatic change scenarios.

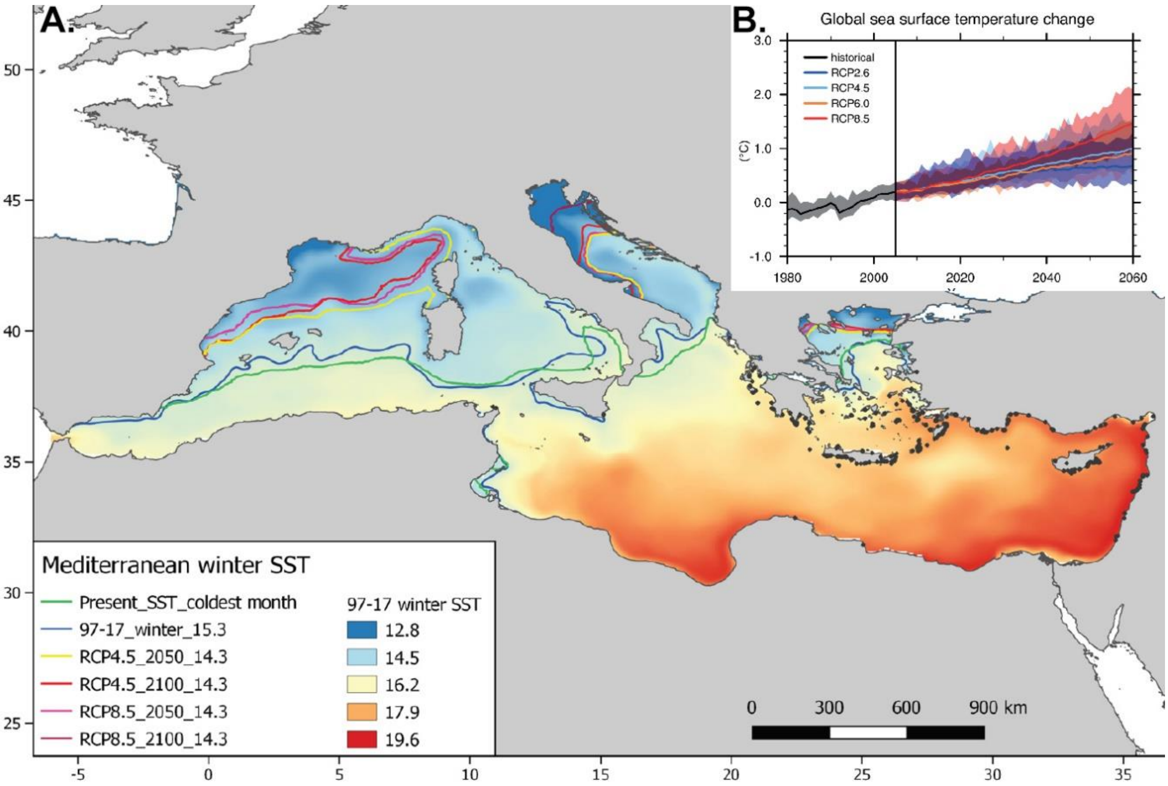

Figure 1.4. A: Mean winter (December to February) Sea Surface Temperature (SST) between 1997-2017 with overlaid contour lines for the 15.3°C isotherm during that period (CMEMS dataset) as well as the corresponding average temperature of the coldest month (=14.3°C) under present conditions and under two climate change scenarios, RCP4.5 and RCP8.5, for the periods 2040-2050 and 2090-2100 (BIO-ORACLE datasets) Black dots represent Pterois miles presence records. Source: Dimitriadis *et al.* (2020); B: Near term global sea surface temperature change based on Representative Concentration Pathway (RCP) scenarios. Source: Kirtman *et al.* (2013).

1.3.2. Lionfish biology and ecology

Lionfish (Figure 1.5) has several biological and ecological traits that contribute to its success as an invasive species. Most of the information derive from empirical evidence from its invasion in the Western Atlantic. To date, limited studies have been carried out on the biology/ecology of lionfish in the Mediterranean Sea.

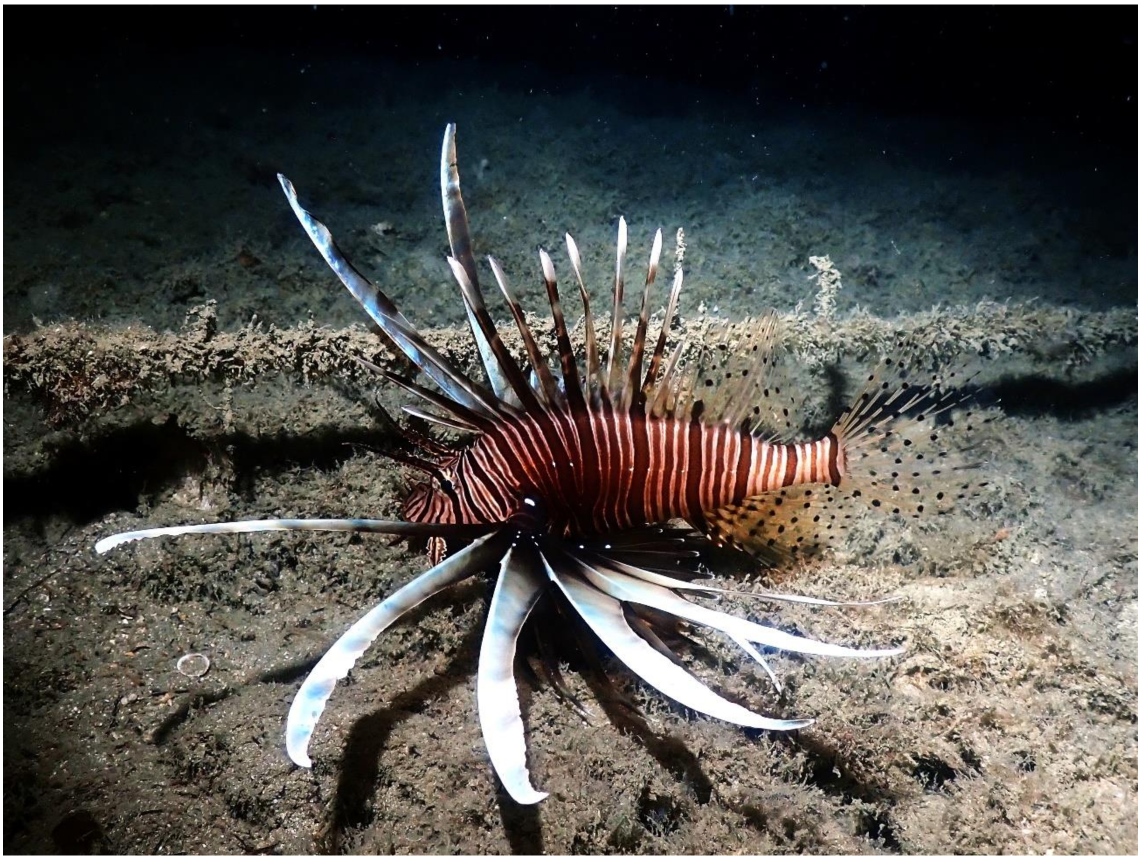

Figure 1.5. Lionfish (*Pterois miles*) foraging during the night with extended pectoral fins at the marine protected area of Limassol, Dasoudi on 06/05/2022.

Habitat range

Pterois miles is mostly found in the depth range of 0 to 50 m (Schultz, 1986), but lionfish individuals are also found at depths greater than 300 m depth (Gress *et al.*, 2017; Andradi-Brown, 2019). In the Mediterranean Sea, they have been found to prefer rocky reefs with crevices or underwater caves to hide during the day (Savva *et al.*, 2020). They are also attracted to underwear artificial structures such as wrecks, and in seagrass habitats of *Posidonia oceanica* (Linnaeus) Delile, 1813, particularly at the edge of the meadow sections and the tall “matte” comprised of rhizomes, roots, and the sediments that fill the interstices (Chapter 2 and 3). Lionfish are also habitat generalists able to inhabit various environmental conditions such as low salinity, turbid waters, and areas with high sediment loads (Cure *et al.*, 2014; Jud *et al.*, 2015).

Diet and foraging traits

Lionfishes are known to be opportunistic predators with a broad, generalist diet that includes a huge array of species with preference on teleosts and crustacean prey (Eddy *et al.*, 2016; Peake *et al.*, 2018; Zannaki *et al.*, 2019). Regional data from the Western Atlantic have shown a transition from a shrimp-dominated diet to a fish-dominated diet through lionfish ontogeny (Peake *et al.*, 2018). The contribution of teleosts in their diet appears to be higher in the Mediterranean but this could be due to the low sample size of the studies conducted so far (Zannaki *et al.*, 2019; Savva *et al.*, 2020). Despite being a generalist predator, evidence have shown that lionfish might selectively target its preys (Chappell & Smith, 2016; Ritger *et al.*, 2020) and in the Mediterranean is showing a preference to naïve native species than species with overlapping native range (Agostino *et al.*, 2020).

Lionfish anatomical and physiological traits optimize its feeding strategy. Green *et al.* (2019) suggested that high rates of consumption might also be associated to a combination of traits such as the effectiveness of unique stalking behaviour, buccal suction, and forward momentum generated during strike events. Similarly, Rojas-Vélez *et al.* (2019) used a functional morphology approach and compared lionfish with native Caribbean reef predators; finding that lionfish has novel locomotion and trophic characteristics such as larger buccal diameters, greater suction capacity and larger protrusion of the premaxilla all of which benefit its feeding processes and allowing it to capture larger and more elusive prey. Small lionfish individuals have also longer pectoral fins in relation to their size (Costello *et al.*, 2012) which they use as signals in initiate cooperative hunting (Lönnstedt *et al.*, 2014), to track preys in small confined areas maximizing catch efficiency (Fishelson, 1997; Lönnstedt *et al.*, 2014), or even to lift benthic invertebrates from the substrate by palpation (Fishelson, 1975). Cryptic nature and general outline of lionfish has also proved to circumvent prey detection and recognition abilities increasing further the success in hunting (Lönnstedt & McCormick, 2013).

Fishelson (1997) studied lionfish in its native range and reported that lionfish can expand over 30 times their stomach volume when foraging and can withstand starvations for periods of over 12 weeks while losing only approximately 10% of their body weight. Such long tolerance to starvation periods could enable it to survive and establish in most areas of the Mediterranean despite low winter temperatures. Steell *et al.* (2019) found that lionfish is able to prioritize feeding over movement to a greater extent than other species; with maximum metabolic rate attained during feeding and digestion than from exhaustive exercise like other species (Steell *et al.*, 2019). Lionfish impacts will likely exacerbate with climate change as it has been found to digest meals more efficiently and rapidly at increased temperature (South *et al.*, 2017; Steell *et al.*, 2019).

<u>Reproduction</u>

Lionfish has an exceptional reproductive strategy that favour its rapid dispersal and population expansion. In all invaded regions, lionfish were found able to mature sexually in less than a year of their life cycle, and at a small size relative to their invaded range; approximately 16 – 20 cm (Gardner *et al.*, 2015; Fogg *et al.*, 2017; Savva *et al.*, 2020). Reproduction occurs year-round every 2-4 days in most invaded areas of the Western Atlantic (Gardner *et al.*, 2015) while in lower latitudes, where winter seawater temperature is lower (e.g. Bermuda), lionfish had a short active spawning period during warm-water months (June-November) and inactive period during the coldest months (Eddy *et al.*, 2019). Similar findings were found in the Mediterranean Sea where lionfish was found to have higher gonadosomatic index but remaining reproductively active during the warm-months (Savva *et al.*, 2020). Female lionfish are iteroparous, broadcast, highly fecund spawners producing up to 10,000 eggs per spawning event (Morris & Whitfield, 2009). The eggs are spawned in a gelatinous mass maximizing dispersal via ocean currents, increasing fertilization by reducing sperm dispersal, and may inhibit egg predation (Fogg *et al.*, 2017). The eggs and later embryos disintegrate within a few days, after which the embryos and/or larvae become free floating. With a pelagic larval phase, lionfish larvae are able to disperse across great distances for about 20-35 days before they settle to benthic habitats (Ahrenholz & Morris, 2010)

<u>Natural defences</u>

P. miles possess venomous dorsal, pelvic, and anal spines that likely protect it from native predators. It has been hypothesized that the dorsal spines are used for intimidation, making the fish look larger while anal and pelvic spines which are stiffer and energy-absorbing they are used for protection as they are located near important internal structures such as the swim bladder (Galloway & Porter, 2019). Nevertheless, several species have been documented to prey on lionfish including groupers, cornetfishes, sharks, spotted moray eel and eagle but these have been rare in the invasive range of the species (Bernadsky & Goulet, 1991; Maljković *et al.*, 2008; Mumby *et al.*, 2011; Bos *et al.*, 2017). In Mediterranean, there are very little evidence of lionfish predation by common octopus (*Octopus vulgaris*) and dusky groupers

(*Ephinephelus marginatus*) (Turan *et al.*, 2017; Crocetta *et al.*, 2021; Ulman *et al.*, 2021). Nevertheless, overfishing of top native predators likely diminishes the biotic resistance of the Mediterranean ecosystems against NIS (Kimbro *et al.*, 2013). For instance, dusky grouper *Epinephelus marginatus* (Lowe, 1834), declined up to 95% in some parts of the Mediterranean (Malak *et al.*, 2011).

In addition to their predators resistance, lionfish have been also found to be less susceptible to parasites in their introduced Western Atlantic range compared to their native one (Tuttle *et al.*, 2017). Parasites can affect energy expenditures and consequently host's behaviour, growth, fecundity, and mortality (Forrester & Finley, 2006; Grutter *et al.*, 2011; Binning *et al.*, 2013). In the Mediterranean Sea, the lionfish was found to be infested from the ectoparasite *Nerocila bivittata* (Antoniou *et al.*, 2019) but no information about the susceptibility extent of lionfish to parasites in the region is available yet. Given the fact that lionfishes grow larger, faster, and in denser populations compared to their native ranges it is unlikely that parasites present a major barrier towards their invasion (Savva *et al.*, 2020).

<u>Biological and ecological differences between the two invaded regions</u>

Generally, studies agree that lionfish in the Mediterranean Sea share similar traits like the ones in the Western Atlantic individuals including an opportunistic diet, fast growth, generalist habitat and depth preferences, high fecundity, early maturity, absence of predators, and naïve prey (Zannaki *et al.*, 2019; Agostino *et al.*, 2020; Savva *et al.*, 2020; Demirel *et al.*, 2021; Mouchlianitis *et al.*, 2021; Ulman *et al.*, 2021). The contribution of teleosts in their diet appears to be higher in the Mediterranean than the Western Atlantic but this could be due to the low sample size of the studies conducted so far (Zannaki *et al.*, 2019; Savva *et al.*, 2020). Furthermore, the reproduction of lionfish in the Mediterranean Sea was found to be more similar to the lower latitudes of the Western Atlantic, where winter seawater temperature is lower (e.g., Bermuda) (Eddy *et al.*, 2019; Mouchlianitis *et al.*, 2021). Specifically, lionfish were found to actively spawn mostly during the warm-water months (June – November) and not with the same intensity year-round (Eddy *et al.*, 2019; Mouchlianitis *et al.*, 2021). Another difference between the two invasions is the lack of genetic bottleneck and that Mediterranean invaders do not show a lowered genetic diversity compared to source population indicating that a large number of propagules was introduced through the Suez Canal (Bernardi et al. under review) in contrast to what was observed for the Western Atlantic lionfish where the invasion originated from few individuals and characterised by low genetic diversity (Selwyn *et al.*, 2017; Hunter *et al.*, 2021).

1.3.3. Threats of lionfish to biodiversity and related ecosystem services

<u>Impacts on local biodiversity</u>

Lionfish traits enable it to spread fast and cause direct impacts to ecologically and socioeconomically important species of the invaded ecosystems (Savva *et al.*, 2020). Its trophic niche was found to expand and adapt over time in the invaded Western Atlantic (Malpica-Cruz *et al.*, 2019). *P. miles* may also outcompete juvenile groupers, particularly *Epinephelus marginatus* which use the same habitat and food resources. In its Atlantic invasive range, the lionfish complex outcompetes Caribbean spiny lobsters and local groupers (Curtis-Quick *et al.*, 2013; Raymond *et al.*, 2015). The fact that lionfish share better traits compared to other mesopredators (e.g. matures in 1 year compared to 4-7 years for a grouper) (Condini *et al.*, 2018; Savva *et al.*, 2020) gives them an advantage to population expansion. Despite having intermediate consumption rates, the much higher densities and catch efficiency of lionfish result in higher impacts to the local biodiversity (DeRoy *et al.*, 2020).

Few studies failed to identify evidence of lionfish impacts on the local biota (Elise *et al.*, 2015; Hackerott *et al.*, 2017). Using an ecological model that uses prey consumption and biomass production, Green *et al.* (2014) suggested that predation effects of lionfish are nonlinear but begin to occur beyond a particular threshold of predation mortality; thus impacts on communities with high biomass is unlikely under low lionfish densities.

Numerous studies have demonstrated that increases in lionfish abundances lead to significant declines in the recruitment, biomass, and abundance of local fish species (Albins & Hixon, 2008; Green *et al.*, 2012; Côté *et al.*, 2013a; Benkwitt, 2015; Ingeman, 2016); with the impacts felt at a regional level (Ballew *et al.*, 2016). Up to 95% of small native species abundance reductions were reported at some invaded sites (Côté *et al.*, 2013a). Apart from direct impacts to local fish communities, lionfish were found capable to drive an overall shift in invertebrate assemblage composition (Layman *et al.*, 2014) and shift sites to algal dominated habitats through predation on herbivorous reef fishes (Lesser & Slattery, 2011; Slattery & Lesser, 2014; Kindinger & Albins, 2017).

<u>Impacts on ecosystem services</u>

It is likely that the presence of lionfish will skew food webs towards a loss of higher trophic groups and a gain in lower order consumers as reported for other human disturbances (Byrnes *et al.*, 2007). Johnston *et al.* (2015) estimated that if populations of lionfish were left uncontrolled, total service losses to recruitment and biomass functions of 26.67 and 21.67 discounted service unit years (DSUYs) (i.e. one DSUY equivalent to the entire quantity of services provided by one area unit of the damaged or replacement system for a given year) per km^2 of a Bahamian reef were expected.

According to the literature (mentioned above), *P. volitans/miles* complex may have significant negative impacts on the local biodiversity and fishery yields (Morris & Whitfield, 2009), hence affecting provisioning services for nutrition. On the other hand, local authorities established management strategies to counteract the threat and to create localised benefits linked to control mechanisms. Exploring and initiating commercial market niches is a current management strategy among the seafood industry, distributors, chefs, researchers, fishers, and conservationists in the Atlantic invasive range. Considering its high nutritional profile and low ciguatoxin content (the leading cause of non-bacterial seafood poisoning associated with fish consumption), lionfish consumption is widely promoted in the Western Atlantic (Chapman *et al.*, 2016; Hardison *et al.*, 2018) so that cost-effective targeted removals remain feasible and endure over time, but also to establish a positive impact on the socio-economic sector. Removed individuals, especially small-sized, which are considered of low economic value in fisheries sector, are also being utilised for jewellery (Ali, 2017). Specifically, artists take advantage of the unique; ornate beautifully patterned spines, rays and tails of lionfish to make and/or sell an assortment of jewellery from them (Ali, 2017)

With the significant impacts on biodiversity reported in the Western Atlantic, other ecosystem services (ES) that are likely negatively affected include provisioning ES related to materials such as genetic materials from all biota and animal-based resources. Impacts caused by lionfish invasion likely indirectly affect regulation & maintenance ES related to mediation of waste, toxics and other nuisances by filtration/sequestration/storage/accumulation, and impacts on maintaining nursery populations and habitats. Lionfish have been recently found as promising species for biomonitoring of oil pollution effects and could potentially be used in the future as bioindicator (van den Hurk *et al.*, 2020).

Lionfish invasion strongly affects cultural ES related to physical and intellectual interactions (both positively with lionfish as the 'model' species and negatively with impacts on other biota); affecting services such as experiential use in environmental settings, physical use in environmental settings, educational services since lionfish is a subject matter of education about invasive species both on location and via other media, In the Western Atlantic, divers and snorkellers demonstrate mixed preferences and heterogeneous attitude against lionfish presence. For instance, Alemu *et al.* (2019) survey on reefs in Tobago has shown that snorkelers are intrigued by the beautiful appearance of lionfish and favour some lionfish on reefs relative to none while recreational divers perceived all lionfish levels as negatives and were willing to pay more than snorkelers for high quality reef attributes. Similar results were found by Malpica-Cruz *et al.* (2017) who surveyed visitors in the Mexican Caribbean and found that casual divers and snorkelers preferred reefs with lionfish and accepted their impacts on the reefs, while in contrary, committed divers disliked lionfish and associated impacts and would elect to dive elsewhere if such impacts were high. Dense populations of lionfish are likely to affect the diving industry in Mediterranean sites such as Cyprus, due to possible envenomation on recreational divers, especially in caves/wrecks, causing fear and reduction of diving destinations attractiveness.

1.3.4. Management of lionfish in the Western Atlantic

In its Atlantic invasive range one of the most common management practices are to remove lionfish using SCUBA to keep their population in levels that do not cause damage to the surrounding biota (Barbour *et al.*, 2011; Green *et al.*, 2014; Harms-Tuohy *et al.*, 2018). The most effective low cost removal practices are the spearfishing (polespear or speargun), vinyl/mesh hand-netting and Hawaiian slings for large individuals (Akins, 2012). Many of these are restricted to divers, while other removal techniques that can be accessed by fishers include traps and hook and line. The former showed to catch lionfish as by-catch in lobster and fish traps, but by-catch of other species needs to also be considered (Pitt & Trott, 2013). The latter has been effective at deeper waters (91-183 m depth) with the inclusion of squid as cut-bait (Akins, 2012). Other fishing techniques such as trawling and seining are deemed to be ineffective and plausibly to negatively impact the populations of other susceptible species (Côté *et al.*, 2013a). Finally, there have been ongoing developments in innovative harvest technologies aimed at catching juvenile lionfish or capturing lionfish from areas beyond recreational diving depths including specialized apparatuses for lionfish catch, e.g. (Gittings, 2019) and Harris *et al.* (2020), and remotely operated vehicles selectively harvesting target species (Wang, 2019).

The frequency of lionfish removals (either in the form of coordinated diving removals or fishing pressure) may in fact allow for population control and mitigate lionfish impacts in priority areas, but it is not considered an ultimate tool for preventing its establishment (Barbour *et al.*, 2011; Côté & Smith, 2018). A trade-off between time spent removing and achieving an increasingly smaller lionfish density exists (Usseglio *et al.*, 2017) and needs to be considered in management interventions to maximize efficiency and rate of success. For instance, multiple removals off Little Cayman Island at irregular intervals over seven month period, restricted the size frequency distribution towards smaller individuals, which allowed decreased predation on ecologically and economically important fish (Frazer *et al.*, 2012). Furthermore, a study on Bonaire and Curaçao, in southern Caribbean, revealed significant reduction in both lionfish densities and biomass compared to sites that were not targeted for culling (de León *et al.*, 2013). Similar results were observed in Puerto Rico. The removals decreased the lionfish densities and re-colonization to the targeted area at the initial densities was gradual and took about nine months (Harms-Tuohy *et al.*, 2018). Using a trophic model, Chagaris *et al.* (2017) suggested that small increases in lionfish harvest can reduce peak biomass by up to 25% in the Gulf of Mexico, and also that reduced harvest of native reef fish predators can lead to lower lionfish densities.

Despite demonstrated results and promises in reversing species decline, intense culling practices could ultimately alter the lionfish's behaviour by turning them more vigilant and as a result to increase the removal effort per se (Côté *et al.*, 2014b). On the other hand, partial culling does not remove all individuals within a local area but it reduces the time and effort by 30% and is still as effective as a complete local eradication (Côté *et al.*, 2014b). According to Barbour *et al.* (2011) and Morris *et al.* (2011a), if 15- 65% per year or 25% per month, respectively of adult population is eliminated, then it would be enough to drive population declines.

The management of lionfish requires sustained effort and commitment, increased awareness, coordination, participation of volunteers and engagement of fishers and stakeholders (Akins, 2012; Scyphers *et al.*, 2015). The management efforts in the Atlantic Ocean were largely guided by volunteers and citizen-science platforms (Clements *et al.*, 2021). Removals of lionfish were conducted as part of public events such as tournaments, daily derbies, and monthly contests. These allowed the removal of up to 2,000 lionfish in Bahamas and Mexico within a single day (Akins, 2012). In these events, participants are equipped with specialized toolkit and pole spear, receive training on removal techniques and safe handling, and compete against other teams or individuals to earn a prize. Their success extends beyond ecological goals and offer multiple benefits as it serves as participatory management where volunteers are incentivized to participate in removal and monitoring of lionfish, and the conservation of marine ecosystems (Clements *et al.*, 2021; Ulman *et al.*, 2022). The specimens that are captured are usually utilized by science – mainly for morphometric measurements and diet studies – to improve the knowledge on the biology and ecology of lionfish, or they are promoted for consumption in live cooking events and jewel-crafting. The events receive powerful media attention and coverage transferring key messages about lionfish beyond local level (Ulman *et al.*, 2022).

The development of a market-based approach to control lionfish densities while diversifying fishers' livelihoods has been prioritized in the Western Atlantic (Chapman *et al.*, 2016), particularly in areas where there is limited capacity to support targeted removals (Graham & Fanning, 2017). Initially, the promotion in the seafood market posed challenges due to concerns about food safety related to ciguatera poisoning or misconceptions about their venomous spines, which led to confusion regarding their edibility. (Morris, 2012). However, lionfish was widely promoted as a safe and environmentally friendly option through public campaigns (Huth *et al.*, 2018; Simnitt *et al.*, 2020; Blakeway *et al.*, 2022), and lionfish market demand increased with prices similar to high-value reef fish such as groupers and snappers (Harris *et al.*, 2023). Commercial SCUBA fisheries were developed to sustain fishery pressure on lionfish populations (Akins, 2012; Malpica-Cruz *et al.*, 2021). In some areas such as the Mexican Caribbean, high harvest levels correlated with declines of lionfish density and landings (Malpica-Cruz *et al.*, 2021). Despite the economic dependency that was developed by the fishers, effective communication between scientists, managers, and fishers helped set common objectives and fishers viewed themselves as conservation leaders accepting that collapse of lionfish can enhance the sustainability of other fisheries (Quintana *et al.*, 2023).

2.1. Framework of this PhD: Invasive species and lionfish in the Mediterranean

With contrasting ecosystems and an eastward trend in NIS to native ratios (Katsanevakis *et al.*, 2014a), the semi-enclosed-and-locked configuration of the Mediterranean Sea make it an appealing natural laboratory for the study of natural and human-induced changes (Aurelle *et al.*, 2022).The establishment of viable populations from over 750 NIS has altered the structural and functional feedbacks among key processes of the Mediterranean ecosystems. A complete halt of NIS spread is impossible. On the contrary, climate change is expected to further diminish large-sized native fish populations in the Mediterranean, some of which with commercial interest, while pelagic, thermophilic, and generally NIS of Indo-Pacific origin will be increasingly favoured (Moullec *et al.*, 2019).

Despite a growing scientific literature published in recent years regarding the NIS in the Mediterranean Sea (Tiralongo *et al.*, 2022), knowledge of NIS in the marine environment has received less attention compared to other environments (Tricarico *et al.*, 2016). The absence of adequate empirical data has been emphasized as a major bottleneck for understanding the different facets and dynamics of Mediterranean bio-invasions and guiding a concerted management approach (Galil *et al.*, 2018b; Kleitou *et al.*, 2021b; Kourantidou *et al.*, 2021).

The dilemma for managers now is how to adapt to these new conditions and move away from the notion that all NIS cause negative perturbations to exploit the benefits that some species might provide, but at the same time, protect the ecosystems from the deleterious impacts that some invasive species can induce. Conservation policies currently focus on maintaining historical compositions and species distributions which albeit important, they do not consider the ecosystem functions and neither design of policy initiatives that incorporate future patterns of biodiversity into conservation planning (Adam *et al.*, 2022).

Due to its sentinel location near the Suez Canal, Cyprus is the first EU-country to directly be affected by the immigrations of Indo-Pacific species into the Mediterranean Sea. It has a strategic role to play in early warning / response of new introductions, monitoring of invasive species impacts at an early stage, and evaluation of potential management measures that could be utilized across the Mediterranean Sea. The PhD started in 2018 at a moment when the Mediterranean Sea was experiencing the lionfish expansion in one of the fastest spreads ever recorded for marine invasive species in the region (Poursanidis *et al.*, 2020). Lionfish invasion characteristics offered a unique and timely opportunity for research and acquisition of fundamental knowledge about management possibilities during escalating invasion stages because:

- It had a demonstrated invasion history with proven detrimental impacts on the ecosystems (Albins & Hixon, 2013; Côté & Smith, 2018), and therefore it received significant attention by the science community which could be used for prompt management response.
- It was a recent invader in the Mediterranean Sea (Kleitou *et al.*, 2021b) thus allowing monitoring of its impacts during a critical period when its spread and population growth was undergoing.
- Management measures for lionfish were already tested and applied in the Caribbean and Western Atlantic, and lessons learnt could be replicated and tested in the Mediterranean Sea (Akins, 2012; Ulman *et al.*, 2022).
- The conspicuous characteristics of the species make it easily distinguished from other taxa and reliable for monitoring purposes even using citizen-science (Giovos *et al.*, 2019; Clements *et al.*, 2021).

- Its stationary territorial behaviour when approached by divers, allows for easy targeted (mechanical) removal especially using spearfishing which proved effective in lowering its numbers at selected locations of the Western Atlantic (Barbour *et al.*, 2011; de León *et al.*, 2013; Harms-Tuohy *et al.*, 2018).
- It is edible and a market-based approach to manage its invasion was promoted in the Caribbean (Chapman *et al.*, 2016), a concept that is highly relevant and emerging for the NIS in the Mediterranean Sea (Kleitou *et al.*, 2021a; Minasidis *et al.*, 2022).
- Its reputation as one of the most harmful fish invasive species attracts the public interest and is being widely promoted as a route to facilitate public education, increase awareness about invasive species while concomitantly involving volunteers in management actions (Clements *et al.*, 2021).

This PhD aimed to produce novel information regarding management actions and possibilities for NIS control in the Mediterranean Sea. To this end, the PhD focused on top management priorities for established NIS, as ranked by Giakoumi *et al.* (2019a), and assessed their ecological or socioeconomic trade-offs, and their efficiency in controlling non-indigenous species populations with emphasis on the lionfish recent invasion. Existing knowledge and practices that were proved effective in the Western Atlantic were replicated and trialled in Cyprus. Through the assessment, recommendation guidelines were developed to guide control of invasive species, adaptation to NIS, and improvement of current policy and management frameworks.

The four priority management actions assessed were:

1) Action 1: Education and public awareness.
2) Action 2: Rehabilitate the environment (protect and restore marine areas).
3) Action 3: Encourage the commercial and/or recreational utilization.
4) Action 4: Targeted (mechanically) remove the species.

Each of the Chapters 1-4 utilised bespoke research method(s) to facilitate new knowledge regarding one or more of the abovementioned Actions. Based on this new knowledge the following Chapters 5-6 provided recommendations to improve legislation, policy, and management strategies, ameliorate the impacts of NIS, and conserve the biodiversity and habitats of the Mediterranean Sea as well as boost the local economy (Table 2.1). The Chapter outputs were complemented by technical management reports such as the compilation of a Risk Assessment to include lionfish in the list of Invasive Alien Species of [European] Union concern (Appendix 4A) and the publication of a regional management guide for lionfish, endorsed by the Prince of Monaco Albert II, that transfers knowledge and cost-effective management practices to Cyprus neighbouring countries (Appendix 5).

This PhD was strongly supported by RELIONMED and MedKeyHabitats II projects. RELIONMED project was an EU project funded by the LIFE instrument and implemented by five partners, including University of Plymouth. The project was implemented between 2017 and 2022 and aimed to make Cyprus the first line of defence against the invasion of the lionfish in the Mediterranean by incorporating the management knowledge gained from the Western Atlantic to the Mediterranean region. RELIONMED had a demonstrative character with three major areas of development, namely the demonstration of surveillance and early detection system, the demonstration of a removal response system, and the lionfish market exploitation (Kleitou *et al.*, 2019c). Ecological and socio-economic indicators were monitored throughout the project to inform managers of the region on the most cost-effective practices identified (Kleitou *et al.*, 2019c). MedKeyHabitats II is a project funded by MAVA Foundation aimed to map marine key habitats and assess their vulnerability to fishing activities, and a case study from Cyprus was used, implemented by Marine and Environmental

Research (MER) Lab in 2020 where interactions of non-indigenous species with fishers and marine ecosystems were assessed.

Table 2.1. Method and objectives of the Chapters of this PhD project.

#	Chapter	Method	Objective
1	Invasive lionfish in the Mediterranean: low public awareness yet high stakeholder concerns	Questionnaire surveys were conducted with a representative cross section of the adult general public (via telephone) and stakeholders (via organised meetings) in Cyprus	- Identify the baseline awareness and perceptions of the public and stakeholders in relation to lionfish. - Record the interactions of people with lionfish and identify any possible impacts they may have. - Collect suggestions from the public and stakeholders on how to respond to the spread of lionfish in the Mediterranean.
2	A Marine Protected Area benefits the invasive lionfish (*Pterois miles*)	Visual census surveys in a marine protected area and adjacent unprotected sites	- Elucidate the effects of fishing on lionfish densities. - Understand the impact from the establishment of new marine protected areas on lionfish densities.
3	Regular monitoring and targeted removals can control lionfish in Mediterranean Marine Protected Areas	Training of divers and implementation of removal events, organisation of removals events, visual census surveys at the sites of the removal events, social	- Assess the efficiency of involving volunteers in monitoring the populations of lionfish and guiding management interventions. - Evaluate the efficiency of targeted removal events by volunteers in decreasing the lionfish numbers from marine protected areas.

#	Chapter	Method	Objective
		surveys with the participants	- Understand socioeconomic dimensions from the participation of the volunteers in lionfish removals.
4	Conflicting interests and growing importance of non-indigenous species in commercial and recreational fisheries of the Mediterranean Sea	Social surveys with fishers at the east of Cyprus	- Assess the contribution of NIS in fishers catches. - Understand socio-economic interactions, knowledge, norms, and intrinsic motivations of fishers with respect to common NIS.
5	The case of lionfish (Pterois miles) in the Mediterranean Sea demonstrates limitations in EU legislation to address marine biological invasions	Synthesis of experiences and recommendations for management improvements	- Present the lessons learnt from RELIONMED efforts to collect early-invasion data and propose lionfish *Pterois miles* for inclusion to the Invasive Alien Species Union List. - Identify challenges for implementation and provide recommendations on the basic IAS Regulation and the Delegated Regulation on risk assessments 2018/968 that could be applied to improve relevance, coverage, effectiveness, and management of marine IAS at a European and regional level.

#	Chapter	Method	Objective
6	Fishery Reforms for the Management of Non-Indigenous Species	Synthesis of experiences and recommendations for management improvements	- Propose an ecosystem-based fishery management for NIS with a structured, iterative, and adaptive framework that considers the range of costs and benefits to ecosystems, ecosystem services, and fisheries to determine whether NIS stocks should be managed using sustainable or unsustainable exploitation. - Suggest fishery reforms such as multiannual plans, annual catch limits, technical measures for sustainable exploitation, and legitimization of unlimited fishing of selected NIS and introduction of new fishery licenses for NIS. - Suggest local investment strategies to protect / enhance natural assets to improve ecosystem resilience against NIS, as well as fishery assets to improve the performance of NIS fisheries.

3. Chapter 1: Invasive lionfish in the Mediterranean: low public awareness yet high stakeholder concerns

3.1. Author contributions

P.K. conceptualized, designed the study, and led the writing of the manuscript. I.S. contributed to the statistical analyses and visualizations. P.K. led the social surveys. P.K. prepared the questionnaires which were reviewed by the other authors. All authors helped in refining its methodology and objectives, critically reviewed the drafts and gave final approval for publication. S.R. and J.M.H. supervised the study. This manuscript is published in the journal Marine Policy.

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3.2. Abstract

A lionfish invasion in the Western Atlantic has been one of the most ecologically harmful fish invasions to date. Experience there has shown that its management is most effective when the public and stakeholders are involved. The lionfish (*Pterois miles*) has recently invaded the Mediterranean, spreading at an alarming rate. To understand lionfish knowledge and perceptions, questionnaire surveys were conducted with a representative cross section of the adult general public (via telephone) and stakeholders (via organised meetings) in Cyprus. Results from 300 public surveys revealed limited awareness about the lionfish but strong support for its local management. Men and older respondents showed stronger support compared to women and younger respondents, respectively. Results from 108 stakeholder revealed high level of awareness and almost unanimous support for management measures. The majority had not experienced any effects from the recent lionfish invasion, but some reported negative impacts such as limited access to dive sites, ecosystem damage and fishing gear destruction. Few stakeholders perceived benefits of this invasive species, e.g. to dive tourism or as a food source. Almost all stakeholders expressed a willingness to get involved in lionfish management, but only around half would consider personal consumption, or sports incentives as good incentives for their participation. Encouragement from scientists through coordination, training and support was suggested as an essential part of effective management strategy. The results of this study can inform an efficient adaptive management process across the Mediterranean region and assist future engagement of citizen scientists in lionfish control and mitigation.

3.3. Introduction

Marine invasive species are adding to cumulative pressures such as overfishing and climate change which in combination are causing rapid changes in coastal marine ecosystems worldwide (Mack *et al.,* 2000). Due to the inherent connectivity of marine systems, invasive species are spreading unchecked and causing widespread environmental change, disrupting ecological functions and in some cases causing fisheries collapses (Mack *et al.*, 2000). A lionfish (*Pterois miles*/*Pterois volitans* complex) invasion in the Western Atlantic has been characterised as the most ecologically harmful marine fish invasion to date, responsible for significant impacts on the biodiversity and ecological functions of the region (Albins & Hixon, 2013).

The impacts of the lionfish in the Western Atlantic are associated to habitat modification (Lesser & Slattery, 2011) and declines in the local biodiversity(Ballew *et al.*, 2016). With high predation rates, lionfish reduces the abundance and recruitment of native biota (Albins & Hixon, 2008; Green *et al.*, 2012; Ballew *et al.*, 2016; Kindinger & Albins, 2017; Tuttle *et al.*, 2017) and outcompetes native predators (Albins & Hixon, 2013; Raymond *et al.*, 2015). While socio-economic impacts have yet to be fully evaluated, the lionfish complex has still the potential to reduce the native fish recruitment success by a significant amount (up to 95 %, on experimental sites) (Côté *et al.*, 2013a) and further lower fisheries yields on economically important fish (Johnston *et al.*, 2015). The biological traits of lionfish, such as early maturity, high growth rates, generalist diet, high reproductive rates, generalist habitat use, long-range larval dispersal, and effective physical and behavioural defences (i.e. venomous spines which are posed in case of a perceived threat, and resistance to ectoparasites) favour its invasive character and successful spread across regions (Figure 3.1**)** (Côté & Smith, 2018).

Figure 3.1. Illustration of a lionfish from the Mediterranean. The lionfish is posing its venomous spines after perceived threat.

Evidence from throughout the eastern Mediterranean shows that a lionfish (*Pterois miles*) invasion is now underway (Kletou *et al.*, 2016; Giovos *et al.*, 2018b). Following an unsuccessful invasion in 1991 (Golani & Sonin, 1992), the lionfish were recorded again in 2012 off Lebanon, and numbers have quickly proliferated and spread, reaching the central Mediterranean Sea in just three years and becoming increasingly abundant along the entire eastern basin (Azzurro *et al.*, 2017). Genetic work revealed that the first lionfish individuals were most likely introduced in the Mediterranean via the Suez Canal (Bariche *et al.*, 2017; Stern *et al.*, 2019). Cyprus sentinel location near the Suez Canal was the first Mediterranean country where lionfish were initially reported to be established, forming pairs along the eastern side of the island (Kletou *et al.*, 2016).

Complete removal of lionfish is currently unrealistic, and efforts are shifting towards understanding and control. Its control however, poses a number of challenges, which can include a lack of on site management resources, divergent stakeholder views about the value of invasive species and opposition to removal techniques (Malpica-Cruz *et al.*, 2016). Experience of trying to manage a lionfish outbreak in the Western Atlantic has shown that it is necessary to build a socioeconomic understanding of effective management strategies through a programme of research and management (Estévez *et al.*, 2015).

The EC Directive 2003/35/EC established a framework for public consultation in environment-related decisions, its objectives are to improve public participation and involve them in drawing up plans and programmes related to sustainable use of the environment. Moreover, the European Regulation 1143/2014 on invasive species highlights the importance of public participation in bringing about effective and timely action to tackle invasive species. Engagement of the public and stakeholders is seen as essential in tackling lionfish invasion in the Western Atlantic; either through the development of a commercial lionfish market or through the participation of citizen-scientists in monitoring and removing lionfish, particularly in areas where commercial fishing is either not permitted or impractical (Malpica-Cruz *et al.*, 2016). Therefore, understanding the perceptions and behaviour of the public and stakeholders is critical towards effective lionfish management.

In this study, a telephone survey was used to census a representative cross section of adults in Cyprus while a series of marine stakeholder meetings was held throughout the country to identify baseline understanding and awareness of the public and stakeholders in relation to lionfish. The questionnaires were designed to record the current interactions of people with lionfish and identify any possible impacts they may have. We also sought suggestions from the public and stakeholders on how to respond to the spread of lionfish in the Mediterranean. Here we report on the results of these surveys and discuss the findings in a wider management framework for lionfish.

3.4. Methods

3.4.1. Survey

Questionnaires combined qualitative and quantitative questions designed to assess general public and marine stakeholder knowledge and perceptions of lionfish. Questions to the public fell into three broad topics; those to marine stakeholders fell into seven topics (Table 3.1**)**. The full set of questions used is presented in Chapter 1A. Members of the general public were contacted using a telephone survey of 300 permanent Cypriot citizens between 20 October to 6 November 2017. Stratified random sampling was used to obtain responses from a representative spread of citizens aged between 18-76 years old living in urban, semi-urban and rural regions of Cyprus. Marine stakeholders were defined as members of the public who make use of the marine environment as a resource (e.g. anglers and divers) as well as people involved in the decision-making such as the Governmental Authorities and Non-Governmental Organisations. Marine stakeholders were interviewed during meetings carried out across different districts of Cyprus; namely Limassol, Paphos, Nicosia, Larnaca, and Famagusta (i.e. Protaras), between 7/11/2017 and 23/11/2017.

Table 3.1. Broad topics covered in lionfish questionnaires to the public and to the marine stakeholders.

Public telephone surveys (n=300)	**Marine stakeholder meetings (n=108)**
Perceptions on lionfish and its potential to cause damages to the environment, economy and human health	Perceptions on lionfish and its potential to cause damages to the environment, economy and human health
Perceptions on future strategies	Perceptions on future strategies
Socio-demographics	Abundance of lionfish
	Effects of lionfish
	Management of lionfish
	Socio-demographics

3.4.2. Data sorting and statistical analysis

Once data collection was completed, all data were pooled. Values from dichotomous (Yes/No) and scale questions (ranking order of preference: 0-10) were entered directly, and key points from open-ended questions were detailed in the same spreadsheet.

Initially, the statistical analysis focused on the differences between the public and the stakeholders for the questions related to perceptions on lionfish and future strategies; which have been asked to both groups. The dichotomous questions were analysed using a Pearson's chi squared test with Yate's continuity correction to test for equal proportions for each scoring category. For scale questions, comparisons between public and stakeholders were focused on two approaches. Firstly, the two groups were tested for differences on their overall scoring tendency based on the ordinal scores using a Mann-Whitney U test. Secondly, the ranking order of preference in each question was binned into 3 nominal agreement categories including disagree (ordinal numbers: 0-4), neutral (ordinal number: 5) and agree (ordinal numbers: 6-10) and tested for equal proportions for each of those groups using a Pearson's chi squared test or Fisher's test, when sample size in one or more cells was below 5. Potential "I don't know" responses were analysed separately and statistically tested with a two-proportion's test with Yate's continuity correction.

The public and the stakeholders were then analysed independently to unravel which of the demographics (i.e. gender, age, education and district) might have played an important role in their responses. For dichotomous questions, a Binomial GLM (Bernoulli GLM) was run, and for the Likert scale questions, a motivational score was calculated as the sum of each respondent's scores from all the questions. A multiple linear regression was conducted after the application of a box cox transformation to satisfy the normal distribution and the homoscedasticity of the errors, which were verified via a Shapiro-Wilk test and Breusch-Pagan test, respectively. For demographics that showed to play a significant role in the motivational scores, they were tested independently to observe which of the levels differed, using non-parametric tests: Mann-Whitney U test when factor comprised two levels or Kruskal-Wallis followed by a Dunn's test with Bonferroni correction, when factor had more than two levels.

For all the statistical analyses, null responses were excluded, and the level of significance α was adjusted to 0.05. All graphics were generated in R-studio; more specifically dichotomous scale and ordinal scale graphs were produced using 'Likert' package (Bryer & Speerschneider, 2016).

3.5. Results

3.5.1. Demographic information

The public respondents reflected the actual population distribution of the Republic of Cyprus. More than half were women (60%) with most of the respondents being residents of Nicosia (40%), followed by Limassol (27%), Larnaca (16%), Paphos (11%) and Famagusta (5%). The public's respondents ranged from 18-76 years old, with the majority (61%) being represented by people of 40 – 64 years old. Most of the public respondents had university or college education (61%).

The majority of the stakeholders were men (79%) of age between 14-68 years old. Stakeholders of different education level, age, and districts contributed in the surveys. Most of them, however, were graduates of university or college education (56%), of ages 25-39 (44%) and 40-64 (42%) years old, and mainly residents of the three districts; Limassol (30%), Larnaca (25%), and Famagusta (24%).

3.5.2. Public vs stakeholders' knowledge and perceptions about lionfish

There were statistically significant differences between the public and the stakeholders in the knowledge and perceptions about lionfish; specifically if they heard about lionfish, if they would recognise it in TV or live, and if they know that it is edible

(Figure 3.2). Most of the stakeholders had heard about lionfish, could recognise it and knew that it is edible (Figure 3.3). The majority of public was unaware of lionfish. From those that were aware about lionfish, half of them would recognise it in a picture, live or on TV and only a small percentage of the respondents were aware that lionfish are edible (Figure 3.3).

The opinion of the public and the stakeholders also differed significantly when asked to scale if lionfish can damage the environment, if lionfish can negatively impact the economy and if lionfish pose a risk to human health. Significantly more members of the public did not think that lionfish could damage the environment, negatively impact the economy, or pose a risk to human health (Figure 3.3).

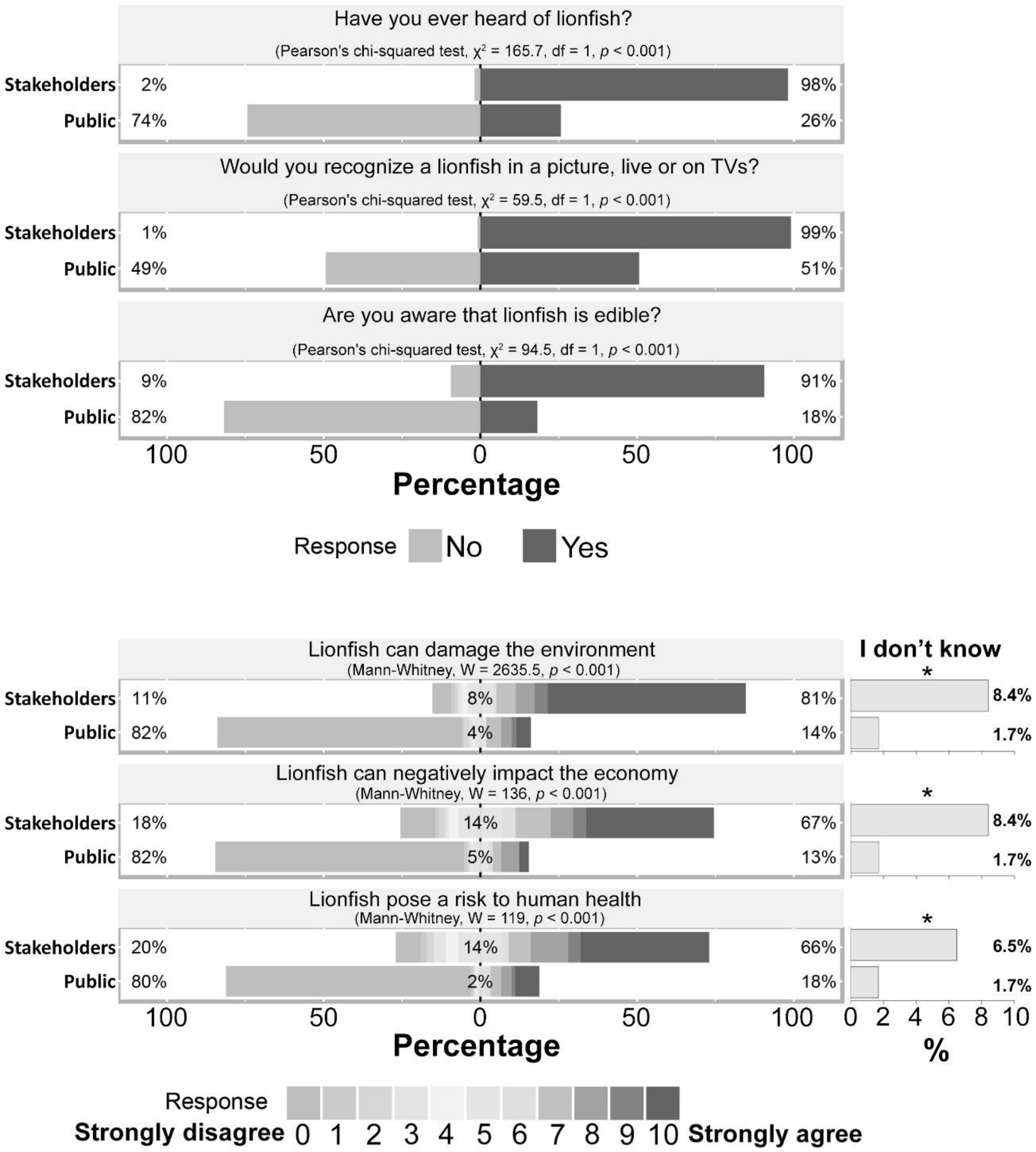

Figure 3.3. Stakeholders and public knowledge and perceptions about lionfish. Proportions for ordinal scores were acquired based on their categorisation to disagree (0-4), neutral (5) and agree (6-10). Statistical differences between the public and the stakeholders are presented below each statement. **Note**: Asterisks (*) represent statistically significant difference (2-Proportions test, $p < 0.05$) concerning the "I don't know" responses between public and stakeholders.

Future strategies

Using a scale of 0 to 10 (with 0 indicating strong disagreement, 5 indicating neutrality, and 10 indicating strong agreement,) stakeholders and the public were asked to provide their level of agreement concerning the following management strategy measures and options:

1. It is necessary to undertake research to understand the potential effects of lionfish on local environment, economy, and human health
2. It is necessary to develop a management strategy for lionfish in Cyprus
3. I support management measures to limit the numbers of lionfish in the marine environment of Cyprus
4. I support management measures for the complete eradication of lionfish from Cyprus waters
5. I would consume lionfish
6. I would buy products made from lionfish

For the first statement the stakeholders appeared to respond similarly with the public, where either showed to disagree/agree or being neutral equally the same (Fisher's exact test, $p > 0.05$) (Figure 3.4). In the second and third statement, both the public and the stakeholders responded the same to each of the agreement categories (Fisher's exact test, $p > 0.05$), but their overall degree of scoring varied significantly (Figure 3.4). For the fourth statement, the two groups showed the same response tendency overall as well as to each of the agreement categories (Pearson's chi-squared test, $\chi^2 = 0.5$, df = 2, $p > 0.05$) (Figure 3.4). While the above statements were associated with a strong positive response from both groups to support the project's aims and the requirement of a management strategy (Figure 3.4), the following statements rather displayed a striking contrast concerning their perceptions. For instance, when the two groups were asked if they would consume lionfish and if they would buy products made from lionfish, the response tendency between stakeholders and the public differed significantly, where stakeholders mostly agreed and the public disagreed with the statements (Pearson's chi-squared test, $\chi^2 = 113.4$, df = 2 and $\chi^2 = 72.6$, df = 2, respectively, $p < 0.001$) (Figure 3.4).

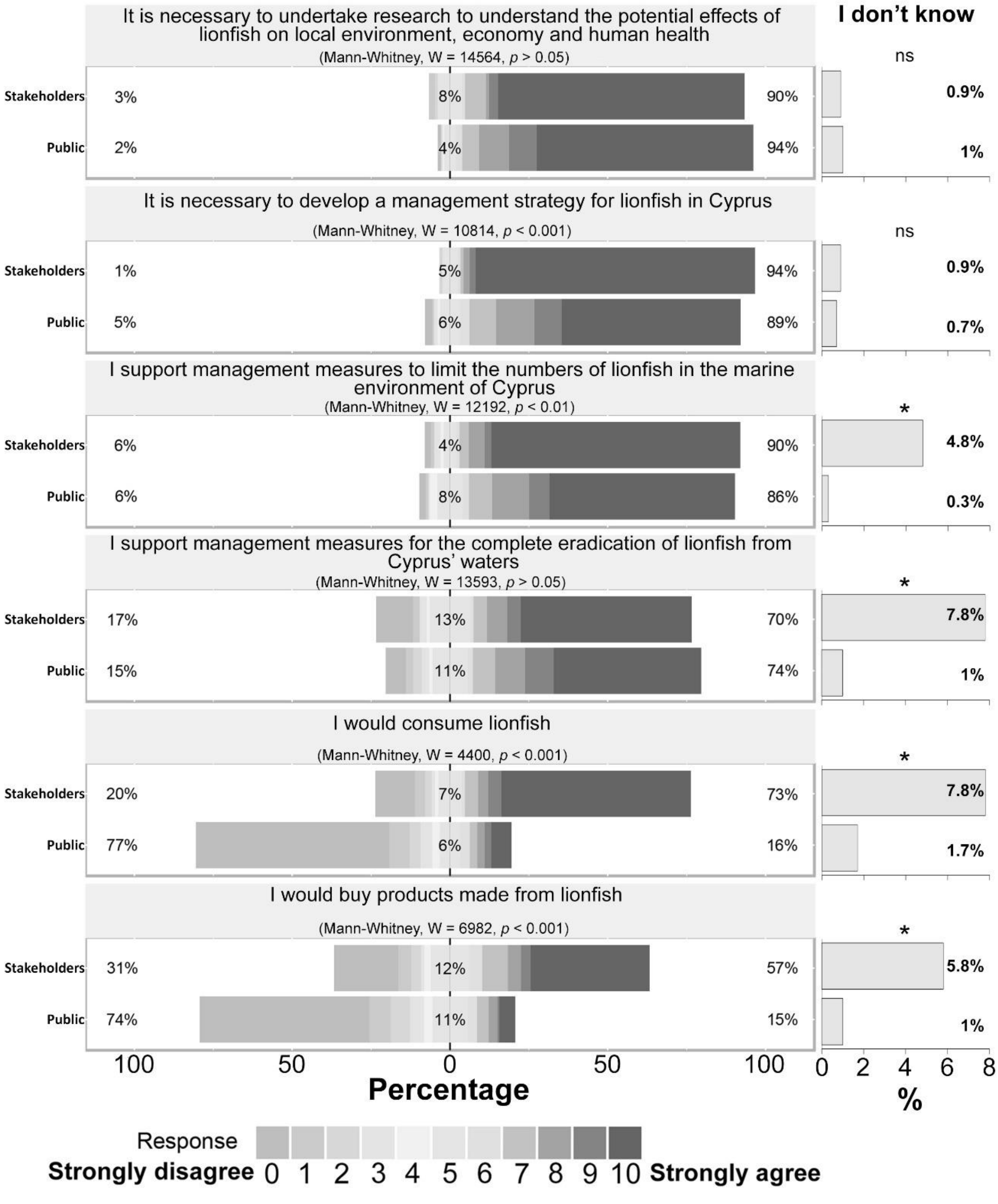

Figure 3.4. Agreement of the stakeholders and the public on different management measures and strategies. Proportions were acquired based on the categorisation of the ordinal scores (0-10) to disagree (0-4), neutral (5) and agree (6-10). Statistical

differences between the public and the stakeholders are presented below each statement. Note: Asterisks (*) represent statistically significant difference (2-Proportions test, $p < 0.05$) and ns indicates that no statistically significant distinctions were found between the "I don't know" responses given by the general public and those provided by the stakeholders..

Demographic differences in knowledge and perceptions about lionfish

The demographic parameter that played the most important role for the public regarding the knowledge about the lionfish was the gender. Specifically, men showed that they were more probable to have heard and recognize the lionfish than women (Bionomial GLM, Z = -2.02, $p < 0.05$). The motivational scores derived from the questions associated to the public perceptions of lionfish (i.e. impact of lionfish and support towards its managements and research; see questions 4 and 5 in Appendix) were shown to be influenced by the gender (Multiple linear regression, df= 1, F = 10.17, $p < 0.05$) and the age (Multiple linear regression, df= 3, F = 6.71, $p < 0.05$). Specifically, men showed higher motivational response scores (more positive) than women (Mann-Whitney, W = 20144, $p < 0.05$), and the youngest ages were less positive compared to older people (Kruskal-Wallis, $\chi^2 = 17.30$, $p < 0.05$) (Figure 3.5). For stakeholders, none of the demographics showed to be responsible for their responses, neither on the knowledge nor the perceptions about the lionfish.

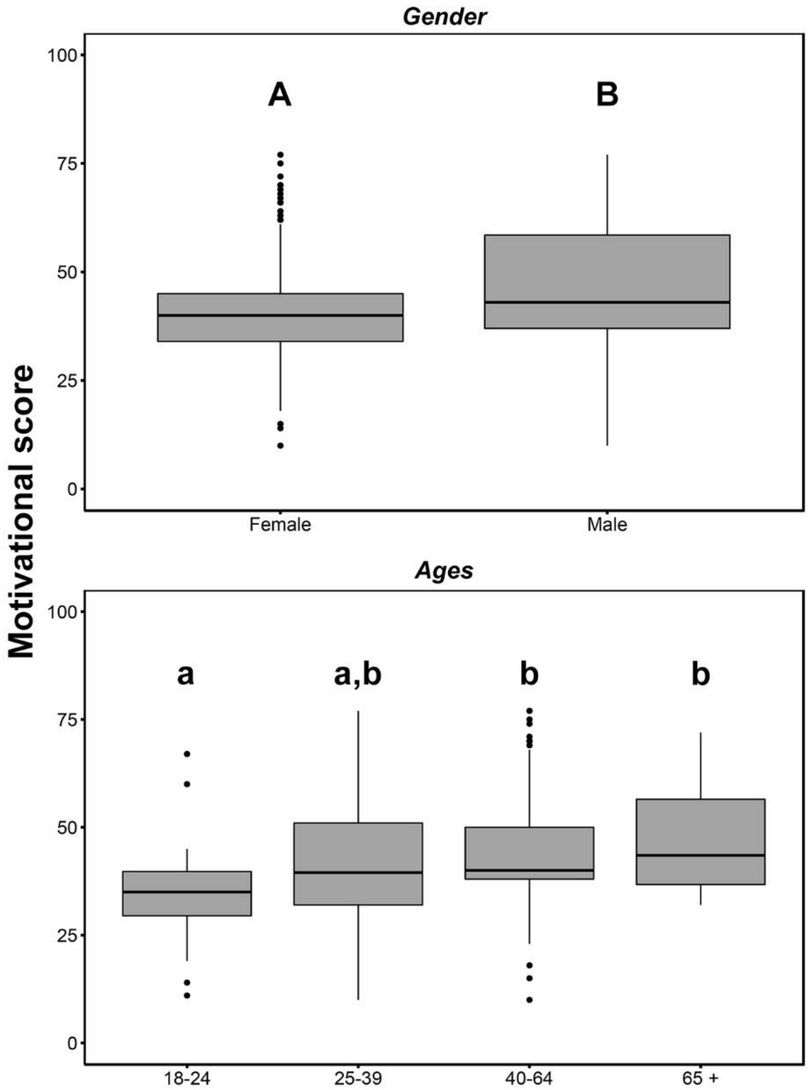

Figure 3.5. Motivational scores and demographic differences of the public regarding lionfish impacts and support towards its research and management. Groups that do not share a letter were significantly different at $p < 0.05$.

The abundance of lionfish

Stakeholders were asked if and when was the first time that they observed a lionfish in the waters of Cyprus. 81% (n=87) answered that they had seen a lionfish in Cyprus marine environment, 16% (n=17) answered that they had not seen; and 4% (n=4) did not answer at all. According to the responses, most first sightings occurred between 2014-2015 (n=41) with some first sightings occurring in 2012 (n=6).

In response to what is the maximum number of lionfish that they have seen in a group, stakeholders' answers varied (mean=7, σ=8.60); with the maximum recorded value of 60 lionfish individuals in one group. Most of the interviewees who observed grouped lionfish weren't able to describe the surrounding habitat where they found them (64%). From those who answered, rocky substrate was reported as the most preferred by lionfish (54%) followed by shipwrecks and artificial reefs (33%).

Stakeholders were asked if they believe that the lionfish population is increasing or decreasing. The vast majority of the respondents stated that the population has increased both since their first encounter with lionfish (89%, n=83) and since the last year (92%, n=79). A minority of stakeholders stated that they had observed constant levels of lionfish. No respondents stated that they had observed a decrease in the population on lionfish.

Effects from lionfish

Stakeholders were asked if they have experienced any effect due to the presence of lionfish (i.e. personal, economic or environmental). From those who responded (n=99), 73% answered that they had experienced no effects while 27% had experienced some effects (positive or negative). According to the responses, during the last year, 23% of the stakeholders had experienced some effects from the lionfish.

The experienced negative or positive effects, as reported by the stakeholders, are presented in Table 3.2.

Table 3.2. Experienced effects from the lionfish as reported by the stakeholders. N represents the number of the records for each effect.

Negative effect	**N**	**Positive effect**	**N**
Limits access to dive sites	6	Increase in diving tourism	5
Removes other fish	6	Food source	1
Environmental threat	2		
Health Hazard	1		
Destruction of equipment	1		

Opinions on the management of lionfish

Stakeholders were asked if they believe (or not) that the lionfish in Cyprus should be managed, if they are willing to contribute in management efforts, and which measures they consider as the most eligible for lionfish management. Most stakeholders reported that the lionfish should be managed in Cyprus' waters and also that they are willing to get involved in removal activities (Figure 3.6). Several possible management measures were raised by the stakeholders such as the creation of a market (for lionfish products, fishing, trapping and general culling of the lionfish population (Table 3.3).

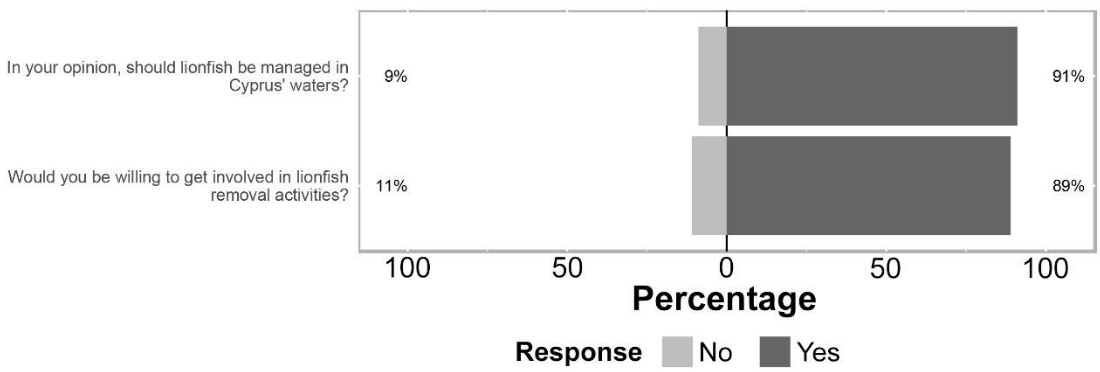

Figure 3.6. Perceptions of stakeholders about lionfish management and their willingness to get involved in removal activities.

Table 3.3. Management measures suggested and number of times raised by the stakeholders.

Management measures	**Number of records**
Fishing	10
Coordinated removals	6
Market creation	6
Spearfishing with scuba	5
Other culling	5
Financial incentives	3
Management	3
Trapping	2
Research	2
Project impact monitoring	2
Education and awareness	2
Competition	1

The stakeholders were provided with specific reasons that could incentivize them in getting involved with removal actions. Using a scale of 0 to 10 with 0 being not willing at all and 10 being very willing, they were asked to state whether they were willing or not willing with each reason. The values indicated a very slight disposition towards agreement (Figure 3.7).

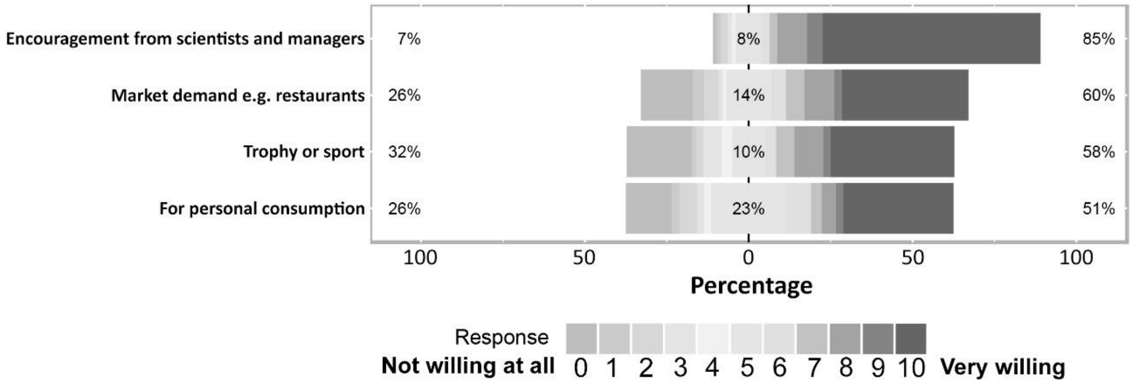

Figure 3.7. Agreement of stakeholders for specific reasons to participate in removal lionfish efforts.

Further, the stakeholders were asked to state reasons that can act as barriers or enablers for them to be involved in removal action efforts. 30% of the respondents (n=32) mentioned 'barrier' reasons while 41% (n=44) mentioned 'enabler' reasons. The most commonly reported barrier was the lack of available time (n=10) and the most commonly reported enabler was proper management, training and support (n=13) (Table 3.4).

Table 3.4. Barriers and enablers that have been reported by the stakeholders to affect their involvement in removal action efforts.

Barriers	**N**	**Enablers**	
No free time	10	Proper Management, training and support	13
Lack of knowledge/skill	6	Other	8
Health hazard	6	Financial support	7
During work hours	3	Equipment	5
Cost	2	Competition/Organised event	5
Improper management	2	Give licenses	3
Believe no action is needed	2	Weekend actions	2
License	1	Market creation	1

3.6. Discussion

Cyprus pioneer role in monitoring and understanding Mediterranean IAS

Cyprus represents the first hotspot of lionfish in the Mediterranean and the first EU country to be affected by Lessepsian immigrations. Thus, it has a pioneer role in understanding introduced species' dynamics, exchanging information, data and best practices including programmes related to public awareness or education. The latter is particularly important for the case of lionfish as the Atlantic experience has shown that its management requires sustained and long-term commitment from both the public and marine stakeholders (Barbour *et al.,* 2011).

Divergences in opinions, knowledge and attitudes

This study identified significant differences in the levels of awareness, recognition and knowledge about lionfish among members of the public compared with marine stakeholders. This dichotomy is to be expected since marine stakeholders in Cyprus are more likely to have encountered lionfish and be aware of potential impacts from their uncontrolled spread. As regard to perceptions, it is interesting to note that a change is already evolving, as a recent study has shown that of 415 stakeholders from Cyprus (mostly divers, fishermen, academics, managers) interviewed between 2012 to 2017, only 65% knew about lionfish and most were against culling (Jimenez *et al.*, 2017). In our survey, there was almost unanimous agreement from both the public and stakeholders that it is necessary to undertake research to understand the potential effects of lionfish, and that its numbers should be limited through management measures. Only five out of 108 indicated that the presence of lionfish may have positive effects on dive tourism.

A divergence in opinion regarding the consumption of lionfish and the purchase of products made from lionfish (e.g. jewellery) was observed. The public were more opposed to these statements rather than the stakeholders. Divergences between groups' opinions on management options was found in other studies (Nisbet *et al.*, 2005; Hicks *et al.*, 2013; Wallner-Hahn & de la Torre-Castro, 2018); attributed to diverse and often competing values and interests. Divergence can be also observed between individuals of the same group due to factors such as different attitudes, personalities and livelihoods (Gelcich *et al.*, 2005). As regards to fish consumption, several models have been proposed to explain consumer behaviour with often interrelated motivational factors taken into account including the availability of fish, meal preparation skills, perceived convenience, health involvement, negative feelings, attitude towards eating fish, social norms, moral obligations, confidence in evaluating the product, etc. (Verbeke & Vackier, 2005).

It is natural that stakeholders with a strong affinity to the sea (e.g. fishers, divers) would be less opposed, more experienced and confident to trial the consumption of a new marine product. If lionfish are not part of the preferred diet (the public social norm) then consumption of the species would require some deliberation on behalf of the consumer. Taste, nutritional value and freshness (quality) of seafood are the overriding factors that influence seafood consumption and buying behaviour (Olsen, 2004). A recent study in the Mediterranean found that lionfish contains higher levels of protein and healthy fatty acids compared to native marine species (Ayas *et al.*, 2018), as it was previously demonstrated in the lionfish of the Atlantic (Morris *et al.*, 2011b). The nutritional value of lionfish could be therefore promoted to influence the norms and attitudes of the public and support its consumption in the Mediterranean.

Gender and age were found to significantly affect the opinions of the public regarding lionfish invasiveness and their support towards lionfish research and management. According to the responses, men were more likely to know of and be able to recognize a lionfish than women. In addition, men and older people were found to be more concerned about the potential impacts of lionfish and were more likely to support lionfish research and management; compared to women and younger people, respectively. Although women usually tend to report stronger environmental attitudes, concern and behaviours than men (Gifford & Nilsson, 2014 and references therein), the differences found in this study can be attributed to the fact that less women are engaging in marine and (recreational) fishing activities in the region. Younger people were surprisingly less concerned about the problem; in contrast to numerous early studies which suggest that they should be more environmentally concerned (e.g. Arcury & Christianson, 1993; Jianguang, 1994; Klineberg *et al.*, 1998). Our study agrees with recent studies, which indicate underlying changes in society and declining trends in youth's environmental attitudes and behaviours (Dietz *et al.*, 2007; Clements, 2012; Liu *et al.*, 2014). Different approaches should be applied to stimulate the interest on the lionfish and involvement of public based on their demographic differences (i.e. age and gender).

Lionfish management using a participative citizen approach

In terms of getting involved in lionfish management, most of the stakeholders (i.e. more than 90%) were willing to get involved. Stakeholders' top-suggested lionfish management measures were fishing, coordinated removals and market creation. However, less than 60% of the stakeholders considered market demand, trophy or sport, or personal consumption as good reasons to incentivize their participation in lionfish removals. On the other hand, encouragement from scientists and managers appears the most preferred incentive, reported by 85% of the stakeholders. This is in line with the most commonly reported enabler (to future involvement) which was focussed on management, training and support; indicating that stakeholders need to be approached by the scientific community, educated, trained and encouraged, in order to participate in the management of invasive species such as lionfish.

The fact that lionfish encounters since 2012 remained vivid in the memory of stakeholders agrees with the results of a recent Lebanese stakeholder survey (Azzurro & Bariche, 2017); and reinforces the evidences that lionfish can be ideally used in a participative citizen approach to monitor and control its invasion (Azzurro & Bariche, 2017). In the Caribbean, surveillance systems driven by citizen scientists, and local removal efforts that make use of trained volunteers have been successful in reducing local densities and biomass of lionfish (de León *et al.*, 2013). Coordinated approaches such as fishing derbies (Malpica-Cruz *et al.*, 2016) can form part of a management strategy as well as bringing economic benefits to the hosting community (Trotta, 2014). The public (though not asked in this questionnaire) may also get involved. It is documented that successful conservation actions require integration of processes that can influence human behaviour (Schultz, 2011). Such processes include motivational messages that enable achievable, specific actions (Schultz, 2011). Motivation messages aimed at the public and stakeholders alike have been used in both the USA and the Caribbean to motivate the hunting and consumption of lionfish including campaigns entitled "Eat them to beat them" and "Do Your Civic Duty, Eat This Fish!" (Carballo-Cárdenas, 2015). Whilst the success of such campaigns has not been evaluated, it may be considered that such an approach may improve the public engagement with lionfish removal efforts.

Application of a multidisciplinary evaluation framework

The integration of the ecological, social and economic sciences into a research evaluation plan can serve to connect the public with a natural environment that underpins aspects of human well-being. The application of an evaluation framework to assess impact (or performance of a management measure) of a project policy or programme can allow for statistical or observational analysis of 'change' that underlies interventions (Rosenbaum, 2010; Gertler *et al.*, 2011). The aim of such approach would be to demonstrate how severe a lionfish invasion may be on the Cypriot (and wider regional) economy and how they pose a direct threat to human health. This interdisciplinary approach is an essential component of a future research plan to influence public knowledge and perceptions and to embed this in a long-term management strategy for lionfish.

3.7. Conclusion

Stakeholder responses corroborate evidence that lionfish are increasing in abundance around the island of Cyprus although most of the public are unaware of this. Stakeholders have concerns that there may be significant impacts on the biodiversity and ecological functions of the region that support human wellbeing (e.g. fisheries, recreation and tourism) if left unmanaged. Moving forward, it is imperative to improve the public's knowledge base on lionfish to influence local and regional political processes about lionfish control though management interventions. Interdisciplinary approaches that support economic and social research along with ecological studies can serve to reconnect the public with the natural environment.

The public were not strongly supportive of a new fishery for local lionfish consumption. A campaign that challenges motivational factors such as social norms, feelings, moral obligations, confidence, attitudes and preferences towards traditional seafood, along with targeted studies on the nutritional value of lionfish in comparison to the preferred seafood dietary choices may engender a shift in consumer choice and create a market for this commodity.

Both groups of respondents expressed strong support for research and management and the stakeholder group demonstrated that they will get involved in management activities. Persistent encouragement, support and training by scientists are reported as essential motivational drivers towards their involvement. To maintain stakeholder engagement, it is necessary to robustly evaluate management interventions on indicators linked to economy, ecology and society. Such knowledge can inform an efficient and adaptive management process that can be shared with wider regional partners in the Mediterranean basin.

4. Chapter 2: Fishery closures in a Mediterranean marine protected area benefit the invasive lionfish (*Pterois miles*)

4.1. Author contributions

P.K. conceptualized, designed the study, analysed, and visualized the results, and led the writing of the manuscript. P.K. led the field activities and monitoring designs with the support of all authors. All authors critically reviewed the drafts and gave final approval for publication. S.R. and J.M.H. supervised the study. This manuscript is currently under review by a scientific journal.

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4.2. Abstract

Marine Protected Areas (MPAs) can protect and restore marine biodiversity and fisheries, but there are concerns that they may also benefit invasive species. The spatial and temporal colonization of invasive lionfish (*Pterois miles)* in the eastern Mediterranean was compared across zones with varying fishing restrictions (no fishing, recreational and commercial fishing, and commercial fishing only), and stations where targeted removal events were conducted by volunteer SCUBA divers. Lionfish density in no fishing areas was nearly double that of areas with commercial fishing only, and over four times greater than in areas where both commercial and recreational fishing were allowed. Lionfish density increased with depth, possibly due to easier human exploitation in shallow waters (0-10 m) that are accessible to recreational spearfishers. Targeted removals by volunteer divers decreased lionfish densities by over 60%, while areas without removals had a 200-400 % increase. Along with management actions, natural and ecological processes might drive lionfish densities within MPAs, and the speed with which lionfish colonized fishery-restricted zones, emphasized the need for a more sophisticated MPA management strategy that considers invasive species impacts and dynamics in an ecosystem-based approach.

4.3. Introduction

Marine Protected Areas (MPAs) can restore depleted fisheries and degraded habitats (Guidetti & Sala, 2007; Fraschetti *et al.*, 2013; Stevens *et al.*, 2014; Blampied *et al.*, 2022), and are a key management tool to conserve marine biodiversity and other marine resources (O'Leary *et al.*, 2016; Duarte *et al.*, 2020). From 2000 to 2020, the number of designated MPAs in the Mediterranean Sea has increased from 109 to 1209, and their coverage has increased over 30-fold (data from MedPAN & SPA/RAC, 2021). More than 100 countries have committed to designate new MPAs and aim to achieve 30% protection of marine areas by 2030 (HAC, 2022). This goal aligns with the EU

Biodiversity Strategy for 2030 (EC, 2020) and the Kunming-Montreal Global Biodiversity Framework (CBD, 2022) which calls for 30% of marine areas to be effectively conserved and protected by 2030 including a target of 10% for highly protected areas.

Species biomass in protected areas, where no extractive activities are allowed (no-take MPAs), can be many-fold higher than in other areas (Sala & Giakoumi, 2018). Increased biomass can, in turn, increase resilience to storms and other perturbations (Sheehan *et al.*, 2013; Sheehan *et al.*, 2021; Davies *et al.*, 2022). The establishment of highly protected areas is limited due to conflicts of conservation with fisheries and other societal goals and needs (Andradi-Brown *et al.*, 2023). As a result, there are many examples of ineffective or counter effective MPAs due to inappropriate management (Claudet & Fraschetti, 2010; Rife *et al.*, 2013; Devillers *et al.*, 2015). However, even when highly protected areas are established, a key question is whether such MPAs will be resilient to uncontrolled disturbances, such as climate change (Pettersen *et al.*, 2022) and the establishment of invasive species (Giakoumi & Pey, 2017).

In the Mediterranean Sea, MPAs are strongly affected by climate change associated impacts such as the spread of warm-water invasive alien species (IAS) that arrive through the Suez Canal (Giakoumi *et al.*, 2019b; D'Amen & Azzurro, 2020; Frid *et al.*, 2023). The presence of IAS can diminish the impact of fishery management measures (Corrales *et al.*, 2018) and there are concerns that MPAs in the Mediterranean, where IAS are a chronic and expanding issue, may not function as biodiversity conservation areas but as breeding grounds for IAS (Galil *et al.*, 2017a; Giakoumi *et al.*, 2019b; Frid *et al.*, 2023). Impacts of IAS are expected to worsen as other human pressures intensify (Geraldi *et al.*, 2020). Long-term and standardized monitoring is essential to inform and synchronize management actions with the evolving understanding of IAS population dynamics and impacts across the expanding network of MPAs in the Mediterranean.

Our research focuses on the colonization and spread of invasive *Pterois miles* (Bennett, 1828) (hereafter, ‘lionfish’) in an eastern Mediterranean MPA where fishery restrictions were recently established. Lionfish are currently expanding in two separate invasions of large marine ecosystems; the Mediterranean Sea and the Western Atlantic Ocean (Ulman *et al.*, 2022). This expansion is being favoured by multiple traits, including an opportunistic diet, fast growth, high fecundity, early maturity, absence of predators, and naïve native prey (Zannaki *et al.*, 2019; Agostino *et al.*, 2020; Savva *et al.*, 2020; Mouchlianitis *et al.*, 2021; Ulman *et al.*, 2021). Lionfish are a major management concern due to their high densities and demonstrated adverse impacts on biodiversity, fisheries, and food web processes (Albins & Hixon, 2008; Lesser & Slattery, 2011; Green *et al.*, 2012; Benkwitt, 2015; Raymond *et al.*, 2015; Ballew *et al.*, 2016; Chagaris *et al.*, 2017; Chagaris *et al.*, 2020). Invasive lionfish have reached high densities in the Western Atlantic, even in areas with intact predator communities such as those found within MPAs (Hackerott *et al.*, 2013; Valdivia *et al.*, 2014). Our objectives were to assess the influence of fishery restrictions on lionfish populations by comparing the lionfish density among different MPA zones. Sites with fishery restrictions were also compared with adjacent sites where targeted removals of lionfish were applied to understand the potential effect of management interventions.

4.4. Methods

4.4.1. Survey design

Study site

Surveys were carried out in the Kavo Gkreko Natura 2000 area (CY3000005), which was designated as a Site of Community Importance (Habitats Directive 92/43/EEC) in

2008, and therefore forms an MPA under EU law. The MPA was mainly established to protect the seagrass *Posidonia oceanica* (Linnaeus) Delile, 1813 (Annex I habitat type with code 1120 of the Habitat Directive). Whole-site protection was established in 2018 (Κ.Δ.Π. 115/2018) with the designation of three zones: (i) zone A where fishing is not allowed (hereafter: No fishing), (ii) zone B where only commercial fishers are allowed (hereafter: Commercial only), and (iii) zone C (hereafter: Fishing allowed) where all legal types of fishing gears/practices are allowed (Figure 4.1). Bottom trawling is prohibited in the entire area as it was provided by Regulation (EC) 1626/1994 for depths shallower than 50 m. Most popular fishing techniques in the area are gillnets and trammel nets, demersal longlines, and fishing pots for commercial fishers, and spearfishing, traps, and shore-based fishing with rods for recreational fishers (Moutopoulos *et al.*, 2021). Between 2018 and 2020, targeted lionfish removals were conducted by volunteer SCUBA divers at sites within the MPA as part of RELIONMED research project (Kleitou *et al.*, 2021c; Kleitou *et al.*, 2022a). Details of targeted removal events are provided in Appendix 2A.

Research design

Two sets of underwater visual surveys were conducted to collect representative data at temporal and spatial scales. First, repetitive monitoring (hereafter, ‘temporal surveys’) was conducted at nine fixed monitoring stations (27 transects) for three years (total number of transects = 81). Six of the monitoring stations were located at 20 m (± 2 m) depth and three at 7 m (± 2 m). All monitoring stations were separated from its nearest same-depth neighbour station by at least 0.5 km and were characterized by rocky substrate. Transects were fixed and surveyed consecutively for three years (2018-2020) during late July or early August (Figure 1A1). Five monitoring stations were in areas where all fishers could operate (Fishing allowed), with two of these being regularly subject to targeted removals by SCUBA divers (Appendix 2A). Two of the monitoring stations were in the No fishing zone and two were in the Commercial only zone. Given that both zones were subject to fishery restrictions, a strategic decision was made to aggregate the stations within these zones into a unified category labelled as 'Protected'. The primary rationale behind this consolidation was to bolster the statistical power of the analysis. Thus, the nine stations were categorized as (i) Fishing allowed, (ii) Fishing allowed & targeted removals (Fishing allowed zone but with additional targeted removals carried out by volunteer divers), and (iii) Protected (the Commercial only and No fishing zones were aggregated).

Second, spatial density sampling (hereafter, ‘spatial surveys’) was conducted in June–August 2020 by surveying 45 reef stations (total number of transects = 135) across the three zones (No fishing, Commercial only, and Fishing allowed) of the MPA. A stratified-random design was employed to cover three depth categories (0–9 m, 10–19 m, and 20–30 m) within each enclosed zone area (Figure 4.1B1). Nine stations were established on *P. oceanica* seagrass or rocky substrate. Specifically, 27 transects were surveyed in No fishing zone with 19 on rocky substrate and 8 on *P. oceanica* meadows, 54 transects were surveyed in Commercial only zone with 30 on rocky substrate and 24 on *P. oceanica*, and 54 were surveyed in Fishing allowed zone with 33 on rocky substrate, 18 on *P. oceanica*, and 3 on sandy substrate (excluded from the statistical analyses). All stations below 10 m depth were located on rocky substrate (Figure 4.1B2).

4.4.2. Visual census surveys

For both temporal and spatial monitoring surveys, three strip transects, 25 m x 5 m (length x width), were surveyed at each station for fish community sampling as described by Katsanevakis *et al.* (2012b). The dive observer positioned a Keson Transect Tape along a 25-meter diving line, establishing the delineation for each strip's dive trajectory. There was no gap between the transects. Within each strip, the observer recorded all fish found within a 2.5-meter radius from the centerline in both directions (Figure 4.1). The number of individuals and estimated size of all fish species were recorded. Individuals (other than lionfish) below 13 cm were categorized as potential prey items for lionfish (Green *et al.*, 2012; Côté *et al.*, 2013b). Species with a trophic level greater than 3.85 (sourced from FishBase) and a maximum size exceeding 80 cm (sourced from FishBase) were categorized as predators, including certain species that Ulman *et al.* (2021) have identified as potential predators or competitors of lionfish.

In the temporal monitoring survey, an additional observer was following a modified technique to monitor only lionfish in three repetitive 25 m x 20 m (length x width) transects as described by (Green, 2012). Lionfish-specific monitoring was conducted by an observer swimming in a zig-zag pattern (Figure 4.1A2) who searched under overhangs, crevices, and cracks in the substratum, using a dive light as needed. This technique was found to be more suitable for accurately understanding lionfish densities as the conventional (25 m x 5 m transect) technique (Green *et al.*, 2013; Kleitou *et al.*, 2022a).

The observers possessed several years of practical experience in counting and estimating the size of fish in their natural habitat. At the commencement of the projects, they conducted field tests to ensure precise measurements. To prevent potential bias stemming from observer discrepancies, the same two observers were responsible for monitoring all stations. For every recorded individual an estimate of its length was made *in situ*. Total densities and sizes were quantified and compared among stations and zones and illustrated using ‘ggplot2’ package in R (version 4.2.0).

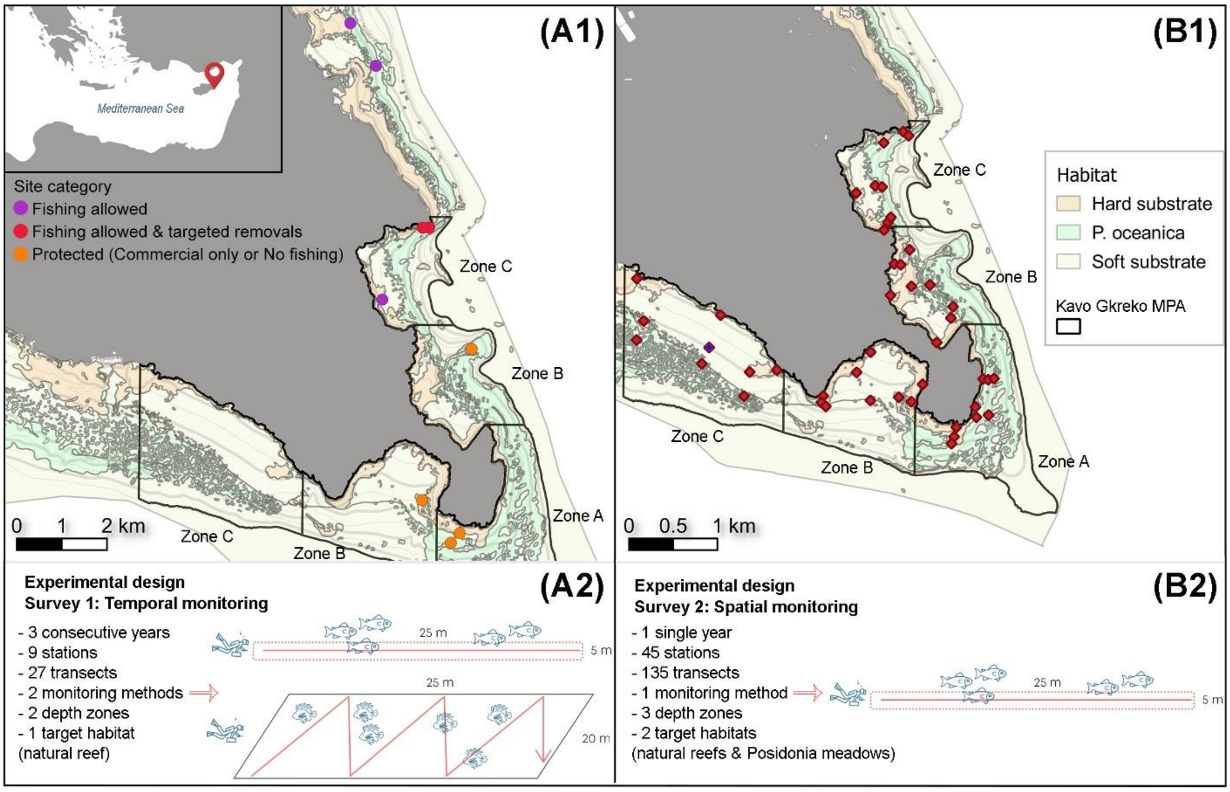

Figure 4.1. Kavo Gkreko MPA with three fishing zones: zone A (No fishing), zone B (Commercial only), and zone C (Fishing allowed). (A1) Location and category of the nine sampling stations and (A2) Methodology applied as part of the temporal survey; (B1) Location of the 45 sampling stations established in the three protection zones and (B2) methodology applied as part of the spatial survey.

4.4.3. *Statistical analyses*

Collected data from the temporal survey had a high degree of multicollinearity (variance inflation factor, VIF > 10) among the investigated predictor variables 'Location' and 'Year'. Thus, we used permutational analysis of variance (PERMANOVA) (Anderson, 2014) which is robust to multicollinearity due to its permutation procedure that disrupts the inherent sample structure. PERMANOVA partitioning was performed using a similarity matrix based on the Euclidean distance of square root transformed lionfish density. To test the effects of location (three levels: Fishing allowed zone, Fishing allowed zone combined with targeted removals, and 'protected' located in No fishing or Commercial only zones), year (three levels: 2018, 2019, 2020), depth (two levels: 7 and

20), and station (nine levels, nested in location and depth) on the lionfish density of each station (three replicates each), a total of 9999 permutations were computed using residuals under a reduced model. The correlations between lionfish densities, prey densities, and predator densities were examined using the Kendall's tau rank correlation coefficient.For data collected from the spatial surveys, lionfish counts were over-dispersed with unequal conditional mean and conditional variance with many zero-captures of lionfish counts. Thus, we fitted a zero-inflated Poisson GLMM with a logit link for the zero-inflation part and a log link for the Poisson part (Brooks *et al.*, 2017) to model the effect of the fishing management measures (three levels: No fishing, Commercial only, and Fishing allowed), depth (continuous in meters), habitat type (two levels: *Posidonia* meadows or rock), and prey-fish density (count per 100 m^2) on lionfish densities (count per 100 m^2). Transects were included as nested random effects within stations and model fit was assessed using maximum likelihood estimation with the 'BFGS' or 'L-BFGS-B' optimizer. Twelve models were fitted including MPA type, habitat type, prey-density, predators, and depth. The correlations between lionfish densities, prey densities, and predator densities were also examined using the Kendall's tau rank correlation coefficient.Akaike's Information Criterion (AIC) (Akaike, 1973) was used to rank the GLMM models, with a decrease in AIC of ≥2 considered a significant improvement (Burnham & Anderson, 2004). The model with management zone, depth, prey density, and habitat as confounding variables was evaluated as the most suitable with the lowest AIC score. To illustrate the spatial distribution of lionfish in a map, the study area was divided into 100 x 100 m cells. The best-fit model was applied to predict the densities of lionfish in the *Posidonia oceanica* meadows and rocky habitats of the entire MPA. The lionfish density map was produced in QGIS. The GLMMs were conducted in R (version 4.2.0) using the 'glmmTMB' package. Model diagnostics were checked with 'DHARMa' and 'performance' packages.

4.5. Results

4.5.1. Temporal surveys

Average lionfish density in the nine stations increased from 77 ± 75.6 (SE) individuals per hectare in 2018 to 114.8 ± 149.6 in 2019 and 169.6 ± 171 in 2020. The increase in lionfish density was more pronounced in the two zones with fishery restrictions (No fishing or Commercial only). Over the three years, those stations had an increase of about 378% in lionfish densities (Figure 4.2A). A smaller increase was observed at stations where fishing was allowed with an increase of 210% in lionfish densities (Figure 4.2A). Stations with targeted removal events had a 64% decrease in lionfish numbers. Stations at 20 m depth had approximately 230% more lionfish compared to those at 7 m depth (Appendix 2B). The interaction between location and year and depth and year had a significant effect on lionfish densities (Table 1). Increases in lionfish densities were not correlated with prey or predator densities (Kendall's Tau, $p > 0.05$; Figure 4.2A). The average estimated lionfish size at stations with frequent targeted removal events decreased from 19.8 ± 1.26 cm (SE) in 2018 to 17.7 ± 1.09 cm and 17.8 ± 0.70 cm in 2019 and 2020, indicating high exploitation. Estimated sizes in protected stations increased from 19.7 ± 1.71 cm (SE) in 2018 to 21.8 ± 0.70 cm in 2019 and to 22.4 ± 0.75 cm in 2020. Similarly, estimated sizes in fished areas increased from 19.0 ± 1.11 cm (SE) in 2018 to 19.2 ± 0.86 in 2019 and 19.6 ± 0.78 in 2020 (Figure 4.2B). However, *in situ* size estimations by the divers might be prone to mistakes (Harvey *et al.*, 2001), therefore, no statistical analyses was performed in size and biomass estimations.

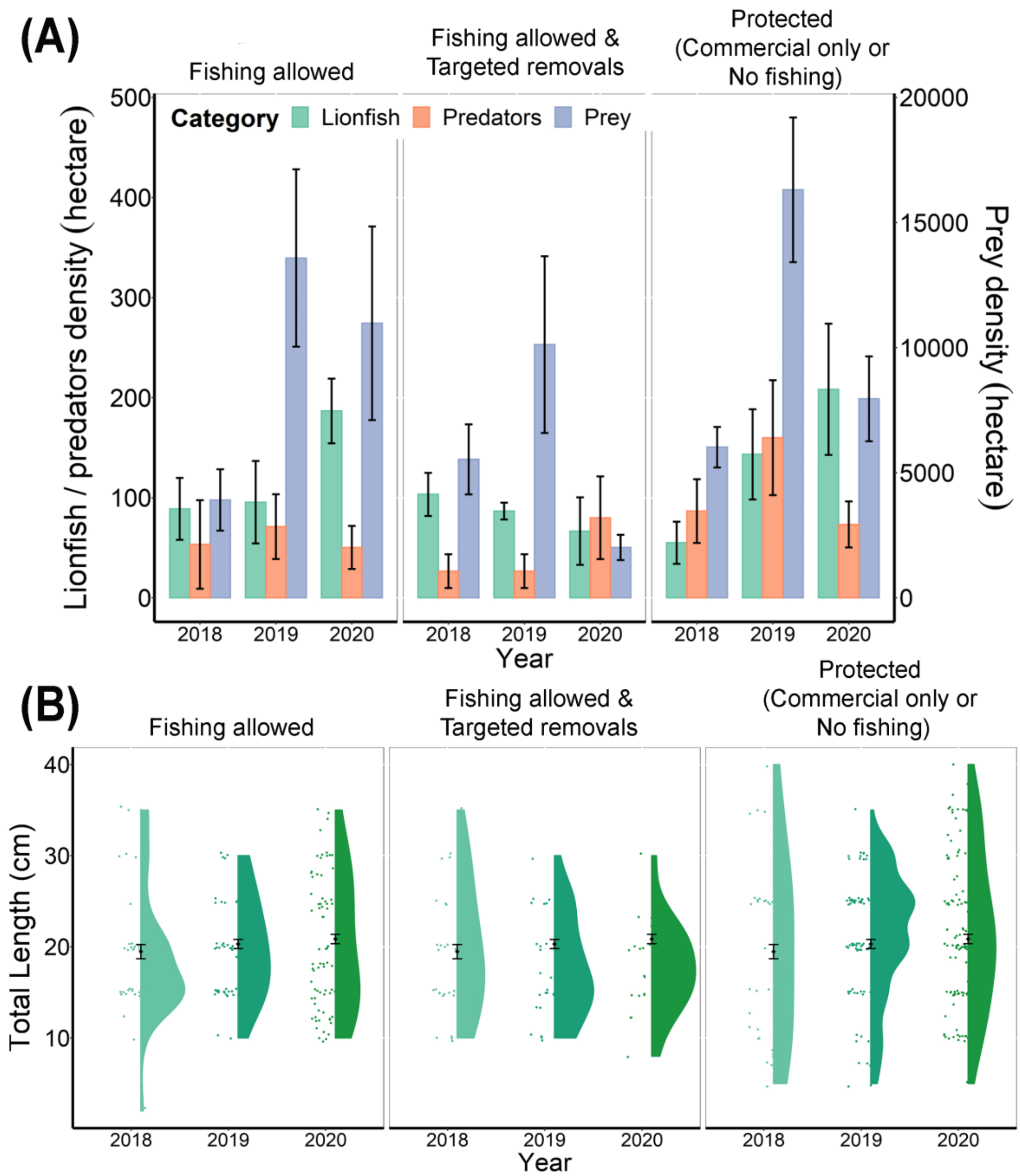

Figure 4.2. (A) Changes of lionfish, predators (defined as species with higher than 3.85 trophic level from FishBase and maximum length more than 80 cm), and prey (defined as <13 cm individuals) densities per hectare between 2018 to 2020 at the nine sampling stations of the temporal monitoring survey. Error bars indicate standard error. (B) Kernel density plot with the mean (± S.E.) illustrating the lionfish size distribution changes from 2018 to 2020.

Table 4.1. Results of PERMANOVA (Type III, partial) regarding the effects of location, year, depth, and station on lionfish density based on a permutation of residuals under a reduced model (9999 number of permutations). The terms Depth, Location, Depth x Location, and Year x Depth x Location were excluded from the analysis due to high p value and/or zero variance explained.

Source	df	SS	MS	pseudo-F	p value
Year	2	3.26	1.63	1.56	0.2190
2018 vs 2020 *(Ye1)*	1	3.25	3.25	3.16	0.0821
2018 vs 2019 and 2020 *(Ye2)*	1	1.89	1.89	1.38	0.2455
Year x Depth	2	5.38	2.69	2.57	0.0860
Ye1 x Depth	**1**	**4.57**	**4.57**	**4.45**	**0.0401**
Ye2 x Depth	1	6.06	6.06	2.16	0.1854
Location x Year	**4**	**15.86**	**3.97**	**3.79**	**0.0085**
Ye1 x Location	**2**	**10.87**	**5.43**	**5.28**	**0.0075**
Ye2 x Location	2	7.56	3.78	1.34	0.3162
Year x Protected vs Fishing allowed *(Lo1)*	2	4.44	2.22	1.91	0.1537
Year x Protected vs Fishing allowed with targeted removals *(Lo2)*	**2**	**8.61**	**4.30**	**7.65**	**0.0017**
Year x Fishing allowed vs Fishing allowed with targeted removals *(Lo3)*	**2**	**10.24**	**5.12**	**3.42**	**0.0439**
Station (nested in Location and Depth)	**3**	**48.37**	**16.12**	**15.39**	**0.0001**
Station (*Lo1* x Depth)	**3**	**48.37**	**16.12**	**13.89**	**0.0001**
Station (*Lo2* x Depth*)*	**2**	**43.26**	**21.63**	**38.44**	**0.0001**
Station (*Lo3* x Depth)	1	5.10	5.10	3.41	0.0705
Residuals	69	72.27	1.05		
Total	80	158.80			

4.5.2. Spatial surveys

The No fishing zone had significantly higher lionfish densities (Figure 4.3 and Figure 4.4; Table 2). The average densities of lionfish in the No fishing zone were 225.19 ± 66.84 (SE) individuals per hectare, compared to 128.89 ± 34.39 individuals in the Commercial only, and 51.76 ± 17.04 individuals in the Fishing allowed (Figure 4.3A). The average size of the lionfish individuals in the No fishing zone was 22.04 ± 0.77 cm (SE) compared to 20.43 ± 0.42 cm in the Commercial only and 18.76 ± 0.60 cm in the Fishing allowed (Figure 4.3B). All zones had similar prey densities (Figure 4.3A). There was a weak negative correlation between lionfish and prey densities (Kendall's

Tau = -0.16, $p < 0.05$) and a moderate positive correlation between lionfish and predator densities (Kendall's Tau = 0.2, $p < 0.05$, Figure 5.3A). Model selection indicated the best fit GLMM was the one with habitat, depth, protection zone, and prey density (Appendix 2C). Habitat type (rocky substrata or *P. oceanica* meadows) had a marginal significant effect on lionfish densities with preference displayed for rocky substrata (Table 2). Most lionfish detected on *P. oceanica* habitat were not found in the actual meadows but mostly at the edge of meadow sections and the tall “matte” comprised of rhizomes, roots, and the sediments that fill the interstices.

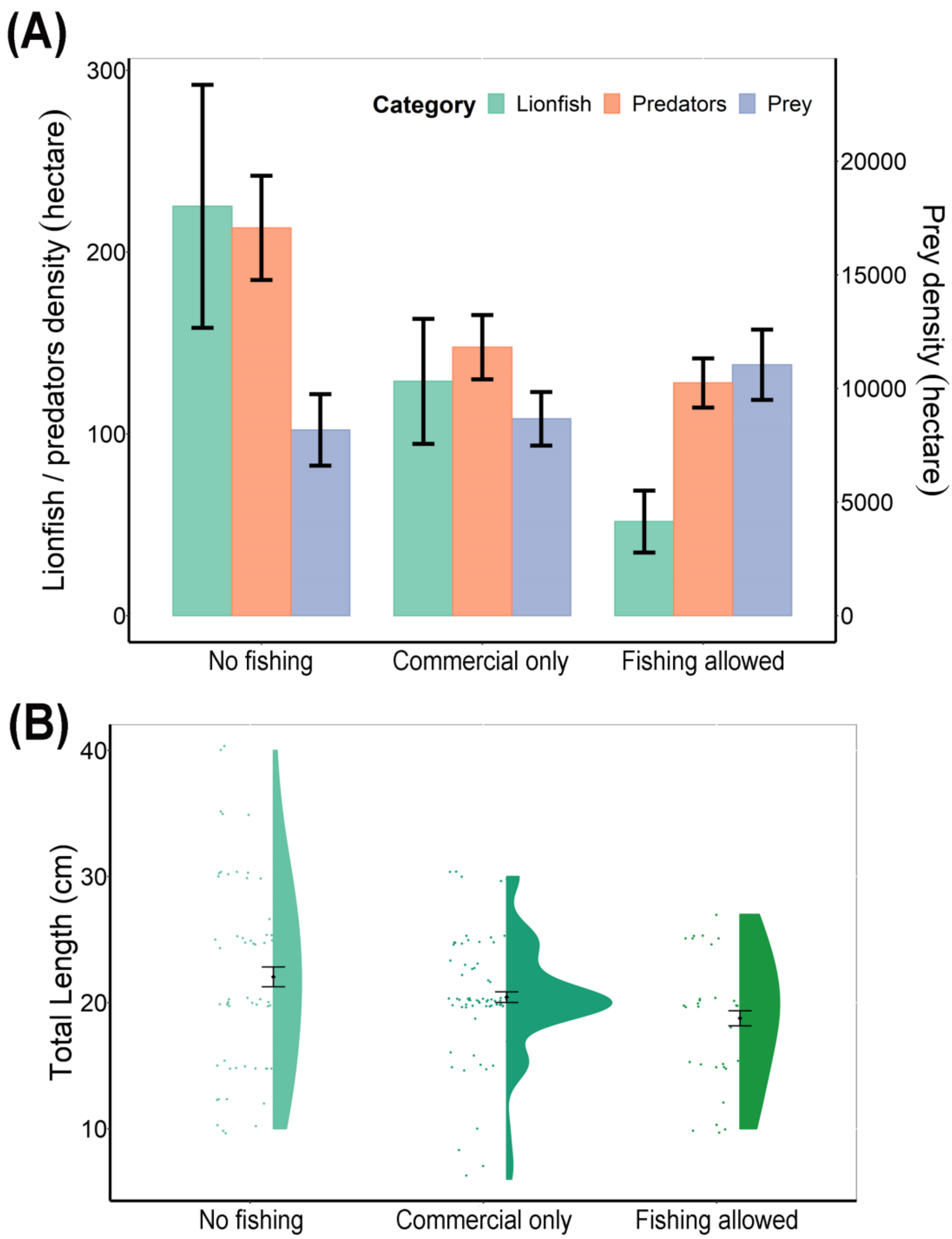

Figure 4.3. (A) Comparison of lionfish, predators (defined as species with higher than 3.85 trophic level from FishBase and maximum length more than 80 cm), and prey (defined as <13 cm individuals) densities per hectare at 45 sampling stations of the spatial monitoring survey. Error bars indicate standard error. (B) Kernel density plot with the mean (± S.E.) illustrating lionfish size differences across the three zones.

Table 4.2. Zero-inflated generalised linear mixed model outputs the changes in mean lionfish population density with depth, habitat, prey density, and protection zone as fixed effects and repeated transect line incorporated as a random effect. Depth,

protection zone, and prey density were included as zero-inflation effects. The habitat was initially included but then removed due to multicollinearity with the rest of the variables. Model used the Poisson family with the log link function and odds ratio represents the odds of observing a change of lionfish density per 100 m^2 area, holding all other variables constant, on the log scale.

Factor	Odds ratio	95% CI	z-value	p-value
Conditional fixed effects				
(Intercept)	0.14	0.02-1.12	-1.86	0.060
habitat (rock)	3.24	0.94-11.2	1.87	0.060
Depth	1.02	0.95-1.11	0.50	0.550
protection zone (Commercial only)	1.63	0.44-6.06	0.73	0.460
protection zone (No fishing)	**6.00**	**1.49-24.2**	**2.52**	**0.010**
prey density	1.21	0.34-4.21	0.30	0.770
Conditional zero-inflation effects				
(Intercept)	**34.92**	**1.16-1053.47**	**2.04**	**0.040**
Depth	0.72	0.47-1.11	-1.45	0.130
protection zone (Commercial only)	0.10	0-2.58	-1.39	0.160
protection zone (No fishing)	2.47	0.12-50.54	0.58	0.560
prey density	6.12	0.73-51.51	1.66	0.100

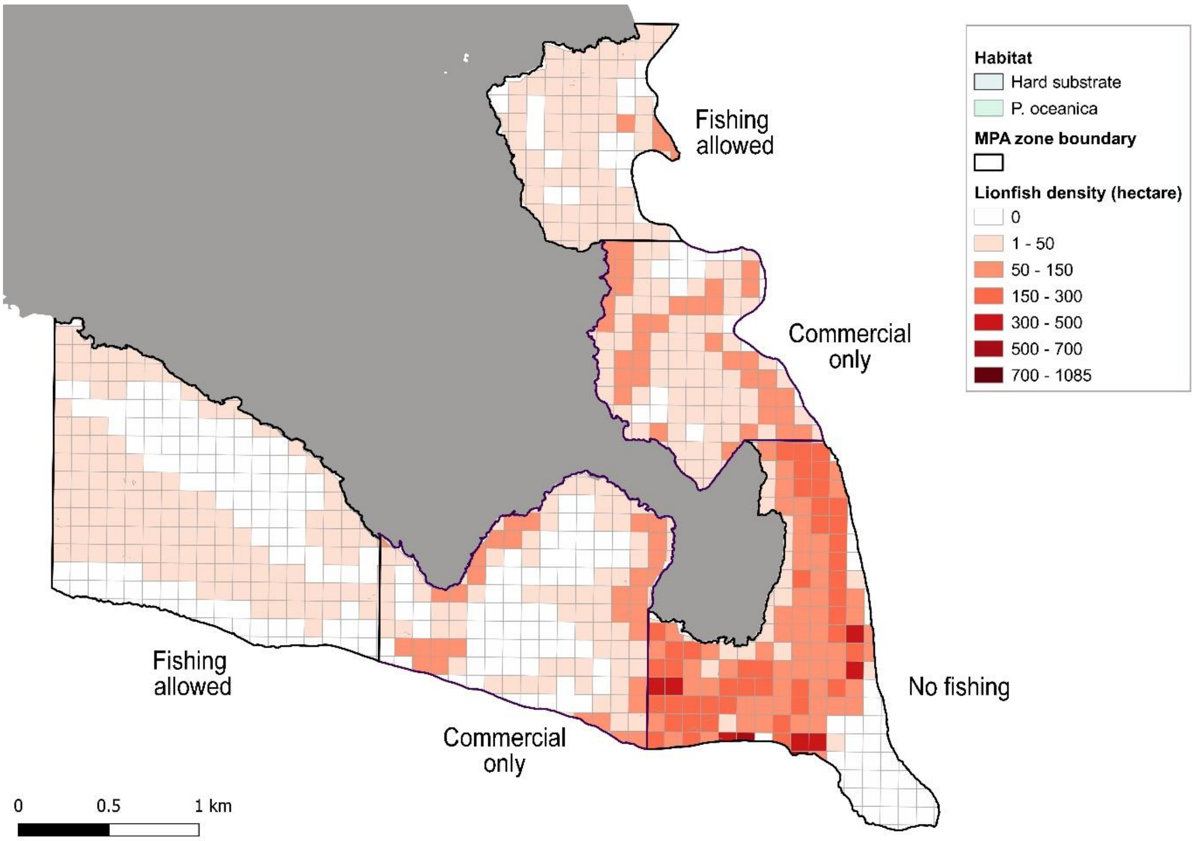

Figure 4.4. Spatial distribution of lionfish densities at the three zones as predicted with the zero-inflated Poisson generalized linear mixed model for hard substrate and *Posidonia oceanica* habitats. Zero lionfish correspond to the habitat 'soft substrate' which was not examined in the present study. Soft substrates are characterized by low (usually zero) lionfish densities. The outputs of the model are shown in Appendix 2D.

4.6. Discussion

Marine Protected Areas should ideally be informed by science and tailored to local fisheries, biological and socioeconomic contexts (Hilborn & Kaiser, 2022) to provide ecosystem-based conservation across suites of habitats (Solandt et al., 2020). Our results show how invasive species can undermine desired outcomes of spatial no-fishing regulations. We found that areas with fishery restrictions (No fishing or Commercial only) had higher lionfish densities than areas that allowed fishing. The No fishing zone had nearly double the lionfish density of Commercial only zone, and over four times higher lionfish densities than nearby areas that allowed fishing. Targeted removals with volunteer divers helped decrease lionfish densities at selected stations, whereas other stations faced 200-400 % increase in lionfish density.

These findings add to evidence that targeted lionfish removals can mitigate their impacts in MPAs (Kleitou *et al.*, 2021c; Kleitou *et al.*, 2022a). Invasive species control programs can often be expensive but the development of ecotourism packages related to selectively fishing for lionfish can contribute toward the sustained control of this invasive fish (Rahman *et al.*, 2022). In this case, cooperative lionfish removal programs can help produce positive social, economic, and environmental benefits (Clements *et al.*, 2021; Kleitou *et al.*, 2021c). Marine management to increase ecosystem resilience and densities to lionfish predators may also help mitigate invasive species impacts (Kleitou *et al.*, 2021c). This would include rebuilding groupers (*Epinephelus* spp.) and octopus (*Octopus vulgaris*) populations which prey on lionfish in the Mediterranean Sea (Crocetta et al., 2021; Ulman et al., 2021).

Fishery investment strategies could be used to motivate fishers and facilitate sustainable pressure on invasive species (Kleitou *et al.*, 2021a). For example, investing in community capacity (awareness, knowledge, skills, and collaboration), markets (increase demand, valorisation opportunities, and development of novel products such as lionfish jewellery), and development of removal tools and selective fishing gears with limited destructive impact on the environment. Market incentives and campaigns to control lionfish populations need to challenge norms and engender a shift in consumer choice (Kleitou *et al.*, 2019d) but at the same time, foster a conservation-minded approach among fishers, which prioritizes ecological sustainability over marine environmental degradation (Kleitou *et al.*, 2022b; Quintana *et al.*, 2023). In addition to targeted removals, commercial spearfishing for lionfish may be a potential market-based solution to control their densities while diversifying fisher livelihoods (Kleitou et al. 2021a; Burgess et al. 2023; Harris et al. 2023a). It was notable that we observed higher lionfish densities at deeper depths. Freediving spearfishing is depth limited, and even SCUBA removals cannot control deeper lionfish populations. Lionfish-specific traps or other specialized gears could be tested in fishery-restricted zones and depths inaccessible for spearfishing removals (Harris et al., 2020b; 2023b).

Lionfish may not proliferate in other MPAs like they did in Kavo Gkreko. Marine protected areas can increase functional redundancy and contribute to resilience to storms and biological invasions (Sheehan *et al.*, 2013; Sheehan *et al.*, 2021; Davies *et al.*, 2022). In a mature ecosystem where niches are occupied by relatively resilient species, novel species are expected to find more resistance in occupying available niches Strict fishery restrictions in Kavo Gkreko were established only two years before this study, and exploited populations in MPAs may need decades to return to baseline levels after fishing pressure is removed (Duarte et al., 2020). Other factors that can affect ecosystem health and resilience in MPAs include enforcement level, MPA size, connectivity, and the intensity of fishing outside MPA (Lester et al., 2009; Edgar et al., 2014; Halpern, 2014; Watson et al., 2014). Illegal fishing appears to be common in the area (Moutopoulos et al., 2021). Although these are valid considerations, the speed at which lionfish colonized the no-take zone (A) of the MPA suggests that additional measures are needed to reduce the rate, and support recovery processes especially in the early years of MPAs' designation.

Climate change is expected to further increase biological invasions of warm water species in the Mediterranean Sea (D'Amen & Azzurro, 2020). Invasive species can reduce ecosystem resilience (Holling, 1973), drive regime shifts, and result in negative socioeconomic effects (Chaffin et al., 2016; Sheehan et al., 2021). Allowing ecosystems to naturally recover without any human support was suggested as a possible, cheap, and easy solution for invasive species management (Giakoumi *et al.*, 2019a); however, this solution should be viewed with caution, especially in MPAs designed to produce conservational benefits for the surrounding ecosystems and fish populations in the eastern Mediterranean which is overfished, highly invaded and changing rapidly due to repeated marine heat wave effects. Inaction on the current lionfish invasions seems ill advised as control of their population densities and adaptation through market promotion and nature-based solutions (protection of predators, ecosystems restoration) are viable options (Kleitou *et al.*, 2021a; Kleitou *et al.*, 2022a). Studies of the Western Atlantic lionfish invasion suggest limited biotic resistance to the invasion (Hackerott *et al.*, 2013; Valdivia *et al.*, 2014; Davis, 2019). Additional management measures that facilitate targeted removals of invasive species would help MPAs achieve their conservation objectives. Lionfish monitoring at sentinel locations is needed to inform management of the growing network of Marine Protected Areas in the Mediterranean, and legal changes might be required to enable their control (Kleitou et al, 2022a).

5. Chapter 3: Regular monitoring and targeted removals can control lionfish in Mediterranean Marine Protected Areas

5.1. Author contributions

P.K. conceptualized, designed the study, and wrote the manuscript. P.K. led the ecological surveys with support from F.C., L.L.C, and J.M.H. P.K. collected the citizen science data with support from F.C. P.K. and D.K organized and coordinated the removal events with support from all authors. Analyses and visualizations were done by P.K. with support from D.K.M. All authors critically reviewed the drafts and gave final approval for publication. S.R. and J.M.H. supervised the study. This manuscript is published in the journal Aquatic Conservation: Marine and Freshwater Ecosystems.

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5.2. Abstract

A lack of biosecurity in the Suez Canal has combined with global warming and other human pressures to cause abrupt changes in the Mediterranean Sea. Throughout this region an influx of species is influencing the outcome of efforts to protect and restore nature. Despite calls for targeted removals of invasive species from protected areas, there is limited information about the effectiveness of this course of action from both an ecological and a socio-economic perspective. In this study, coordinated removals of lionfish (*Pterois miles*) by volunteers/SCUBA divers at three marine protected sites of Cyprus were conducted. The removal efficiency was monitored using visual-census surveys and citizen science data. Removals significantly decreased lionfish numbers but long-term suppression of lionfish would require monitoring and repetition of removals when necessary, since population recovery was sometimes rapid. Citizen science yielded the data needed to understand lionfish population changes and guide the timing of removal events, but characterized by large variation and potential outliers; highlighting the need for large sample size. Questionnaire surveys were used to assess the social impact of participation in lionfish removals; these showed that involvement had a strong positive impact on knowledge about lionfish and motivation to support marine conservation activities – the divers were even willing to pay extra to remove lionfish. Management reforms would be needed to capitalize on this societal motivation, and enable effective lionfish removals by SCUBA divers, coordinated by competent authorities. The EU aims to protect at least 30% of the marine waters by 2030. Removal events could help shield selected conservation sites from the adverse effects of lionfish and at the same time help establish links with local communities, strengthening the sustainable use of marine systems both at corporate and at social levels.

5.3. Introduction

Translocation of marine species beyond their native ranges is centuries old, but has been accelerating in recent years due to increasing transcontinental shipping, aquaculture and ocean sprawl (Firth *et al.*, 2016; Seebens *et al.*, 2017). Some of these species can disrupt ecosystems, often assisted by changes in climate and human impacts on habitats

(Chaffin *et al.*, 2016; de Castro *et al.*, 2017; Geburzi & McCarthy, 2018), overfishing of native predators and limited biotic resistance of the recipient ecosystems (Kimbro *et al.*, 2013; Crocetta *et al.*, 2021). Sometimes non-native species have beneficial effects, such as the provision of biogenic reef and the filtration of eutrophic water by oysters (Davis *et al.*, 2011; Lemasson *et al.*, 2017). Human introduction of lionfish (*Pterois* spp.) into the Western Atlantic (Albins & Hixon, 2013; Côté & Smith, 2018) caused widespread negative effects such as reduction of native fish abundance (Green *et al.*, 2012; Côté *et al.*, 2013a; Ballew *et al.*, 2016) and a shift in benthic habitats in favour of macroalgae rather than corals (Lesser & Slattery, 2011).

Since 2016, lionfish have been spreading rapidly in the Mediterranean Sea (Kletou *et al.*, 2016; Kleitou *et al.*, 2019d). They arrived from the Red Sea via the Suez Canal with multiple subsequent introductions increasing the genetic diversity of the Mediterranean population (Bariche *et al.*, 2017; Dimitriou *et al.*, 2019). In just a few years, lionfish have become established in the Levantine Sea, southern and central Aegean Sea, the Greek Ionian Sea, and individuals have reached Tunisia and Italy (Dimitriadis *et al.*, 2020; Kleitou *et al.*, 2021b); this is one of the fastest rates of spread of a Red Sea fish in the Mediterranean (Poursanidis *et al.*, 2020). Lionfish in the Mediterranean have similar biological traits to those of the Western Atlantic, such as generalist predatory behaviour, early maturity, and rapid growth (Savva *et al.*, 2020), combined with access to naïve prey (Agostino *et al.*, 2020).

Invasive species such as lionfish are spreading in areas designed to protect habitats and species from local stressors such as destructive development, fishing, and pollution (Galil *et al.*, 2017; Sala & Giakoumi, 2017). In the eastern Mediterranean, invasive species can be found in greater abundances in marine protected areas than in adjacent waters (Giakoumi *et al.*, 2019b; D’Amen & Azzurro, 2020) so protected areas might end up providing refuges for invasive species with spillover and larval subsidy effects on adjacent areas (Galil, 2017; Corrales *et al.*, 2018; Di Lorenzo *et al.*, 2020).

Targeted removal has been suggested to manage invasive species in marine protected areas (Giakoumi *et al.*, 2019a; Giakoumi *et al.*, 2019b), but there is a lack of information on its ecological and socioeconomic efficiency. As spearfishing has been effective at lowering lionfish numbers at selected locations in the Western Atlantic (Barbour *et al.*, 2011; Johnston & Purkis, 2015; Chagaris *et al.*, 2017; Harms-Tuohy *et al.*, 2018; Harris *et al.*, 2019), trials of this approach were organized in Cyprus where lionfish have started to become common in marine protected areas (Kleitou *et al.*, 2019b). In this study, the efficiency of removal events was monitored using visual census of fixed transects on rocky habitats by researchers and by volunteers (i.e. citizen science) surveys on a shipwreck. A questionnaire was used to assess social dimensions of such measures. The study aimed to assess:

(i) the efficiency of involving volunteers in monitoring the populations of lionfish and guiding management interventions,

(ii) the efficiency of targeted removal events by volunteers in decreasing the lionfish numbers from marine protected areas, and

(iii) the socioeconomic dimensions from the participation of the volunteers in lionfish removals.

5.4. Methods

5.4.1. Training and implementation of removal events

From May-Nov 2019 five removal events were organized for volunteer divers to catch lionfish at three marine protected sites off Cyprus (Chapel, Cyclops, and Zenobia wreck) (Figure 5.1). For these events, divers were trained and formed Removal Action Teams (RATs) of lionfish, following permission (special licence) acquired by the coastal police and the Department of Fisheries and Marine Research (Ministry of Agriculture, Rural Development and Environment) of Cyprus.

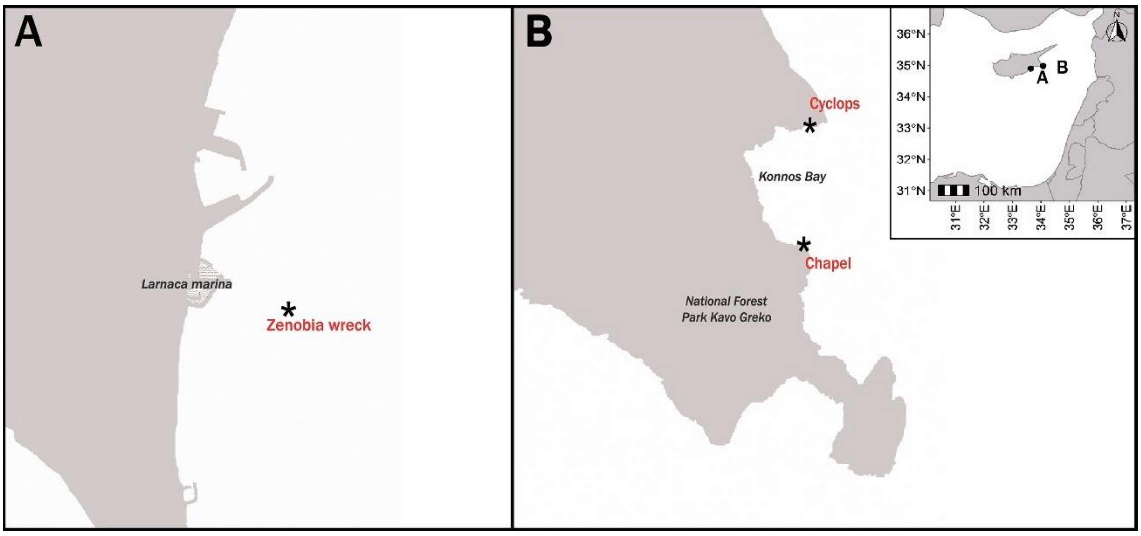

Figure 5.1. Lionfish removals were conducted by volunteers using scuba at three Marine Protected Sites off Cyprus in 2019 (one site at a, two sites at b). (a) Site of the Zenobia shipwreck off Larnaca, a no-fishing area. (b) The popular diving sites Cyclops and Chapel within Cape Greco Marine Protected Area.

Specifically, three recurring events were conducted at Cape Greco, Larnaca, and Limassol. The events were attended by 66 experienced divers, 56 were men and 11 were women. All participants were residents of Cyprus; 43 of whom had Cyprus nationality. All participants had at least an Advanced Open Water Dive qualification or equivalent, and 30% were SCUBA instructors. During the workshops (Figure 5.2A), divers were informed about the lionfish invasion, biology, ecology and edibility of lionfish, its safe handling, and the use of removal toolkit (pole spears, containers and puncture resistant gloves) that was assembled by the project for the removal of lionfish, and approved by the Cyprus authorities.

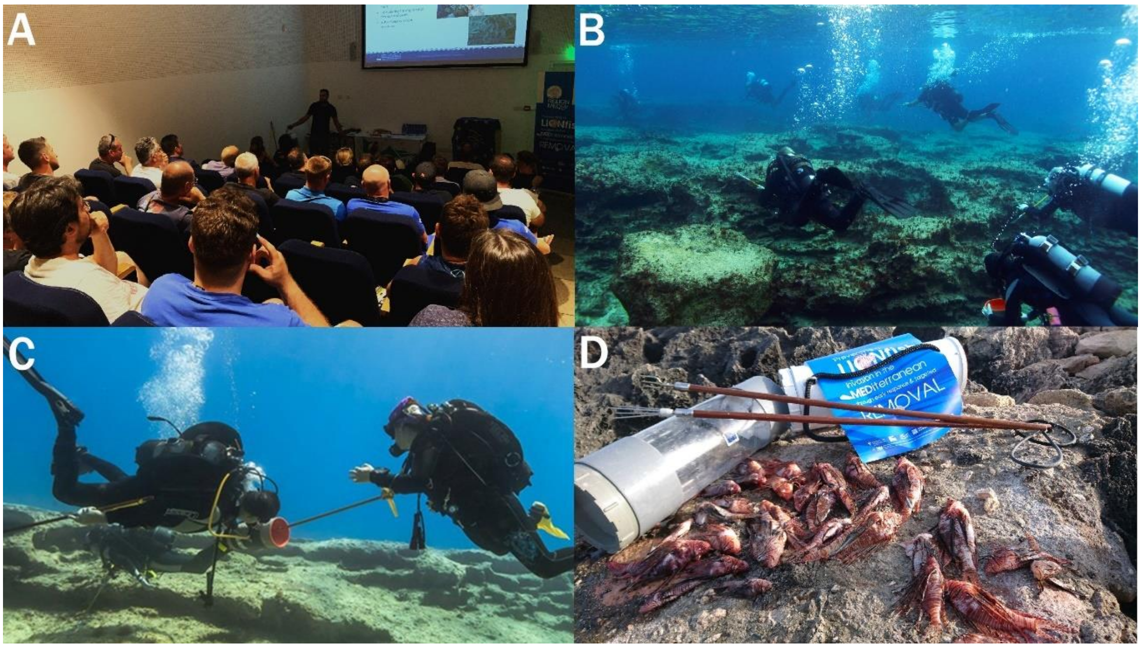

Figure 5.2. (A) Diver training event about lionfish and their safe removal that took place at Cape Greco Environmental Information and Education Centre on 25 May 2020; (B) groups of up to 18 divers worked together to remove lionfish, here at about 5 m depth on rocky reef habitat within Cape Greco Marine Protected Area at *Cyclops*; (C) each time a lionfish was speared it was held and removed using a special container for safe handling of multiple specimens (26 May 2019 at 10 m depth at *Cyclops*). Picture was provided by the Removal Action Teams member 'Pantelis Kranos' (Cyprus). (D) Spears and container with catch contents emptied onto the shore (6 June 2019 at *Cyclops*)

The efficiency of the removal events in reducing lionfish numbers and increasing public participation was monitored using three methods; citizen science, fixed transect monitoring, and structured questionnaires. Following removal events, the specimens were provided to the participants for consumption.

5.4.2. Citizen science monitoring of the Zenobia shipwreck

Fishing is prohibited on the Zenobia, a 172 m length, 28 m width, and 21 m height steel shipwreck with the starboard side on a level muddy-sand seabed at 42 m and the port side at 16 m depth off Larnaca (Figure 5.1A). The wreck is far (> 4 km) from rocky and seagrass habitats that lionfish commonly use in the Mediterranean Sea (Savva et al., 2020). Lionfish were first seen at this regularly dived site in 2015 (Kletou, Hall-Spencer & Kleitou, 2016). From May–Dec 2019, the divers were provided with logbooks and asked to report their Zenobia lionfish sightings via email, phone, or social network platforms. They were asked to provide information about all lionfish observed on each of their dives on this wreck, along with dive duration, dive gear used, depth range of the dive, depth of lionfish sightings, habitat, bottom and surface temperature, time of the day, exact location of the dive, and any other qualitative information that they think of relevance. To standardize lionfish observed per unit effort, the number of lionfish seen per minute dive time (Observation per minute, OPUE) was used. To correlate citizen science sightings and observations per minute effort, the Kendall's tau rank correlation coefficient was used. To avoid the effect of management interventions and measure the correlation between the lionfish sightings and bottom/surface temperature, the dataset was split in three; one with the data received before the first removal event, one with the data received between the first and second removal event, and one with the data received after the second removal event. The correlation between citizen sightings and bottom/surface temperature was examined for all three intervals using the Kendall's tau rank correlation coefficient.

5.4.3. Fixed transect monitoring in Cape Greco Marine Protected Area

To assess the efficiency of targeted removals, fixed transects were established and monitored at two sites set about 1 km apart in the Cape Greco protected area (Figure 5.1B) where targeted removal events were conducted. Cyclops was rocky (Figure 5.2C-D) with boulders and small caves and crevices to 15 m depth with *Posidonia oceanica* meadows to over 35 m and then soft substrate. Chapel had steep rock to 10-15 m, followed by sandy expanses intermixed with hard substrata and patches of *P. oceanica*. During the removal events, the divers were free to move/swim in any direction and habitat of their choice, but they were restricted in an area of about 300 x 200 m at each site. At both sites, six 50 m long fixed transects were randomly established on hard substrata between 5 and 20 m, ensuring an even distribution over the targeted area for the divers. The transects in each area were monitored three times: before and after the removal events.

Lionfish density and biomass were estimated using an underwater visual census method developed by Green et al., (2013) since it was found, after pilot studies, to detect lionfish more reliably compared to othe techniques (Kleitou et al., unpublished data). Survey divers swam in a zig-zag pattern, searching crevices and overhangs (using a dive torch when needed) to record all lionfish 10 m either side of the transect line. For every lionfish recorded, its length was estimated in situ. Total length data were used to calculate fish biomass using the equation $W = a \times L^b$, where W is the net mass (g) and L the total length (cm). Parameters a and b were based on Savva et al. (2020). The surveys were conducted by the same researchers at the same six strip transects in each site, prior to and shortly after the removal events, on 24/05/2019, 31/05/2019 and 12/06/2019.

Lionfish sizes, abundance, and biomass were compared using a 1-way repeated measures ANOVA (also known as a within-subjects ANOVA) for each of the areas. Post hoc comparisons were analysed using paired t-tests with a Bonferroni correction.

The data were checked for significant outliers (boxplots), normality (Shapiro-Wilk normality test and QQ plots), homogeneity of variance (model residuals plot and Bartlett test), and homogeneity between the repeated measures (Mauchly's test $p = 0.002$). When assumptions were not met (i.e. biomass data at Chapel), square root transformation was applied. For all statistical analyses a significance level was set at 0.05, and their computation was carried out using R-Studio (v 1.2.1335).

5.4.4. Monitoring the social dimension of removal events

Questionnaires were carried out face-to-face with 25 randomly selected participants during their first participation at the training or removal events; prior they receive the caught fish. They were designed to assess their knowledge about lionfish, their motivation to be involved in marine invasive species conservation activities, and willingness to pay a fee to observe lionfish, participate in removal activities, or support efforts in controlling lionfish. Specifically, 11 questions were asked as shown in Table 5.1. All interviews were carried out by the same trained person, ensuring that questions were presented in an identical manner, and that prompts or influences should have been similar across all interviewees. The encounters were held privately, on one-to-one sessions, to prevent influence or interference by other people. To avoid distrust, respondents were approached informally and asked if they were willing to answer a few questions about their participation in the events. The responses about the willingness of divers to pay extra for a dive to observe/find, remove or support others in controlling lionfish were binned into two nominal categories: not pay and pay a fee (from €1 to >€10), and tested for equal proportions using a chi-square goodness of fit test for each statement.

Table 5.1. Questions used (in Greek and in English) to assess knowledge and attitudes amongst volunteers involved in lionfish removal events.

Questions	**Possible answers**
Part A: Impact of divers participation in removal events	
On a scale of 0 to 10 where 0 = strongly disagree and 10 = strongly agree to what extent did the removal events helped or encouraged you to:	Scale:
1. Support potential management measures against invasive species	ranking order of preference 0–10, where 0 = strongly disagree, 5 = neutral, and 10 = strongly agree)
2. Collaborate with scientists and management authorities	
3. Participate in conservational activities	
4. Understand lionfish potential ecological and socioeconomic impacts	
5. Understand that lionfish is edible	
Part B: Willingness to pay extra fee in a dive	
	Multiple choice:
Would you pay extra fee to:	(a) No, I wouldn't pay extra
	(b) I would pay €1 extra for the dive
1. Observe lionfish underwater in the Mediterranean	(c) I would pay €2-5 extra for the dive
2. Participate in a dive and remove lionfish in the Mediterranean	(d) I would pay €6-10 extra for the dive
3. Support others (e.g. management authorities) in controlling the lionfish in the Mediterranean	(e) I would pay more than €10 for the dive
Part C: Socio-demographic information	
Gender	Dichotomous: Male/Female
	Multiple choice:
	a) 18-24 d) 45-54
Age	b) 25-34 e) 55-64
	c) 35-44 f) Over 65
Nationality	Open ended question

5.5. Results

5.5.1. Removal events

Removal events went smoothly, helped by the fact that the volunteers were experienced divers operating in warm waters with minimal currents and exceptionally good underwater visibility compared to most coastal environments (Figure 5.2B-C). Between 35-119 lionfish were removed per day by 9 to 27 divers at each protected site (Figure 5.2B-D, Table 5.2). The catch efficiency (percentage of lionfish caught / lionfish detected) ranged between 56.92% and 83.22% (Table 5.2). The catch per unit effort (CPUE) was lower at the Zenobia wreck compared to the two rocky sites where less dives were conducted (Table 5.2). Both CPUE and catch efficiency decreased after a removal event (Table 5.2).

Table 5.2. Lionfish removals by volunteers at three marine protected sites off Cyprus in 2019 showing dates and numbers of divers, dives, lionfish removed, Catch Per Unit Effort – CPUE (number of lionfish caught / (number of divers * number of dives)), lionfish seen but not caught, and catch efficiency % (number of lionfish removed / lionfish seen). The CPUE and catch efficiency values were coloured according to the percentile of their category (green for percentile over 50, white for 50 and red for less than 50).

Site	Removal event date	# Divers participated	# Dives conducted	Lionfish removed	CPUE	Lionfish missed	Catch efficiency (%)
Cyclops	26/05/2019	18	1	72	4	38	65.45
	06/06/2019	11	1	35	3.18	21	62.5
Chapel	26/05/2019	9	1	38	4.22	16	70.37
Zenobia wreck	15/07/2019	22	2	119	2.7	24	83.22
	24/11/2019	27	1	37	1.37	28	56.92

5.5.2. Citizen science monitoring of the Zenobia shipwreck

Citizen science dive records from the Zenobia (N=104) provided lionfish sightings on 58 days out of a 233-day monitoring period that started on the 27/04/2019. Most records (88%) were sent via email with filled data logbooks, followed by communication via social networks (10%), and 3% via telephone. All these dives were carried out between 09:00 am and 13:30 pm. The maximum dive depth of the dives ranged from 23 to 42 m. According to the additional qualitative information received by the divers, lionfish were not that common inside the wreck and very dark places; with reports received such as "No lionfish inside the wreck" and "Most lionfish were on outside, but a couple were inside in the twilight areas."

Based on the citizen science records, lionfish numbers peaked in May-July 2019 prior to the first removal event (e.g. 58 lionfish observed in a single dive on 09/05/2019). The observations per dive minute correlated significantly with the total number of lionfish observed on dives (Kendall's Tau = 0.62, $p < 0.05$, Figure 5.3A). Both fell sharply after removal events; especially after the first one (Figure 5.3A). Lionfish numbers did not completely recover, at least for three months after the first removal (Figure 5.3A). Due to large variation, it's not clear whether the drop in the lionfish observations after the second removal was natural (e.g. favoured by the observed temperature decrease) or due to the removal event, and more sightings were needed for valid conclusions.

Dive computers provided detailed *in situ* temperature data, showing clear thermal stratification of the water column from May-October and uniform temperature-depth profiles after a breakdown of the thermocline in November-December (Figure 5.3B). The surface temperature did not correlate with the lionfish observations received prior the first removal event (Kendall's Tau = 0.0022, $p > 0.05$), between the first and second removal event (Kendall's Tau = 0.12, $p > 0.05$), and after the second removal event (Kendall's Tau = 0.18, $p > 0.05$). Similarly, the bottom temperature did not correlate with the lionfish observations received prior the first removal event (Kendall's Tau = -0.039, $p > 0.05$), between the first and second removal event (Kendall's Tau = 0.12, $p > 0.05$) or after the second removal event (Kendall's Tau = 0.82, $p > 0.05$).

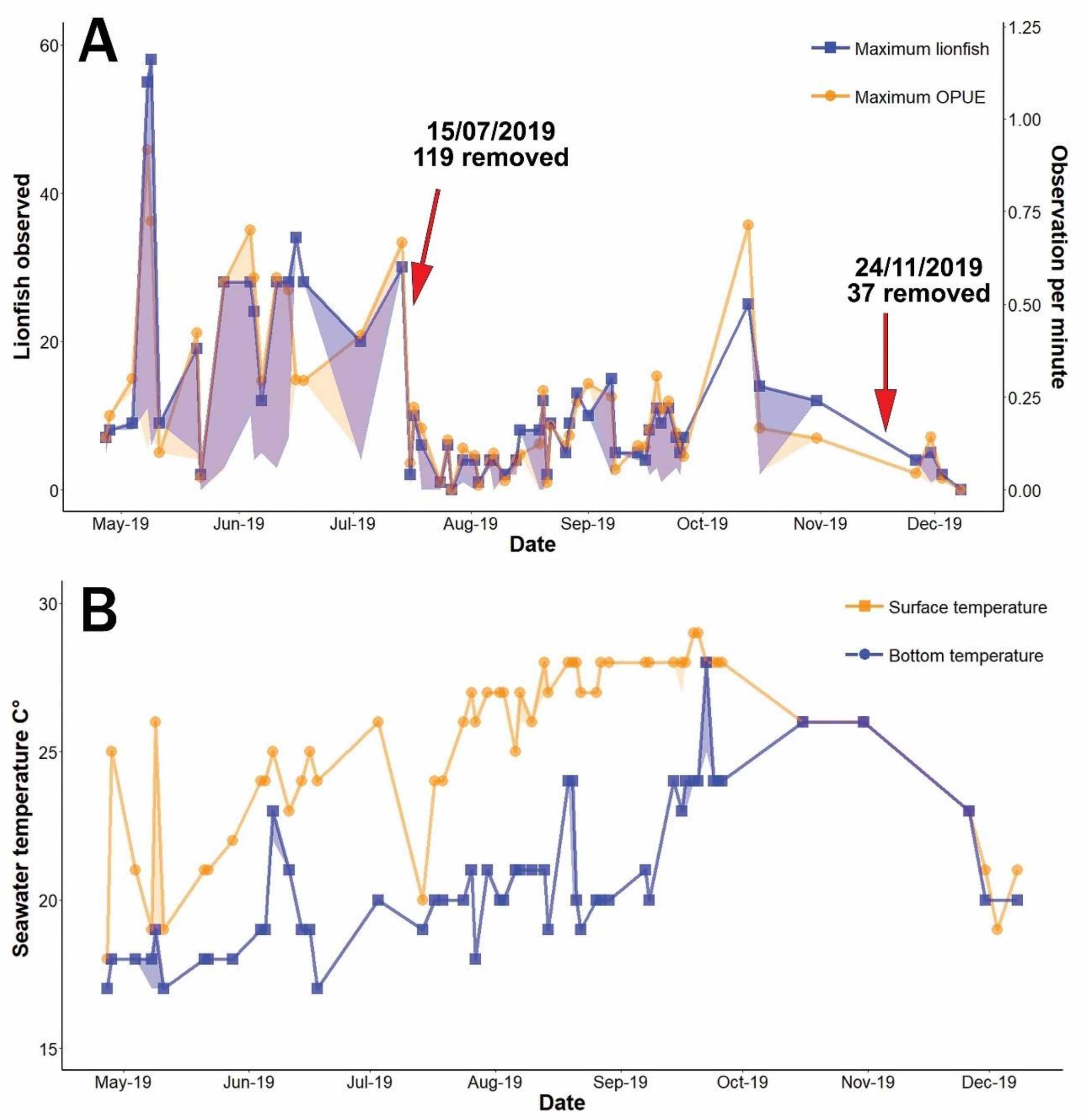

Figure 5.3. (A) Highest daily number of lionfish observed (blue) and highest dive observations per minute (OPUE) (orange) by volunteers on the *Zenobia* wreck, Cyprus in May to December 2019. Accordingly, the blue and orange shades indicate the lowest daily records of observations and OPUE (when more than one dive record was received). Red arrows show removal events. (B) Average bottom and surface seawater temperatures provided by scuba divers using their dive computers on the *Zenobia* wreck, Cyprus, May to December 2019.

5.5.3. *Fixed transect monitoring in Cape Greco Marine Protected Area*

As with citizen science records of lionfish numbers per dive, visual census of fixed transects also revealed that lionfish abundance decreased after removals, but the transect surveys were also able to estimate changes in lionfish abundance and biomass per unit area. Lionfish abundance at Cyclops decreased significantly over the series of removals (1-way repeated measures ANOVA (F (2,10) = 6.22, p < 0.05, $\eta^2 = 0.50$) from 10.5 ± 1.28 individuals per 1000 m^2 before the removal events to 6.66 ± 1.74 individuals per 1000 m^2 after one removal, and to 3.5 ± 0.43 individuals after two removals (Figure 5.4). Lionfish biomass at Cyclops decreased by about 50% after the initial removal event, although this was not statistically significant (1-way repeated measures ANOVA (F (2,10) = 3.49, p > 0.05, $\eta^2 = 0.32$)) as only a few transects (n=6) were able to be used due to logistical constraints on manpower, reducing the ability to detect statistically significant changes. The size of lionfish did not change significantly across the samplings (ANOVA (F (2,10) = 1.13, p > 0.05, $\eta^2 = 0.16$) and ranged from 14.53 ± 2.58 in the first sampling to 14.54 ± 6.17 cm in the second and slightly increase to 17.91 ± 1.96 cm in the third due to an increase of records of lionfish in the range of 20-25 cm (Figure 5.5).

At Chapel, lionfish abundance was much lower overall, and although it decreased after a removal event (2.33 ± 0.56 to 1 ± 0.63 individuals per 1000 m^2), this did not vary statistically over the surveys (1-way repeated measures ANOVA (F (2,10) = 2.57, p > 0.05, $\eta^2 = 0.19$). On the other hand, biomass dropped significantly (1-way repeated measures ANOVA (F (2,10) = 5.38, p < 0.05, $\eta^2 = 0.19$), reflected on the second survey (paired t-tests with a Bonferroni correction, p < 0.05), which was preceded by a removal event (Figure 5.4). There was a significant shift in the size of lionfish at Chapel (ANOVA (F (2,10) = 4.99, p < 0.05, $\eta^2 = 0.33$) after the removal event; which dropped from average 22.05 ± 4.69 cm in the first sampling to 10.58 ± 8.66 cm in the second and increased to 15.77 ± 8.59 cm in the third (Figure 5.5). Within the 12 days that intervened between the second and third survey when no removal event took place, lionfish were able to almost recover their numbers (on a daily increase of 0.97 lionfish individuals per hectare).

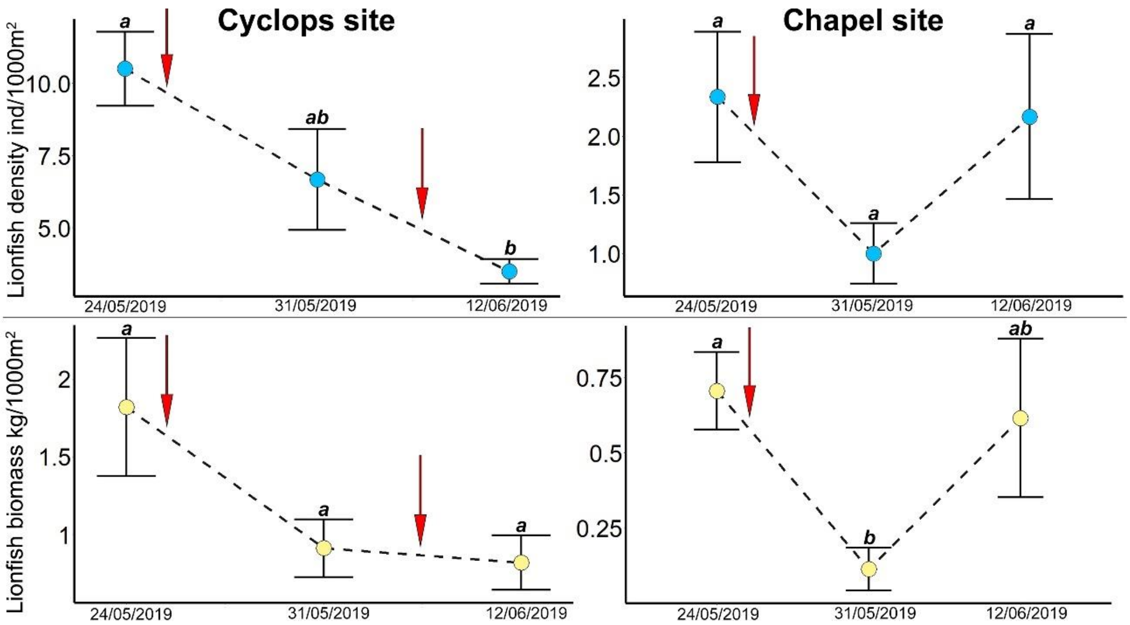

Figure 5.4. Average (±SE, n = 6) lionfish density and biomass of lionfish at two sites (*Cyclops* and *Chapel*) in Cape Greco marine protected area, Cyprus, 2019. Red arrows indicate removal events. A total of 72 lionfish were removed (38 missed) by 18 divers in the first removal at *Cyclops* on 26/05/2019, and 35 were removed (21 missed) by 11 divers in the second removal on 6 June 2019. At *Chapel*, 38 lionfish were removed (16

missed) by nine divers on 26 May 2019. Surveys that do not share a letter are significantly different at $P < 0.05$ (paired t-tests with a Bonferroni correction).

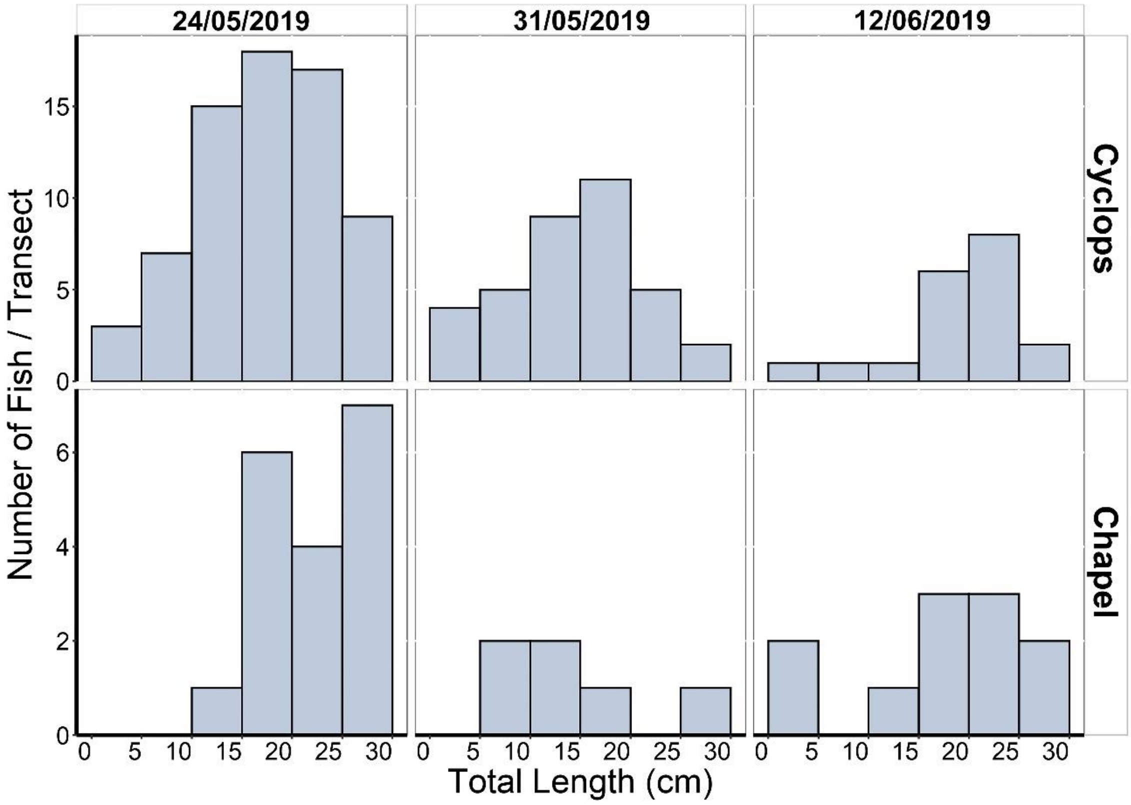

Figure 5.5. Length frequency histogram of the lionfish observed at *Cyclops* and *Chapel* in each of the visual census monitoring surveys.

5.5.4. Social aspects of removal events

Of the 25 participants that took part in face-to-face questionnaires, most were men (80%). Responses were taken across a well distributed adult age range; with two being 18-24, six being 25-34, six being 35-44, four being 45-54, and six being 55-64. One respondent did not report their age. The majority of participants were Cypriots, accounting for 52% (n=13) of the total sample, followed by British participants, who constituted 35% (n=8) of the study group. According to these divers, their participation in the lionfish training and removals improved their knowledge about lionfish and motivated them to support management efforts. None of the participants reported negative effects of involvement on their motivation and knowledge (Figure 5.6). In all questions, more than 80% of the respondents reported positive impact (Likert scale score = 6 - 10) due to their participation (Median = 10; Figure 5.6) and that removal events strongly encouraged them (Likert scale score = 10) to support other management measures against invasive species (71%, n=17), collaborate with scientists and managers (70%, n=16), participate in conservation activities (70%, n=16), understand lionfish potential impacts (68%, n=15), and understand that lionfish are edible (59%, n=13) (Figure 5.6).

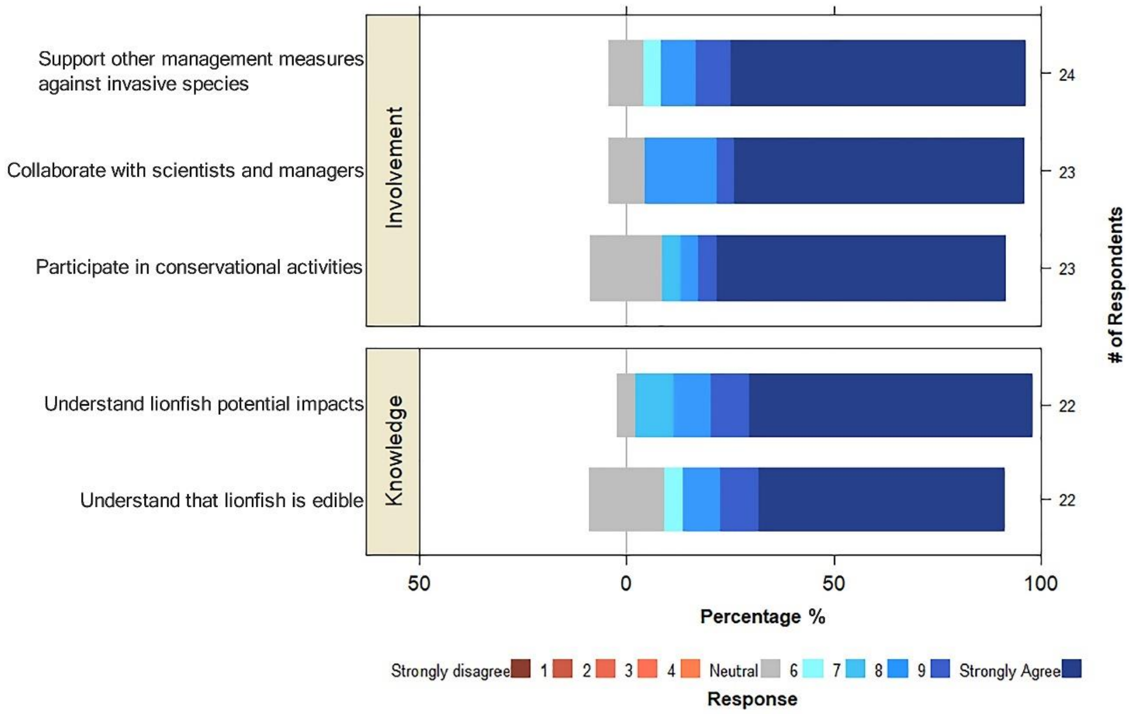

Figure 5.6. Agreement of divers from Cyprus about the effect of their participation in removal activities on their involvement and knowledge about lionfish. Proportions were acquired based on the categorization of the ordinal scores (0–10) to disagree (0–4), neutral (5) and agree (6–10).

The willingness of divers to pay was negative when asked to dive to observe lionfish as the majority (80%) was not willing to pay at all (Pearson's chi-squared test, $\chi^2 = 9$, df = 1, $p < 0.05$). On the other hand, divers were willing to pay to remove lionfish (Pearson's chi-squared test, $\chi^2 = 8.33$, df = 1, $p < 0.05$), specifically 78% would pay at least €2 extra to remove lionfish, 26% to pay at least €5, and 22% reported that they would be willing to pay €10 extra (Figure 5.7). When they were asked about supporting others efforts in controlling lionfish, responses whether to pay or not were statistically similar (Pearson's chi-squared test, $\chi^2 = 0.36$, df = 1, $p > 0.05$).

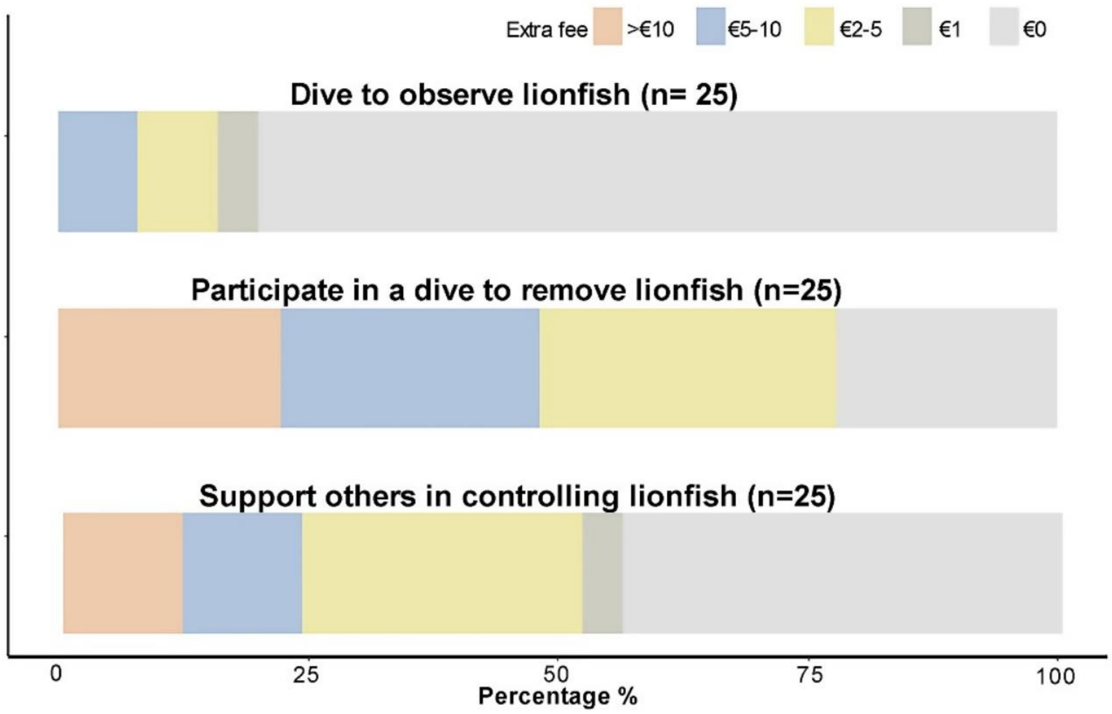

Figure 5.7. Percentage divers from Cyprus asked if they would be willing to pay extra to (a) dive to observe lionfish, (b) participate in a dive to remove lionfish and (c) support other people in controlling lionfish.

5.6. Discussion

In 2015, a 35 km long section of the Suez Canal was deepened and expanded from 61 to 312 m wide. This doubled shipping capacity and decreased transit time from 18 to 11 hours for most vessels, which pay around $450,000 per trip to use this waterway. Galil *et al.* (2015a) were quick to point out the biosecurity dangers of this expansion, and the need for cost-effective mitigation strategies since the Canal was already one of the most potent corridors for marine species invasions in the world. In 2016, an incipient lionfish invasion was first noted in the region, leading to urgent calls for improved Suez Canal biosecurity (Kletou *et al.*, 2016). Within just four years, lionfish from the Red Sea became established over far too wide an area for eradication to be feasible (Kleitou *et al.*, 2019d; Booy *et al.*, 2020).

This study drew upon experiences gained in dealing with invasive lionfish in the Western Atlantic (Frazer *et al.*, 2012; Usseglio *et al.*, 2017). There, it has been shown that removal efforts with divers can be effective at suppressing lionfish populations in localized areas (Barbour *et al.*, 2011; de León *et al.*, 2013). Using biomass production of lionfish prey and rate of prey consumption by lionfish, Green *et al.* (2014) developed a size structured simulation model and predicted threshold damaging densities of lionfish beyond which native fish biomass start to decline; indicating that removal efforts without complete eradication could be effective in preserving/restoring the native biota. Similarly, Chagaris *et al.* (2017) used a trophic dynamic model and have shown that even relatively low levels of lionfish harvesting can be translated into increases of the biomass of the rest of the community.

The successful removal events used in the Caribbean were replicated, and this study explored whether it could work in the socioeconomic and environmental context of the Mediterranean protected areas. It is illegal to spearfish with SCUBA in all Mediterranean countries (Gaudin & De Young, 2007), so a derogation from the government was given agreeing that a small number of well-trained divers could be involved in the trial program. The results of this first attempt to address the spread of lionfish in the Mediterranean could be pivotal for the management authorities of countries where lionfish has already invaded (i.e. Cyprus, Greece, Israel, Italy, Lebanon, Libya, Syria, Tunisia, and Turkey).

Lionfish removal kits were assembled to furnish dive teams with the required lionfish handling and removal equipment. Training events were then followed by dives, attended by groups of 9-27 divers, who removed up to 119 lionfish in a single day from marine protected areas. The participants engaged with the project enthusiastically and, on average, caught about 67% of the lionfish that they saw. The study has shown that divers-volunteers could play a critical role in Mediterranean lionfish management, supporting monitoring and reducing lionfish numbers at target sites. Involvement by citizens was also socially beneficial since according to the divers it increased their knowledge and encouraged their participation and collaboration in conservation.

Our rocky habitat fixed transect monitoring and shipwreck citizen science surveys showed that removals decreased lionfish numbers within the marine protected sites surveyed. Although these data showed large impacts of the removals on both abundance and biomass of lionfish, the decline was not always statistically significant. This can be attributed to factors such as low statistical replication, absence of control (i.e. no removal) sites (Underwood, 1992), different capacity of divers-volunteers in removing lionfish, and divers targeting or focus in large lionfish and potentially neglecting smaller individuals; thus there were cases where biomass was statistically reduced but the abundance was not. Despite the absence of control sites, it was evident that the decrease of lionfish populations was not due to natural variability but due to the removal events; especially considering the short intervals between samplings and the fact that lionfish are characterized by very high site fidelity and consistent site population densities (Jud & Layman, 2012; Akins *et al.*, 2014; Tamburello & Côté, 2015; Bos *et al.*, 2018).

The citizen-science shipwreck survey provided more updates as the Zenobia was dived regularly by our volunteers, confirming the ability of citizen science to collect vast amounts of data in a cost-effective manner. Common challenges faced by citizen-science projects such as misidentifications and poor data quality (Giovos *et al.*, 2019) were potentially overcome by the fact that volunteer divers were trained, experienced, and that lionfish can be easily distinguished from other taxa due to their conspicuous characteristics. Social media networks are effective at recording the spread of invasive species in Mediterranean countries (e.g. Gerovasileiou *et al.*, 2017; Chartosia *et al.*, 2018; Kleitou *et al.*, 2019a; Kousteni *et al.*, 2019) but tend to lack the detail needed to accurately estimate population levels. In our study, they have been found effective in approximately understanding the trends of populations and guide management interventions; especially in isolated sites such as shipwrecks where data are more standardized. The electronic log-books yielded the data needed to guide the timing of removal events, although interpretation was needed – for example lionfish were much more common outside the wreck than within it, so data from teams that focused on exploring the wreck interior reported low numbers.

Using the sightings received by volunteers, large fluctuations in lionfish records were observed even within the same days; and observations could be influenced by a range of factors such as the profile/reason of the dive (e.g. explorative, instructional etc.), observer, area of wreck exploration, time of the dive, environmental conditions, etc. In days when more than one dive record was received, the use of the one with the maximum number of lionfish was considered as the most reliable that dealt better with detectability. The variation in observations highlight the importance of big sample sizes in citizen science monitoring. The observations per dive minute were correlated significantly with the total lionfish observed indicating that standardization with unit effort (i.e. dive time) might not be prerequisite in citizen science initiatives targeting isolated and remote areas such as shipwrecks. However, the collection of data that can enable standardization of citizen science dives, like dive duration, together with additional data such as the temperature, approximate area/location, the time, and the reason of the dive are strongly recommended since they can provide useful and vital information for understanding the changes that are observed.

Lionfish population recovery rates after removals (either from spill-over/arrival of large individuals or larval subsidies from adjacent areas) varied amongst the study areas and should be taken into consideration in management efforts since they are related to the effort required for achieving significant conservation effects. Keeping lionfish numbers below threshold damaging densities (Green *et al.*, 2014) would need monitoring with removal events organized to deal with rising numbers of fish. For instance, relatively low initial lionfish numbers were able to recover to near pre-removal levels in two weeks in the areas of the fixed transects, while high initial lionfish numbers did not recover for at least three months after the first removal on the Zenobia wreck. Different recovery rates could reflect habitat connectivity; interconnected rocky habitat might allow spread from adjacent sites and so recovery can be rapid, whereas the Zenobia wreck was at least 4 km from the nearest rocky and seagrass habitats that lionfish commonly use in the Mediterranean Sea (Savva *et al.*, 2020), and could explain the slower population recovery. In addition, the isolation of the wreck could imply that recruitment was primarily occurred through larval settlement as opposed to the other two sites where immigration of larger fish from connected areas could more easily occur. The latter was confirmed by the length frequency of lionfish which indicated that large lionfish individuals were re-introduced, especially at Cyclops. At Chapel, the number of large individuals decreased substantially which suggest that they were targeted by the divers.

A trade-off between effort spent removing and achieving a smaller lionfish density was identified; as shown by the framework developed by Usseglio *et al.* (2017). The higher removal effort (44 dives) at the isolated Zenobia wreck was characterized by lower catch per unit (dive) effort (CPUE) compared to the removal events of the other areas where less dives were conducted (<20 in each event). The CPUE further decreased to relatively low levels in the last removal event indicating a potential depletion effect; justified by the slow recovery of lionfish numbers. Therefore, even 1-2 big removal events each year could be enough to protect remote sites such as the Zenobia wreck. On the other hand, CPUE of the rocky sites was 1.5-2.5 times higher indicating that more intense and/or frequent effort was required to achieve depletion effects. In addition to the decrease of CPUE, the catch efficiency of lionfish also decreased after each removal event. Anecdotal reports by the participants suggested that lionfish became alerted and more difficult to catch after removal events. A similar phenomenon was observed in the Western Atlantic and should be taken into account as it can have implications for the impact of the invasive species and for the design and success of management measures (Côté *et al.*, 2014b).

The results of this study indicated that removal events can be effective in suppressing lionfish population in targeted location, however long-term and larger scale monitoring is needed to accurately understand the effects of site features such as connectivity and complexity, and decisively estimate the minimum effort that is needed to efficiently achieve depletion or suppression of lionfish populations below damaging levels. In addition, targeted removals of SCUBA are usually conducted in recreational depths of less than 30 m, and management efforts could be undermined by populations in deeper waters where individuals can be larger and consequently more fecund (Andradi-Brown *et al.*, 2017). In the Western Atlantic, specialized traps and harvesting robots targeting lionfish have been formulated to face deeper populations (Harris *et al.*, 2020; Abadjiev *et al.*, 2021), and their usage could be tested and promoted in the Mediterranean Sea.

High costs hinder the success of invasive species control programs worldwide, leading to temporary results with the remaining invasive individuals re-expanding (Britton *et al.*, 2011; Pluess *et al.*, 2012). Management reforms would be needed to enable systematic commitment to lionfish removals (Kleitou *et al.*, 2021a). In our study, divers were willing to pay an extra fee to participate in removal events or support others in removing lionfish, and specialized licenses with an indicative cost could be established for protected areas to be able to sustain removal activities. The removal events conducted as part of this study have shown that when monitored by competent authorities/people, regulated and coordinated, illegal activities such as spearfishing grouper can be avoided. Similar mechanisms exist in other parts of the world. For example, Bonaire has a well-established marine conservation program, the main body of which is run by the national park authority, and charges the non-resident visitors a dive fee of $45 per calendar year for scuba diving, and $25 for other water activities. Actions funded by this fee include a lionfish hunting program, patrols to enforce fishing restrictions, and coral reef monitoring (Roberts *et al.*, 2018). Bermuda is running a program in which interested local volunteers are trained and receive an annual permit for lionfish removals while they can adopt a section of reef to regularly visit and cull lionfish (Gleason & Gullick, 2014). Hunting lionfish for consumption needs to be widely promoted as an ethically correct choice, supported by prominent animal ethics, with benefits to the ecology and environmental health (Noll & Davis, 2020).

In line with global targets to restore the ocean, the European Union aims to protect at least 30% of its marine waters, with one third strictly protected by 2030 (EC, 2020; Laffoley *et al.*, 2020). Marine protected areas are vulnerable to the spread of invasive species, and no fishing zones are especially vulnerable to the spread of invasive fish such as lionfish (Galil, 2017). Citizens could play a pivotal role in monitoring and managing the species. Permitting divers to remove these fish using SCUBA gear will need to be applied with caution and strictly regulated to avoid illegal fishing. If implemented correctly, removal events could protect selected areas from the adverse effects of lionfish, while at the same time help to establish rich and deep links with local communities, strengthening responsibility and surveillance at corporate and social levels, and stimulating public environmental awareness.

6. Chapter 4: Conflicting interests and growing importance of non-indigenous species in commercial and recreational fisheries of the Mediterranean Sea

6.1. Author contributions

P.K. conceptualized, designed the study, and wrote the manuscript. P.K. designed the questionnaires and led the social surveys with support from I.G., M.E., and A.C. Analyses and visualizations were done by P.K. All authors critically reviewed the drafts and gave final approval for publication. S.R., D.K. and J.M.H. supervised the study. This manuscript is published in the journal Fisheries Management and Ecology.

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6.2. Abstract

Non-Indigenous Species (NIS) are spreading, reshaping Mediterranean Sea biological communities and fishery resources. The present study used fisheries data and structured interviews to assess the impacts of NIS on recreational and commercial fishers in Cyprus. Non-indigenous species that have been present in Cyprus for more than two decades were mostly perceived by local fishers as native, NIS with high market value were considered to be beneficial, and venomous or poisonous NIS were considered to be deleterious. The pufferfishes (Tetraodontidae) were identified by fishers as causing significant economic damage that undermines the sustainability of the commercial fishing sector. The most popular and highly priced NIS were rabbitfishes (*Siganus* spp.). In terms of commercial landings, six non-indigenous taxa contributed over a quarter of the total landings value and more than half during the summer season. The study emphasized the multifaceted interactions of NIS with the fishing sector, and how policy objectives may not align with social and commercial fishery interests.

6.3. Introduction

Mediterranean marine ecosystems are deteriorating due to increasing human activities and pressures (Coll *et al.*, 2010). Invasions by non-indigenous species (NIS) are rapidly changing the marine ecosystems in the region (Edelist *et al.*, 2013; Katsanevakis *et al.*, 2014a). The rate of NIS introductions is accelerating and is greater than in any other region worldwide; reaching over 600 established multicellular species in 2017 (Zenetos *et al.*, 2017; Galil *et al.*, 2018b). Major pathways for NIS include shipping (transfer via ballast waters or as biofouling), the Suez Canal, aquaculture, and aquarium releases (Katsanevakis *et al.*, 2014a). The Suez Canal is the dominant pathway responsible for the majority of the NIS present (Galil *et al.*, 2015b). Enlargement of the Suez Canal, overfishing and climate change are combining to allow more warm water Indo-Pacific species to become established in the Mediterranean Sea to the detriment of native species (Galil *et al.*, 2017; Moullec *et al.*, 2019).

Some NIS are called invasive alien species (IAS) when they cause negative ecological effects. Such effects include reducing native species richness and abundance, increasing the risk of native species extinction, reducing the genetic diversity of local populations, introducing novel parasites or diseases, changing native species behaviour, altering ecological processes, and reducing ecosystem services (Chaffin *et al.*, 2016; de Castro *et al.*, 2017; Geburzi & McCarthy, 2018). Invasive alien species have also become a major social issue; inflicting economic losses in a range of millions to billions of dollars per year (Warziniack *et al.*, 2021), impacting human health, and interacting with recreational activities and aesthetic values (Pyšek & Richardson, 2010). A number of recently introduced IAS in the Mediterranean are poisonous or venomous and so could adversely affect tourism and fisheries (Galil, 2018). For example, pufferfishes (Family: Tetraodontidae) have high concentrations of tetrodotoxin (TTX) in their tissues and can be fatal when consumed (Katikou *et al.*, 2009). Some species damage fishing gear and catch, such as the pufferfishes, the striped eel catfish *Plotosus lineatus*, and the nomad jellyfish *Rhopilema nomadica* (Kalogirou, 2013; Galanidi *et al.*, 2018).

Positive effects of NIS are underestimated due to a perception bias and focus on the negative effects (Katsanevakis *et al.*, 2014b). Some NIS might replace lost ecological functions, add redundancy, and enhance ecosystem services (Chaffin *et al.*, 2016; Kleitou *et al.*, 2021a). In addition, some NIS have become lucrative target species of the fisheries (Demirel *et al.*, 2021; Ugarković & Crocetta, 2021) and provide potential to stabilize fishery revenues (Michailidis *et al.*, 2019; van Rijn *et al.*, 2019; Saygu *et al.*, 2020).

Little is known about the impacts of NIS on people and society (García-Llorente et al., 2008; García-Llorente et al., 2011). A few recent studies have explored the socioeconomic effects of NIS in the Mediterranean Sea (Galanidi *et al.*, 2018; Peyton *et al.*, 2019; Peyton *et al.*, 2020) but such studies have focused on the negative impacts of NIS and positive impacts might have been overlooked (Bonanno, 2016; Kleitou *et al.*, 2021a).

Commercial and recreational fisheries are both important to the local people in the Mediterranean (Giovos *et al.*, 2018a; Lloret *et al.*, 2018). Inherent difficulties in monitoring (FAO, 2020), such as the diverse structure of fishing fleets (Lloret *et al.*, 2018), the diverse national data collection programmes (Pauly & Zeller, 2016), and a lack of data on recreational fisheries (Pita *et al.*, 2018) all pose challenges for sustainable management of the sector. Non-indigenous species are gradually becoming a source of revenue in the eastern Mediterranean (van Rijn *et al.*, 2019) but insufficient consideration of stakeholder perspectives and priorities can lead to inaccurate assessments of species impacts, poor policy decisions, and loss of support for management measures (Barney & Tekiela, 2020; Oficialdegui *et al.*, 2020). The multifaceted costs and benefits of NIS for local people need to be better understood and incorporated into marine management strategies.

This study used (i) fishery data from official Cyprus national sources (Department of Fisheries and Marine Research, Ministry of Agriculture, Cyprus) and (ii) structured interviews with commercial and recreational fishers, to assess the socioeconomic interactions, knowledge, norms, and intrinsic motivations of fishers with respect to common NIS.

The study focused on a Marine Protected Area (MPA) in Cyprus where NIS of Indo-Pacific origin now dominate (Kleitou *et al.*, 2019c; Savva *et al.*, 2020). Two fishing fleets operate in this area; namely small-scale inshore boats and polyvalent vessels. The small-scale inshore boats (overall length 6-12 m) target predominantly demersal species using mainly bottom set nets (trammel nets / gillnets) and bottom longlines. The polyvalent vessels (overall length 12-24 m) target pelagic species with drifting longlines, as well as operate bottom-set trammel nets / gillnets and bottom longlines. All recreational fishers, irrespective of their fishing technique/tools, were included in this study. Recreational fishers use traps, spearfishing, boat-fishing using bottom fishing, trolling, jigging, bottom longlining, deep-dropping, and shore-fishing using casting, spinning, squid jigging (eging), and shore jigging (Moutopoulos et al., 2021). The catches of recreational fishers are not monitored by official schemes.

6.4. Materials and Methods

6.4.1. Targeted non-indigenous species

The research is focussed on 12 target NIS (Table 6.1), which were selected based on their known high abundance or identified as priority species in relation to fisheries (GFCM-UNEP/MAP, 2018).

Table 6.1. Selected non-indigenous species targeted through structured interviews and sorted with the year of their first record in Cyprus. This selection was focused on priority species identified through the GFCM-UNEP/MAP 2018, and local expertise.

Species	**Common name**	**Year of first record in Cyprus - Reference**
Siganus rivulatus	Marbled spinefoot	**1928 -** Norman (1929)
Saurida lessepsianus	Lizardfish	**1960 -** Ben Tuvia (1962)
Sargocentron rubrum	Redcoat	**1961 -** Fodera (1961)

Species	Common name	Year of first record in Cyprus - Reference
Siganus luridus	Dusky spinefoot	**1964 -** Demetropoulos and Neocleous (1969)
Sphyraena chrysotaenia/flavicauda	Yellowstripe barracuda	**1964 -** Demetropoulos and Neocleous (1969) / **2014** - Iglésias and Frotté (2015)
Pempheris sp.	Sweeper fish	**1995–96 -** Iglésias and Frotté (2015)
Fistularia commersonii	Bluespotted cornetfish	**1999 -**Wirtz and Debelius (2003)
Torquigener flavimaculosus	Yellowspotted puffer	**2009** - Michailidis (2010)
Sepioteuthis lessoniana	Bigfin reef squid	**2009 -** Tzomos *et al.* (2010)
Pterois miles	Devil firefish (lionfish)	**2012 -** Kletou *et al.* (2016)
Lagocephalus sceleratus	Silver-cheeked toadfish	**2014 -** Iglésias and Frotté (2015)
Parupeneus forsskali	Red Sea goatfish	**2014 -** Iglésias and Frotté (2015)

Note: This selection was focussed on priority species identified through the GFCM-UNEP/MAP (2018)and local expertise.

6.4.2. National fishery data

Monthly national fishery data (landings quantity (kg), value (€), and effort (landings per trip)) for the selected species were provided by the Cyprus Department of Fisheries and Marine Research (DFMR). These data derive from various sources of information such as logbook records of fishers and sales notes from fishmongers. Data were acquired for the landings of the four nearest (<15 km distance) to the Cape Greco (MPA) landing areas, namely Ayia Triada, Paralimni, Ayia Napa and Potamos for 2017-2019 (Figure 6.1).

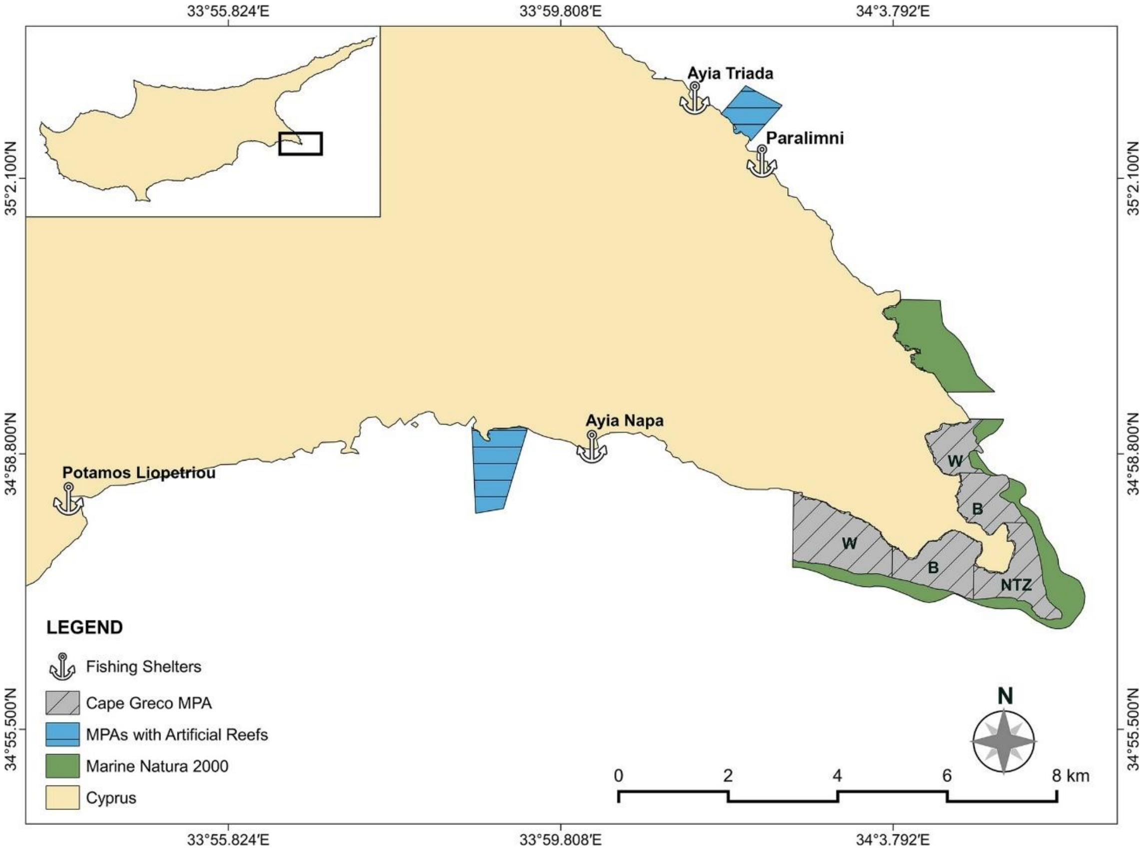

Figure 6.1. The study area focused around the first established natural marine protected area (MPA) with fishery prohibitions of Cyprus (Cape Greco; with grey colour in the map) and nearby landing areas (namely Ayia Triada, Paralimni, Ayia Napa and Potamos for 2017–2019). NTZ: No take zone (fishing is prohibited for everyone); B: Buffer zone (fishing is prohibited only for recreational fishers); W: Wider Zone (fishing is allowed). Blue colour indicates areas with artificial reefs established by the Department of Fisheries and Marine Research to promote dive ecotourism, and where fishing is prohibited for everyone.

6.4.3. Structured interviews

Structured interviews were conducted with both commercial (CFs) and recreational (RFs) fishers during June and July 2020 at the same landing areas (i.e. Ayia Triada, Paralimni, Ayia Napa and Potamos) and adjacent locations on the coast while interviewees were fishing. Contact details of the licensed CFs were provided by the local fishery associations and the DFMR. Before the interview, fishers were informed that their participation was optional, and that personal data would remain confidential.

All interviews were carried out by the same trained person, ensuring that questions were presented in an identical manner. The interviews were held privately, on one-to-one sessions, to prevent influence or interference by other people.

The structured interview (Appendix 3A) consisted of three sections of questions, with regard to the 12 target NIS, to describe the respondent's: 1) demographic profile; (2) perceptions about the impacts of NIS (encompassing all species); 3) species specific knowledge, perceptions and interactions of fishers . The target species' common name(s) were used and an image of the species was shown to ensure that the interviewee was providing comments on the correct species. Species-specific questions quantified the fisher's: a) knowledge about the non-indigenous nature of each species in the Mediterranean Sea; b) perceptions for each species impacts; (c) discard rates; (d) catch frequency (i.e. probability of catch in a fishing trip) and proportion (i.e. percentage contribution in the overall catch biomass of a fishing trip); (e) damage to catches (through depredation) or fishing tools; (f) injuries caused by the species; and (h) alterations of fishing tools, location and/or duration due to the presence of the species. Fishers were separated into categories based on their activities: Small *vs* large vessel (polyvalent) for the CF category, and boat fishers using demersal techniques, boat fishers using pelagic techniques, shore fishers, and spearfishers for the RF category. Descriptive statistics were applied, providing percentage contribution, mean, standard deviation (SD) and standard error (SE) values for absolute values such as landings weight and value, damages (costs), and injuries caused by NIS. For scale questions, the frequency of occurrence/reports (%) was found for each fisher category. Questions were analysed for associations using a 1-sample chi square (χ^2) proportion test or an exact binomial test (using proportion of 0.5). Relationships between the profile of fishers (RFs and CFs) and the responses were assessed using the Pearson's χ^2 test, with Yate's continuity correction for dichotomous questions, or the Fisher exact test (when sample size in one or more cells was below 5). For percentage-based scale questions, the rank-based Kruskal-Wallis H test followed by a Dunn's test with Bonferroni correction was applied to examine differences between species. Correlations between recognition of species as non-indigenous by fishers with the year of their first record to Cyprus waters and their retail price (i.e. mean of last three years based on official data) were examined using Kendall's Tau (τ) rank-correlation coefficient. All statistical analyses and graphics were carried out in Microsoft Excel and R-studio (Version 1.2.1335).

6.5. Results

6.5.1. National fishery data

In 2019, 78 licensed CFs were active at the four landing areas. Landing data for yellowspotted puffer *Torquigener flavimaculosus* and silver-cheeked toadfish *Lagocephalus sceleratus* were both reported as *Lagocephalus* spp., yellowstripe barracuda *Sphyraena chrysotaenia* and yellowtail barracuda *S. flavicauda* data were sold as *Sphyraena* spp. and could not be separated from other native species (e.g. European barracuda *Sphyraena sphyraena*), and no data were available for bigfin reef squid *Sepioteuthis lessoniana* (sold as the native common squid *Loligo vulgaris),* sweeper *Pempheris* sp., and lizardfish *Saurida lessoniana* (which were both sold in an aggregated category as 'various'). Between 2017 to 2019, six non-indigenous taxa (bluespotted cornetfish *Fistularia commersonii, Lagocephalus spp.,* Red Sea goatfish *Parupeneus forsskali,* common lionfish *Pterois miles,* redcoat *Sargocentrum rubrum,* dusky spinefoot and marbled spinefoot *(Siganus* luridus and Siganus rivulatus) contributed 29% (97,292 kg) of the total landings weight and for 28% (€340,802) of landings value, equal to an annual income of €1,456 per each fisher individual.

The *Lagocephalus* spp., the *S. rubrum*, and the *Siganus* spp. were the most common NIS contributing for 13%, 8.7%, and 6% of the total landings weight of 2017–2019, respectively. Peak NIS landing was apparent during summer when their contribution was over half of both total landings and value (Figure 6.2a). Total landings and catch per unit effort (kg per trip) followed a similar temporal pattern for *Siganus* spp., but a peak was evident during the summer months mainly for *Lagocephalus* spp. and *S. rubrum* (Figure 6.2b, c). The value of *Lagocephalus* spp. landings in 2019 was about €73,550, equal to €943 per fisher. Rabbitfishes *Siganus* spp. contributed 6% of the total weight, but it represented 17% (or €269,399, equal to €3,454 per fisher) of the total value of the landings (Figure 6.2b). Since 2019, landings increased sharply for *P. forsskali*, and the first reports of *P. miles* were also recorded. The two *Siganus* species and *P. forsskali* were the most commercially valuable species with retail prices over €10 per kg (Figure 6.2d).

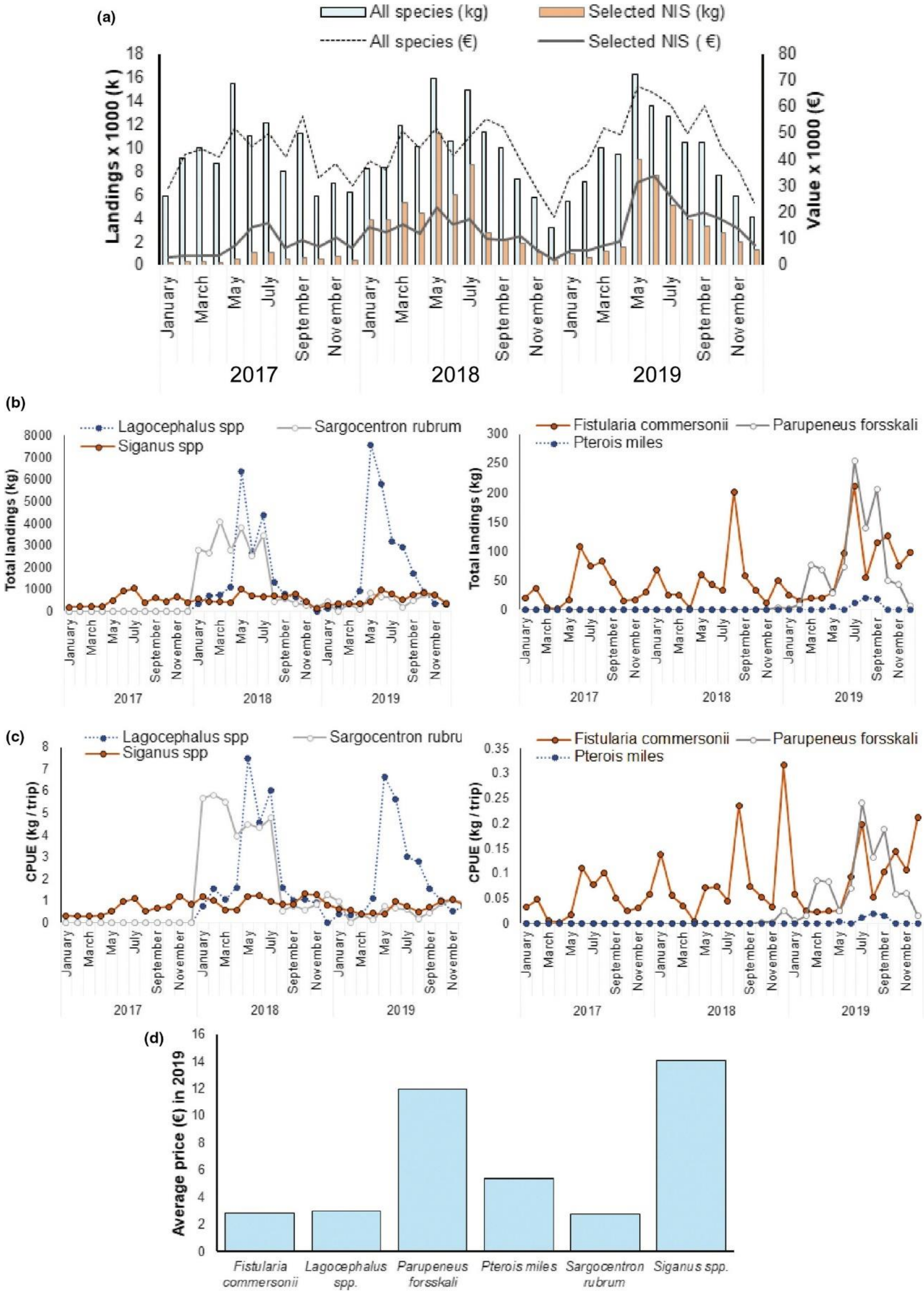

Figure 6.2. (a) Monthly landings (kg) and value (in €) of fishery catches, and for selected non-indigenous species combined (*Lagocephalus* spp., *Sargocentron rubrum*, *Siganus* spp., *Fistularia commersonii*, *Parupeneus forsskali*, and *Pterois miles*), (b)

Monthly landings for each species, (c) Monthly Catch Per Unit Effort (CPUE) for each species, and (d) Mean retail price (in €) per kg for each species in 2019.

6.5.2. Interview results

In total, 55 fishers were interviewed, 20 of whom were CFs (17 small-scale fishers and three polyvalent corresponding to 25.6% of the licensed CFs of the area) and 35 RFs some of which used more than one fishing mode (five fishing demersal species with boat; five fishing pelagic species with boat; 28 fishing with a rod from the shore; and 4 fishing with freedive and speargun). These fishers were male. The mean age of the CFs was 49.9 (SD: 16.3) and the corresponding of the RFs was 51.6 years (SD: 12.1). About 70% of RFs and 85% of CFs were graduates of secondary education or lower, respectively. A high percentage of the RFs (> 70%) did not own a recreational fishing license (no license exists for shore fishing in Cyprus) or a fishing vessel, whereas all of the CFs owned a professional fishing license (70% owned a Type A license, 10% a Type B, 5% a Type C and 15% owned polyvalent license. Information about the different license types, the demographic profile, the fishing intensity and the spatio-temporal activity distribution of the interviewed fishers are presented in Moutopoulos *et al.* (2021).

The vast majority (overall *ca.* 95%) of both CFs and RFs stated that they were aware of what a non-indigenous species is. Using a scale of –2 to +2 (–2 = very negative, 0 = neutral and +2 = very positive), the vast majority of fishers reported that NIS cause very negative ("–2") impacts (*ca.* 81%, $n = 45$) (binomial test, $p < 0.05$).

Only five (i.e. L. *sceleratus, T. flavimaculosus, P. forsskali, P. miles,* and *F. commersonii*) of the twelve species were correctly recognised by most fishers as non-indigenous for the Mediterranean waters (Figure 6.3). On the other hand, *S. rubrum, Sphyraena* spp. *Pempheris* sp. and *S. lessepsianus* were falsely viewed as native to the region by most fishers (Figure 6.3). The responses were contradictory for *S. luridus, S.*

rivulatus, and *S. lessoniana* as there was equal proportion of fishers who viewed them as non-indigenous or native (Figure 6.3). The responses did not vary significantly between RFs and CFs except for *S. lessoniana* which was recognised as non-indigenous by 90% of CFs but only from 54% of RFs, and *Pempheris* sp. which was recognised as non-indigenous by 40% of CFs but only from 6% of RFs (Figure 6.3). There was a significant positive correlation between the recognition of species as non-indigenous and the year that the species was first recorded in Cyprus (Kendall's $\tau = 0.54$, $p < 0.05$, Figure 6.4a); with species that were first recorded after Year 2000 being recognised as non-indigenous. There was a negative but not significant correlation between the recognition of the species as non-indigenous and their retail price (Kendall's $\tau = -0.18$, $p > 0.05$, Figure 6.4b), as well as the price of the species and the year of its first record in Cyprus (Kendall's $\tau = -0.14$, $p > 0.05$, Figure 6.4c).

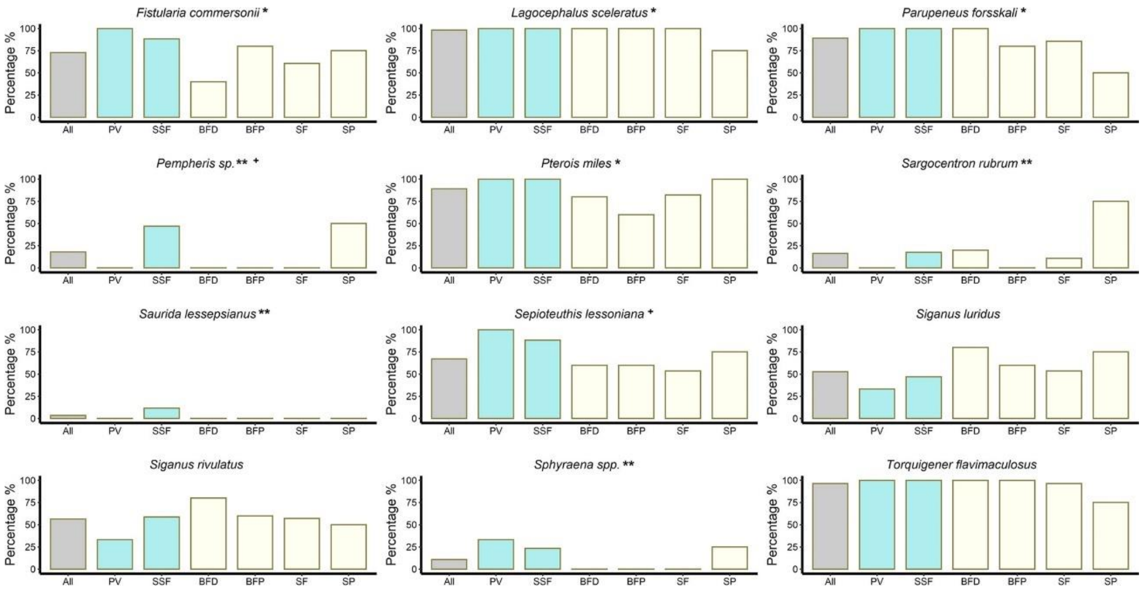

Figure 6.3. Knowledge of fishers about whether the species is non-indigenous or native to the Mediterranean Sea. Commercial fishers (SSF: Small-scale fishers; PV: Polyvalent) and recreational fishers (BFD: Boat fishing demersal; BFP: Boat fishing pelagic; SF: Shore fishing; SP: Spearfishing). Grey colour shows all responses, blue colour indicates commercial fishers, and yellow colour indicates recreational fishers. Asterisk (*) represents statistically significant identification of species as non-indigenous by most fishers and two asterisks (**) represent significant identification of

species as native (p <0.05, binomial test using proportion of 0.5). Cross (+) represents significant differences between the responses of commercial and recreational fishers (Fisher's exact test or Pearson's Chi-squared test, p < 0.05).

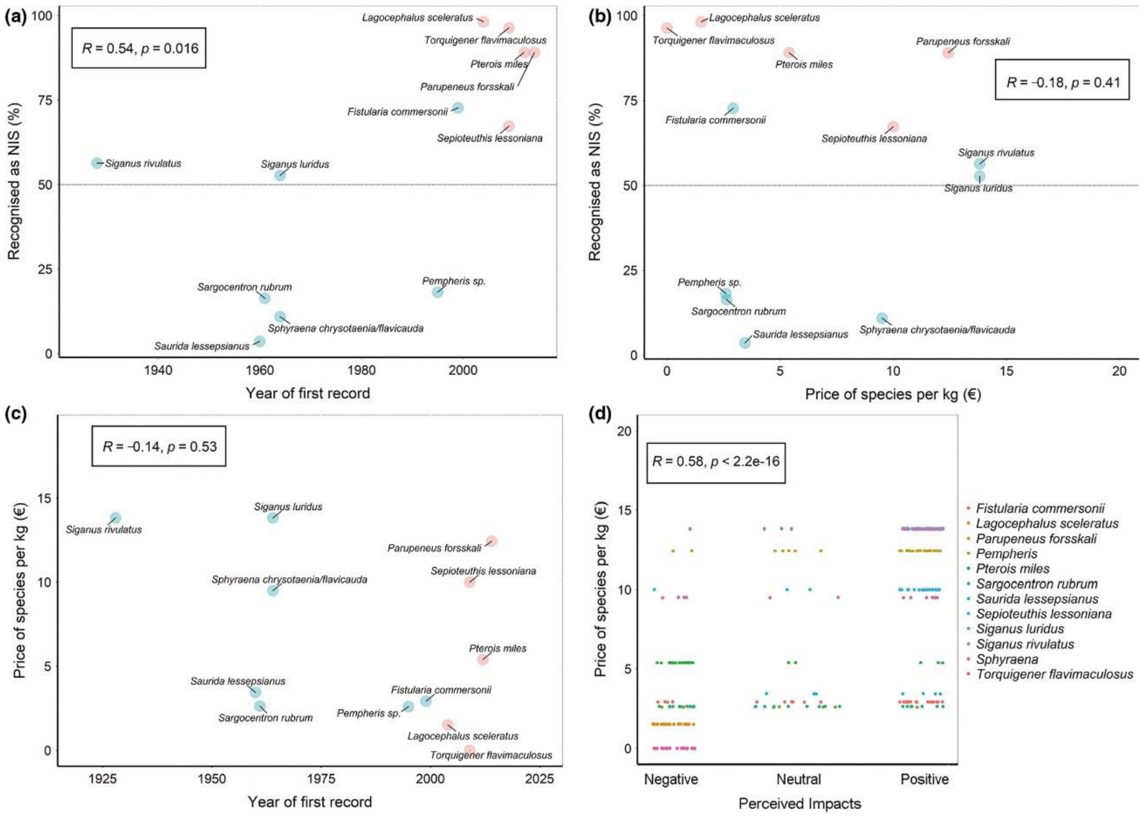

Figure 6.4. Associations between (a) Year of species first record in Cyprus and recognition as non-indigenous, (b) Price of species and recognition as non-indigenous, (c) Year of first record and price of species, and (d) Price of species and perceived impacts to the ecosystem. The boxes show the Kendall rank correlation coefficient and p-value.

Opinions regarding the impacts of each species varied. Species that were correctly recognised as non-indigenous were more likely to be viewed as negative (Pearson's χ^2 = 38.057, df = 2, p < 0.05). Moreover, species market value was strongly correlated with the perceived impacts of the species (Kendall's τ = 0.58, p < 0.05, Figure 6.4d). Highly priced *Siganus* spp. *P. forsskali* and *S. lessoniana* were generally viewed as positive whereas poisonous *L. sceleratus* and *T. flavimaculosus* and venomous *P. miles* were perceived as negative (Figure 6.5). Commercial and recreational fishers responded similarly for all species impacts except for *Pempheris* sp., *S. lessepsianus*, and

Sphyraena spp., for which most RFs responded “they don’t know” but CFs perceived mostly positive impacts (Figure 6.5).

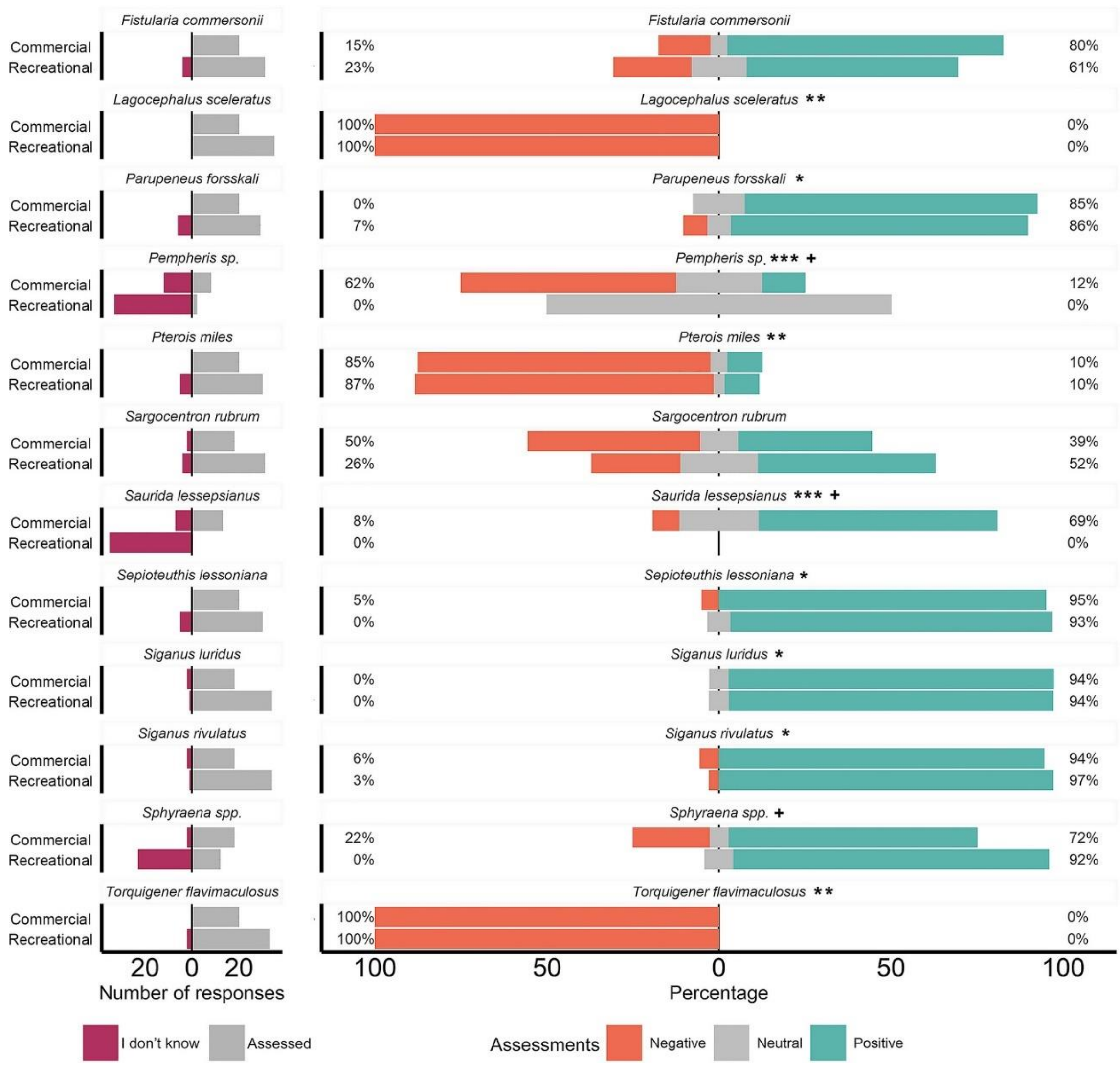

Figure 6.5. Perceptions about the impacts (positive, negative or neutral) of the selected NIS as stated by the commercial and recreational fishers (right plot). Left plot shows the number of fishers who reported that they don’t know versus those who assessed the impacts. Asterisk (*) represents statistically significant view of species impacts as positive, two asterisks (**) represent statistically significant view of species impacts as negative, and three (***) represent statistically significant “I don’t know” responses (p <0.05, exact binomial test using proportion of 0.5). Cross (+) represents significant differences between the responses of commercial and recreational fishers (Fisher exact test or Pearson's chi-squared test, $p < 0.05$).

When asked about the frequency (i.e. probability of catch in a fishing trip) and proportion (i.e. percentage contribution in the overall catch biomass of a fishing trip) of each NIS, the responses were consistent with the official landing data of commercial fishery by recognizing the two pufferfishes (*L. sceletarus* and *T. flavimaculosus*) as the most commonly-caught species. Small deviations were also identified; for example, the two rabbitfishes (*S. rivulatus* and *S. luridus*) were reported as being more common than the *S. rubrum.* (Figure 6.6). Responses for both frequency and proportion varied significantly amongst species (Kruskal-Wallis, $\chi^2 = 57.73$, df = 11, $p < 0.05$, $\varepsilon^2 = 0.088$ and Kruskal-Wallis, $\chi^2 = 57.73$, df=11, $p < 0.05$, $\varepsilon^2 = 0.088$, respectively). In addition, CFs and RFs responded differently for the catch frequency and catch proportion of all species (Fisher exact test, $p < 0.05$) apart for the frequency of *T. flavimaculosus* and proportion of *S. rivulatus* for which the two groups responded similarly ($p > 0.05$). Only S. *lessoniana* was reported as being caught more frequently by RFs (i.e. 29% with over 50% frequency and 37% with over 20% proportion) compared to CFs (20% and 10% for frequency and proportion, respectively). All other species were more common for CFs; e.g. only 3% of RFs reported over 50% frequency for *P. miles, F. commersonii* and *P. forsskali*, compared to 85%, 75%, and 55% (respectively for each species) of CFs indicating a potential non-selectiveness of RFs for these species. Recreational fishers reported no encounters with *S. lessepsianus* and *Pempheris* sp., whereas *Sphyraena* spp. were found either very frequently or never by RFs (23% with 100% frequency and 77% with 0% frequency). Information for each (sub)-category of fishery and the reported catches of each species are displayed in Appendix 3B.

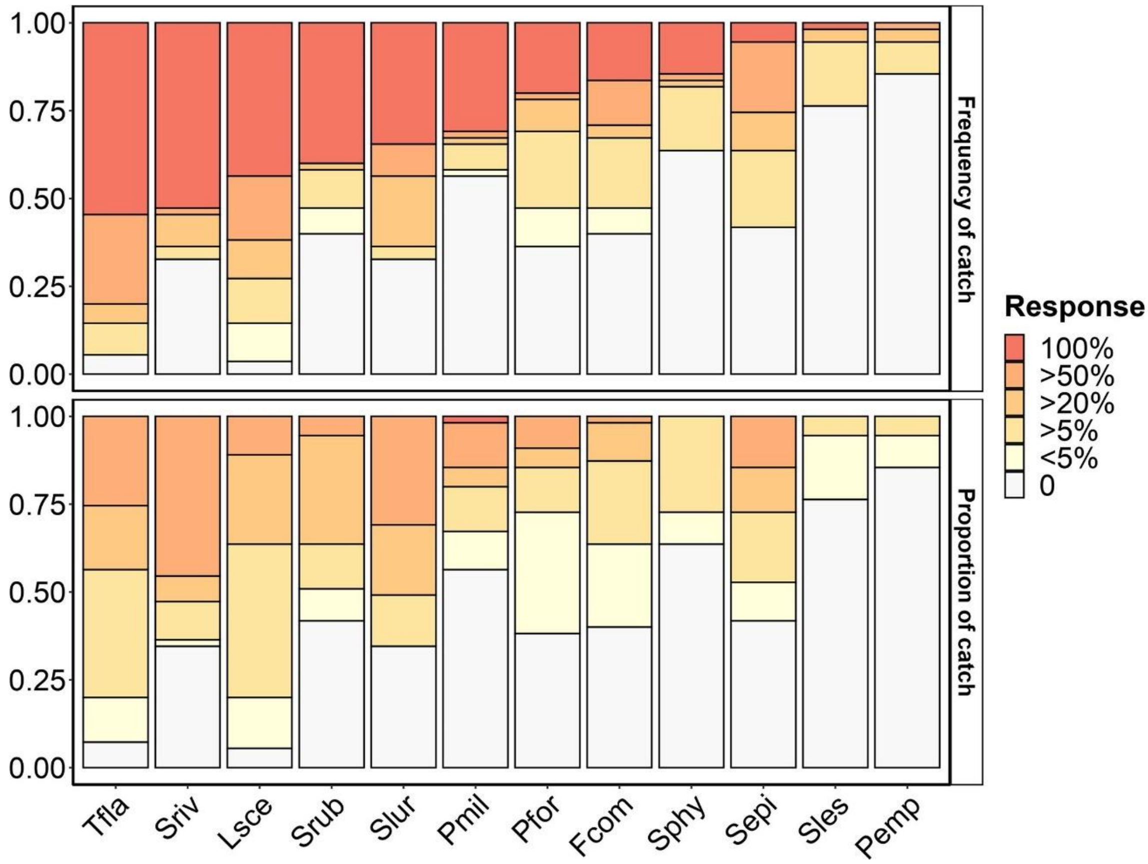

Figure 6.6. Catch frequency (i.e. probability of catch in a fishing trip) and proportion (i.e. percentage contribution in the overall catch biomass of a fishing trip) for each species (Tfla: *Torquigener flavimaculosus,* Sriv: *Siganus rivulatus*, Lsce: *Lagocephalus sceleratus*, Srub: *Sargocentron rubrum*, Slur: *Siganus luridus*, Pmil: *Pterois miles*, Pfor: *Parupeneus forsskali*, Fcom: *Fistularia commersonii*, Sphy: *Sphyraena* spp., Sepi: *Sepioteuthis lessoniana*, Sles: *Saurida lessepsianus*, Pemph: *Pempheris* sp.).

According to fishers' responses, the pufferfish species *L. sceleratus* and *T. flavimaculosus* had the most chances of being discarded (Figure 6.7); however responses for the two species varied between CFs and RFs (Figure 6.7) with the first group reporting less discard rates. This was especially the case for *L. sceleratus* which was more likely to be kept by CFs (binomial test, $p < 0.05$). High discard rates were also reported for *Pempheris* sp. and *P. miles* but with no significant probabilities of either being discarded or kept (binomial test, $p > 0.05$). Commercial and recreational fishers responded differently for *P. miles* (Pearson's Chi-squared test with Yates' continuity correction, $\chi2 = 6.34$, df = 1, $p < 0.05$) and CFs were more likely to keep the fish instead of discard it (1-sample proportions test with continuity correction, $p < 0.05$). Commercial and recreational fishers responded similar discard rates for all other species (Fisher exact test, $p > 0.05$) (i.e., *P. forsskali*, *F. commersonii*, *S. lessoniana*, *S. luridus*, *S. rivulatus*, *S. chrysotaenia*/*flavicauda*, *S. lessepsianus*, and *S. rubrum*) who were more likely to keep the catches than discard them (binomial test, $p < 0.05$) (Figure 6.7).

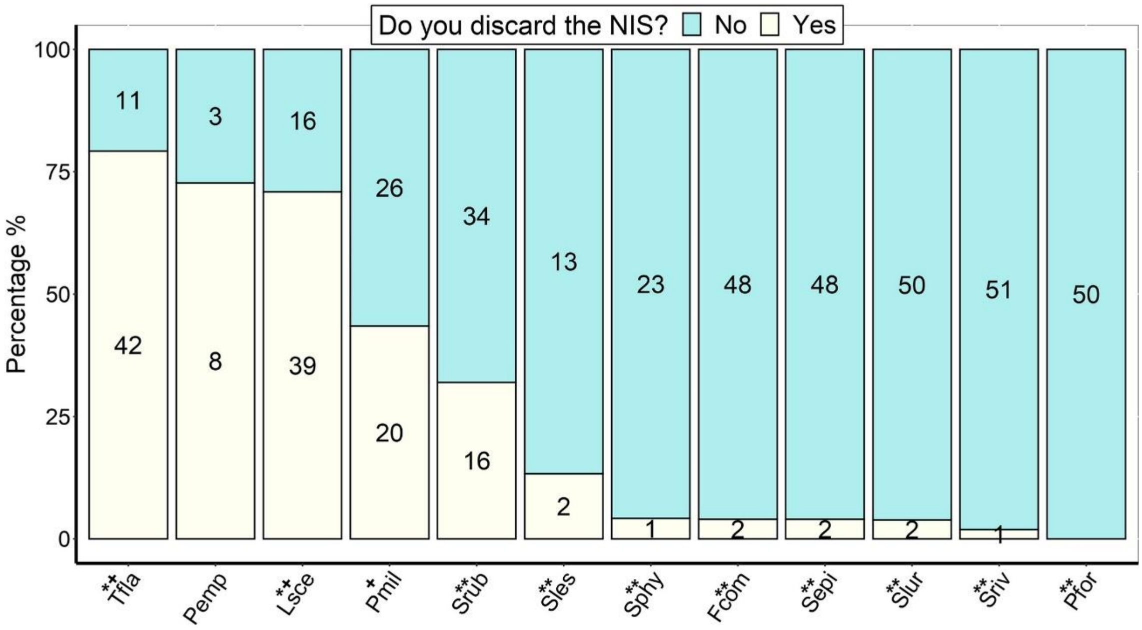

Figure 6.7. Discard rates of each non-indigenous species according to the fishers' responses (Tfla: *Torquigener flavimaculosus*, Pemph: *Pempheris* sp., Lsce: *Lagocephalus sceleratus*, Pmil: *Pterois miles*, Srub: *Sargocentron rubrum*, Sles: *Saurida lessepsianus*, Sphy: *Sphyraena* spp., Fcom: *Fistularia commersonii*, Sepi: *Sepioteuthis lessoniana*, Slur: *Siganus luridus*, Sriv: *Siganus rivulatus*, Pfor: *Parupeneus forsskali*). Asterisk (*) represents statistically significant retainment and two asterisks (**) represent statistically significant discard ($p < 0.05$, 1-sample proportions test with continuity correction or binomial test using proportion of 0.5). Cross (+) represents significant differences between the responses of commercial and recreational fishers (Fisher exact test or Pearson's chi-squared test, $p < 0.05$).

Fishers reported no direct financial impact of each NIS on in-net/pot predation of other catch or causing damage to the fishing gear, except for pufferfishes (*L. sceleratus* and *T. flavimaculosus*). For the pufferfish, the greatest impact was identified by CFs who reported direct economic losses were equal to €4173.53 (±2524.88) per year for each small-scale fisher (Appendix 3C). The extrapolated financial impact of pufferfishes to the full fishing fleet in the studied area (78 fishers) is estimated as €325,535 per annum, which represents 56% of the total value of all fishery catches reported in 2019 from the four landing areas.

Regarding the indirect impact caused by the NIS, about 30% of the fishers reported that they change their fishing area, duration or tools due to the presence of pufferfishes (*L. sceleratus* and *T. flavimaculosus*) in their target area (Appendix 3D). The proportion was significant for small-scale fishers; approximately 76% reported that they change their fishing tools or practices, such as fishing with larger mesh nets, fishing for smaller durations, changing locations, etc. (binomial test, $p < 0.05$).

Fishers did not report any personal incidents of injury from the selected NIS apart from one fisher who reported that he got stung by lionfish three times in the past year.

Finally, CFs fishers stated that non-indigenous by-catch and subsequent damage to gear increased the time spent fishing to achieve their income (55% of the CFs stated an increase of one to one and a half hour per fishing trip).

6.6. Discussion

Non-indigenous species are increasingly reshaping the ecosystems of the Mediterranean Sea (e.g. Giovos *et al.*, 2019; Kleitou *et al.*, 2019b; Michailidis *et al.*, 2020b); altering commercially important species assemblages. As native species are overfished, the contribution and interactions of NIS with fisheries have increased (Kleitou *et al.*, 2021a). Some invasive NIS exert adverse impacts whereas others provide welcome revenue, and some may provide both. These details can inform a management policy that acknowledges the multifaceted interactions of NIS with stakeholder groups.

Six of the selected NIS contributed over a quarter of the commercial fishery catch in the study area, and the catches comprised more than half of both total landings and value in the summer, highlighting the need for fishery reform to optimise their exploitation (Kleitou *et al.*, 2021a). The contribution of the six species was higher than the catch contribution of all non-indigenous species in the Cyprus fleet, which was estimated by Michailidis *et al.* (2020a) using telephone surveys (about 19%) but comparisons should be made with caution.

The Cyprus government has identified issues with the data reporting system such as the misidentification or grouping species under a common commercial name, especially in cases of relatively high number of species and low quantities (DFMR, 2020). The absence of discards data (Kleitou *et al.*, 2017; D'Andrea *et al.*, 2020), and the omission of recreational fisheries from the national data collection programmes further impair the management of NIS. Integration of multiple sources of data in monitoring schemes would improve accuracy and allow for better informed management decisions (Giovos *et al.*, 2020).

Differences between the interview and official landing data highlighted that monitoring would benefit from an improved reporting system. Official fishery records are data deficient for some NIS, e.g. species at an early stage of their invasion or species that are sold in aggregated categories along with native species; this prevents timely decision making that can enable management of the NIS before they cause economic impact. For instance, the lack of official data for some NIS, which have been reported as relatively frequent catches (e.g. *S. lessoniana*), indicated either the presence of these species in aggregated species categories or a potential mislabelling of the catches. The low taxonomic resolution of the official landings data also prevents for the disaggregation of non-indigenous species from the native ones (e.g. *Sphyraena* spp.). The *P. miles,* which is also established in the waters of Cyprus since 2015 (Kletou *et al.*, 2016), was first recorded in the official data in 2019. Since then, it was listed in low concentrations despite being reported as very common in our interviews with fishers (>95% frequency of catch); indicating a potential misreporting for the early years of the invasion or an absence of reporting due to discarding or misreporting.

The contribution of NIS varied both between CFs and RFs and among gears used. The most popular and highly priced fish was rabbitfish (*Siganus* spp.). The present results agree with those of an earlier study (Michailidis *et al.* (2019) in whcih *Siganus* spp. were reported to be the most important species (in terms of weight and value) for the marine recreational fishery of Cyprus. A peak in the catches of the CFs was evident in the summer of 2018 and 2019 for *Lagocephalus* spp., and in 2018 for *S. rubrum*. Since 2010, the Department of Fisheries and Marine Research is providing a compensation to fishers from €1 to €3 per fish individual or kilogram of *Lagocephalus* spp. caught (the price varied over the years of the programme implementation; in 2019 the compensation was € 3 per kg) to incentivize fishers to hunt the species and mitigate the impacts. In 2019, the compensation covered (based on the landings value) about 23% of the reported damages (catch and/or gear) that were caused by the pufferfishes (as estimated by the fishers interviewed this study). Rigorous monitoring is needed to better understand the ecological and socioeconomic effects of this DFMR compensation scheme.

A peak of *Lagocephalus* spp. catches coincided with the *L. sceleratus* reproduction peak (Rousou *et al.*, 2014) and it is likely that the species aggregate to spawn during the summer (anecdotal information by fishers). Fishers adapted to fishing pufferfishes in the summer months to benefit from the government subsidies. Aggregations of the *Lagocephalus* spp. populations could offer opportunities for alternative fishing practices (e.g. fishery-related tourism/pesca-tourism) and management strategies that would guide massive and targeted removals of the species.

From the structured interviews, it was evident that RFs reported significantly less frequency of catches than CFs for many of the selected NIS including *P. miles, F.*

commersonii and *P. forsskali*. Recreational fishers' motivations often extend beyond key economic drivers and might be driven by traditional norms for larger and 'trophy' fish which are often keystone top-predators (Giovos *et al.*, 2018a; Mackay *et al.*, 2018; Michailidis *et al.*, 2020a; Sbragaglia *et al.*, 2021). Future strategies for NIS management need to consider challenging social norms, feelings, and moral obligations to enhance fishing pressure to nuisance NIS and alleviate pressure from native keystone species such as groupers (Kleitou *et al.*, 2021a). Spearfishing of lionfishes *Pterois* spp. has been widely recognised as the best control mechanism (Kleitou *et al.*, 2021c). Spearfishing with free dive is very popular in Cyprus, with over 2,000 licences per year (DFMR data, 2021) and management strategies can aim to engage and motivate them.

Generally, fishers tended to perceive NIS (as a whole) as negative, but when asked about species-specific impacts, their responses were contradictory, and many species were viewed positively, and by many respondents considered to be native. Less than half of the species were correctly recognised by fishers as NIS in the Mediterranean and this knowledge was strongly correlated with the year of species introduction in Cyprus (species that arrived prior 2000 were viewed as native).

Negative perceptions were reported for the poisonous *L. sceleratus* and *T. flavimaculosus*, which do not have a market value (apart from compensation/reward by the government), and the low-priced venomous *P. miles*, which can injure fishers. On the other hand, highly-priced species, such as *P. forsskali*, *Siganus* spp.*, and S. lessoniana*, were perceived positively by >90% of respondents. These species are among the most common in the area, therefore, fishers did not perceive these species negatively, based on high abundance, as has been reported in other studies (e.g. Cerri *et al.*, 2020). Fishers' perceptions of *Siganus* spp. are apparently conflicting, with evidence provided by studies in which the presence and expansion of *Siganus* spp. has been shown to cause profound impacts on the native communities in the Mediterranean infra-littoral zone through overgrazing of important algae (Giakoumi, 2014; Vergés *et al.*, 2014). *Siganus* spp. were also considered amongst the 100 worst invasive species in the Mediterranean in terms of their socioeconomic impacts (Streftaris & Zenetos, 2006). Damage to ecosystems is often not visible to the public and ecosystem state change can occur without immediate negative economic impacts. Divergent views and knowledge between stakeholder groups need to be exchanged, acknowledged, and prioritization of issues (i.e. ecological vs social and economic issues) need to be harmonized to coordinate management strategies.

The low market price of NIS was mentioned by respondents as a major driver of discards and it limited targeting of NIS by fishers. There is potential here for fishers to become part of the management solution to NIS. In instances where fishing effort can play a role in the management of NIS that are invasive, a market-based management approach to increase demand for selected NIS is strongly recommended (Kleitou *et al.*, 2019d; Kleitou *et al.*, 2021a). In the present study, high discard rates were reported for lionfishes (≈ 45%) as there was a limited commercial market. Conversely, in the Western Atlantic the demand for lionfishes as a food source is outweighing supply (Chapman *et al.*, 2016), with market forces providing the management control necessary for this particularly invasive NIS. The present study has demonstrated how NIS, over time, have become intertwined with commercial fishing practice and income. Kleitou et al (2021a) recommend a cost-benefit analysis to align management of NIS within the ecological system with changing social and economic dynamics.

It was evident that pufferfishes (*L. sceleratus* and *T. flavimaculosus;* reported as *Lagocephalus* spp.) had the worst negative interactions with the fishery; gears, techniques, catches and operations; particularly to small-scale fishers. Incidences of injury with venomous NIS were rare with only one CF reporting that he got stung by *P. miles* three times. However, the risk for injuries may increase as venomous species, such as *P. miles*, are becoming established in the Mediterranean Sea (Galil, 2018). When direct impact of pufferfishes were extrapolated for the entire commercial fishing fleet of this area, the costs were equal to over 50% of the total value of all landings reported in 2019. Apart from this direct impact, 30% of all fishers and 76% of small-scale commercial fishers reported that they have changed their fishing strategies (e.g. larger mesh nets, fishing for smaller durations, changing locations, etc.) because of the presence of pufferfish. The destruction of nets, and the loss of catches, has had a negative impact on fishing income and as a result, put at a risk the economic sustainability of the small-scale fishery (STECF, 2020). This is similar to the impact of pufferfishes on the small-scale fishery of Turkey, where a loss of 2 million € (fishing gear and labour losses) per year was estimated (Ünal *et al.*, 2015).

The findings of the study need to be used with caution. A sample of fishers operating in the study area was interviewed and results cannot be generalised to the entire Cyprus fishery fleet. However, the use of fishers knowledge is frequently used as an alternative source of information when empirical data are not available (Lopes *et al.*, 2019), and the present study provides additional insights and potentially corrects the above-mentioned inherent limitations of the official data. Interview methods also come with limitations such as reliance on fishers, trust between researcher and fisher, fatigue, and potential reticence to provide accurate information (Maurstad, 2002; Gill *et al.*, 2019). All of these issues were largely overcome due to the excellent relationships with the fishers, the proper design and the experience of researchers in conducting interviews.

6.7. Conclusion

The current management strategy against NIS of the Mediterranean Sea is based on the traditional narrative approach of NIS as having only negative effects; it fails to account for positive contribution of species in ecosystems and fisheries. It was evident that the worst socioeconomic effects of NIS are being caused by pufferfish species and management solutions are urgently needed to mitigate the effects of their invasions. Other species such as rabbitfish were perceived as highly beneficial by the fishers. To decide on the NIS management strategy, an ecosystem-based fishery approach is needed at which fishery revenues and losses are assessed together with the ecological loss costs or benefits in an integrative framework (Kleitou *et al.*, 2021a). Fishers could be important allies if they are properly informed and involved in in collaborative and communicative management processes (Morales-Nin *et al.*, 2017). Improved data collection programmes, research, citizen science, market campaigns, and monitoring are also vital in improving the management of NIS and consequently the performance and sustainability of the fisheries in region.

7. Chapter 5: The case of lionfish (*Pterois miles*) in the Mediterranean Sea demonstrates limitations in EU legislation to address marine biological invasions

7.1. Author contributions

P.K. conceptualized, designed the study, and wrote the manuscript. All authors helped in refining its methodology and objectives, critically reviewed the drafts, and gave final approval for publication. Analysis and visualizations were done by P.K. with support by S.S. All authors helped in refining its methodology and objectives, critically reviewed the drafts and gave final approval for publication. The study used experiences of the RELIONMED project to collect data and complete a risk assessment for lionfish. All authors participated in the RELIONMED implementation, and the risk assessment and risk management which were submitted as Appendices were led by P.K. with contributions from all authors. This manuscript is published in the journal Marine Science and Engineering.

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7.2. Abstract

The European Regulation (EU) 1143/2014 on Invasive Alien Species entered into force in 2015, with the aim to fulfill regional and international biodiversity goals in a concerted manner. To date, the Regulation listed 66 Invasive Alien Species (IAS) that are subject to legal controls. Only one of these is marine. A recent lionfish (*Pterois miles*) invasion has been closely monitored in the Mediterranean and a detailed risk assessment was made about the profound impacts that this invasive fish is likely to have on the fisheries and biodiversity of the region. In 2016-21, lionfish rapidly became dominant predators along Eastern Mediterranean coasts, yet the process for their inclusion on the EU IAS list has been lengthy and is ongoing. There is an urgent need to

learn from this experience. Here, we recommend improvements to the Regulation 1143/2014 and the risk assessment process to protect marine ecosystems and secure the jobs of people that rely on coastal resources.

7.3. Introduction

Globalization and intensification of human activities are driving an accelerating number of non-indigenous species (NIS, also known as alien, exotic, introduced, or non-native species) to areas beyond their natural ranges, reshaping local communities and altering ecosystem services (Simberloff *et al.*, 2013; Seebens *et al.*, 2017). A subset of NIS, known as invasive alien species (IAS), have harmful impacts on the economy, environment, and health of the recipient ecosystem (IUCN, 2000). They are one of the primary threats to global biodiversity and human livelihoods (MEA, 2005; Brondizio *et al.*, 2019). Europe is heavily affected by NIS with over 13,000 alien or cryptogenic taxa currently reported in the European Alien Species Information Network (Katsanevakis *et al.*, 2015; *EASIN*, 2021). Quantitative simulations on future trajectories until 2050, have projected that Europe will face the highest continental increases (+2,543 ± 237) of established NIS (Seebens *et al.*, 2020). Even moderate increases are expected to cause major impacts on most socioecological contexts and these can be mitigated only if rapid and comprehensive actions are taken (Essl *et al.*, 2020).

As invasive species are numerous, it would be impossible to adopt dedicated measures against all. In 2014, Europe adopted an innovative and ambitious legislation on IAS (EU Regulation no.1143/2014; hereafter: IAS Regulation) that represents a major advance towards a coordinated and harmonized procedure for IAS management (EC, 2014). The IAS Regulation came into force in 2015 to fulfill international and regional legislation such as the Action 16 of Target 5 of the EU 2020 Biodiversity Strategy, and the Aichi Target 9 of the Strategic Plan for Biodiversity 2011-2020 under the

Convention of Biological Diversity. Its importance is highlighted in the EU Biodiversity Strategy for 2030, which states that the IAS Regulation must be stepped up "to minimize, and where possible eliminate, the introduction and establishment of alien species in the EU environment" (EC, 2020).

At the core of this legislation, the list of IAS of Union concern ("the Union list") identifies species whose adverse impact requires concerted action at a Union level. The need for concerted action must be demonstrated through a detailed risk assessment (Article 5.1), while socio-economic aspects to ensure that disproportionate or excessive costs will be avoided need to also be considered. Species that are included in the Union list are subject to stringent provisions for prevention, early detection and rapid eradication, and management. The import, transit within the Union, trade, possession, breeding, transport, use, and release into the environment are restricted (Article 7). European member states are obliged to identify the pathways which require priority action for the IAS of Union concern and then establish and implement at least a single action plan to address those pathways (Article 13). Moreover, member states are obliged to establish a surveillance system for the IAS of concern (Article 14), immediately attempt eradication at an early stage of their invasion (Article 17), or place effective management measures to minimize the spread and impacts of already established IAS (Article 19).

The IAS Regulation departed from traditional approaches and set a precautionary, yet challenging approach towards IAS management (Justo-Hanani & Dayan, 2020). The first years of its implementation offered critical insights and opportunities for improvement. A noteworthy case is the disproportionately low presence of marine species on the Union list, which does not fully acknowledge or address the threat they pose to the EU marine environment (Tsiamis *et al.*, 2020). European Seas host the highest number of NIS worldwide with over 800 taxa considered as established

(Tsiamis *et al.*, 2018). The majority of these NIS are found in the Mediterranean Sea where they are spreading rapidly while indigenous species are declining; thus impairing the function, structure, and integrity of the marine ecosystems (Edelist *et al.*, 2013; Zenetos *et al.*, 2017; Corrales *et al.*, 2018; Azzurro *et al.*, 2019b). In the eastern Mediterranean, NIS together with climate change are driving biodiversity collapse (Albano *et al.*, 2021). However, only one marine species, *Plotosus lineatus* (Thunberg, 1787) is currently included on the IAS Union list (Tsiamis *et al.*, 2020), which includes 66 terrestrial and freshwater NIS (EC/2019/1262).

A marine species currently under consideration by the EU for inclusion on the Union list is the lionfish, *Pterois miles* (Bennett, 1828), first reported in the Mediterranean Sea in 2012 from Lebanon (Bariche *et al.*, 2013) after an unsuccessful invasion attempt in 1991 (Golani & Sonin, 1992). Lionfish quickly became established in the Levantine (Jimenez *et al.*, 2016; Kletou *et al.*, 2016) and spread towards the central Mediterranean (Azzurro *et al.*, 2017; Dimitriadis *et al.*, 2020), demonstrating one of the fastest fish invasions ever reported in the region. The species was already involved in a major invasion of tropical and subtropical habitats in the Western Atlantic basin (Hixon *et al.*, 2016). Due to its documented invasion history, an EU horizon-scanning exercise concerning new or emerging species ranked lionfish as second on a list of 95 species that should be prioritized for risk assessment (Roy *et al.*, 2015).

To respond swiftly to this invasion of the Mediterranean Sea, the European Union funded the RELIONMED project, through the EU Commission's LIFE programme 2014-2020 (LIFE16 NAT/CY/000832) that aimed to make Cyprus the first line of defense against the invasion (Kleitou *et al.*, 2019c). The project aims to address the invasion at an early stage, collect the necessary data, and guide concerted actions against the lionfish (*P. miles*) management in the basin by adding the species to the Union list.

In this document, we (1) present the RELIONMED efforts to collect early-invasion data and propose lionfish *Pterois miles* for inclusion to the Union list, 2) document lessons learnt from this effort, and (3) provide recommendations on the basic IAS Regulation and the Delegated Regulation on risk assessments 2018/968 that could be applied to improve relevance, coverage, effectiveness and management of marine IAS at a European and regional level.

7.4. The Lionfish (*Pterois miles*) Invasion History

The native range of *Pterois miles* (Figure 7.1) is restricted to the Indian Ocean, specifically from the Red Sea all the way down to eastern South Africa, including the Arabian Sea, Persian Gulf, Gulf of Oman, Laccadive Sea, Bay of Bengal, Andaman Sea and Indonesian region (Kulbicki *et al.*, 2012). Around Indonesia, *P. miles* population overlaps with the congeneric *P. volitans* and *P. russelii*. *Pterois miles* and *P. volitans* (known as lionfish complex) invaded the north-western Atlantic in late 1980s and expanded throughout the region, northwards along the east coast of the USA reaching as far as Rhode Island, eastwards to Bermuda, and southwards throughout the Gulf of Mexico, Central America, South America, Caribbean and Brazil (Morris & Whitfield, 2009; Goodbody-Gringley *et al.*, 2019). Several biological and ecological traits have contributed to their invasion success including, an opportunistic predator and generalist diet (Eddy *et al.*, 2016; Peake *et al.*, 2018), anatomical and physiological traits that optimize its feeding strategy (Green *et al.*, 2019; Rojas-Vélez *et al.*, 2019), defensive venomous spines (Galloway & Porter, 2019), rapid maturity (Fogg *et al.*, 2017), iteroparous, broadcast and highly fecund spawning (Morris & Whitfield, 2009), and a pelagic larval phase that allows dispersion of larvae across great distances for about 20-35 days (Ahrenholz & Morris, 2010).

Despite having intermediate consumption rates, the higher densities and catch efficiency of lionfish has resulted in high impacts to the local biodiversity (DeRoy *et al.*, 2020). Numerous studies from the Western Atlantic have demonstrated that an increase in lionfish abundance can lead to a significant decline in the recruitment, biomass, and abundance of local fish species (Albins & Hixon, 2008; Green *et al.*, 2012; Côté *et al.*, 2013a; Benkwitt, 2015; Ingeman, 2016); with the impacts felt at a regional level (Ballew *et al.*, 2016). At some invaded sites there have been reports of up to 95% reduction in abundance of small native species (Côté *et al.*, 2013a). Apart from direct impacts on local fish communities, lionfish were found capable to drive an overall shift in invertebrate assemblage composition, (Layman *et al.*, 2014) and shift sites to algal-dominated habitats through predation on herbivorous reef fishes (Lesser & Slattery, 2011; Slattery & Lesser, 2014; Kindinger & Albins, 2017). Using an ecological model that uses prey consumption and biomass production, Green *et al.* (2014) suggested that predation effects of lionfish are nonlinear but begin to occur beyond a particular threshold of predation mortality; thus impacts on communities with high biomass are unlikely under low lionfish densities.

Figure 7.1. A lionfish (*Pterois miles*) individual photographed at the reefs of the Kavo Gkreko (Cyprus) Marine Protected Area in May 2019

7.5. Proposal of Lionfish for Inclusion to the Union List

7.5.1. Data collection and species proposal

The RELIONMED proposal was submitted on September 2016, when lionfish populations were still limited and restricted to the eastern Mediterranean. In 2017, the four-year project was accepted for funding and successfully initiated on September 2017. The early project actions aimed to cover the elements of the risk assessment as specified in the Article 5(1) of the IAS Regulation and the delegated Regulation (EU) 2018/968. These elements include organism information, native and alien distribution, pathways and probability of introduction, probability of establishment and spread under present and future climatic conditions, and magnitude of impacts (on biodiversity, ecosystems, ecosystem services, socio-economy and human health).

Under the RELIONMED project actions, lionfish specimens were collected and examined; taxonomic identity and pathway of introduction were studied using molecular analyses; growth rates were estimated based on otoliths; reproduction was investigated by studying gonads and; foraging behavior and potential impacts to local biota were analysed through stomach contents examination (More details on the methodologies can be found in Dimitriou *et al.*, 2019; Savva *et al.*, 2020).The introduction patterns of lionfish under different environmental conditions were analysed using observations by citizen-scientists (Kleitou *et al.*, 2019c; Savva *et al.*, 2020), while questionnaire surveys were conducted targeting the general public and stakeholders to elucidate known uses of lionfish in the market, as well as perceptions and knowledge about the invasion (Kleitou *et al.*, 2019d). To cover information on the risk management (Article 4(3)(e) and Article 4(6)), the efficiency of targeted lionfish removals was monitored through ecological and socioeconomic surveys to assess the costs of removals relative to the cost of inaction from social and economic points of view.

Results of the project were compiled with data from the literature to produce a comprehensive risk assessment together with evidence for the cost-effectiveness of the species management. The scoring and classification for the risk assessment evaluations were based on a combination of protocols as suggested by the EU (Appendix 4A). Possible measures to manage the lionfish invasion in the Mediterranean Sea were identified for (i) prevention, (ii) eradication, and (iii) long term control. Both documents were peer-reviewed by two independent scientists before submission to the EC in February 2019. Following review by the Scientific Forum of the EU and comments by stakeholders, a revised risk assessment was submitted in 2020. The submissions were deemed by the Scientific Forum as robust and fit-for-purpose in November 2020, and the species inclusion will be brought for discussion to the IAS Committee with a view to be screened against the criteria of Article 4(3), with due consideration to Article 4(6) in June 2021.

7.6. Results of the lionfish Risk and Management Assessments

The results of this effort have confirmed the imminent threats of the lionfish invasion in the Mediterranean, and identified potential management measures that could be applied to limit the potential damages.

The risk assessment concluded with high confidence that there is a high degree of risk (social, ecological and economic) associated with the future spread of lionfish in the Mediterranean and the European Union. Most notably, in the years from the first sighting to submission of the risk assessment, lionfish were able to rapidly spread and establish in the entire Levantine Sea, southern and central Aegean Sea, Greek Ionian Sea, and reach Tunisia and Italy (Kletou *et al.*, 2016; Azzurro *et al.*, 2017; Giovos *et al.*, 2018b; Dimitriadis *et al.*, 2020). This demonstrates one of the fastest fish invasions ever reported in the eastern Mediterranean Sea (Poursanidis *et al.*, 2020) (Figure 7.2; Figure 7.3; Appendix 4B). The reported lionfish sightings by citizen scientists (sea users, divers, fishers, etc.) of count (number of reports) and density observed (number of lionfish) have increased substantially over these years; from 1-3 individuals to over 50 observed in a single day (Figure 7.2; Figure 7.3; Appendix 4B). Indicatively, over 300 lionfish were removed from three single-day eradication events in 2019-2020 from small areas (about two hectares) within Cyprus Marine Protected Areas (RELIONMED data).

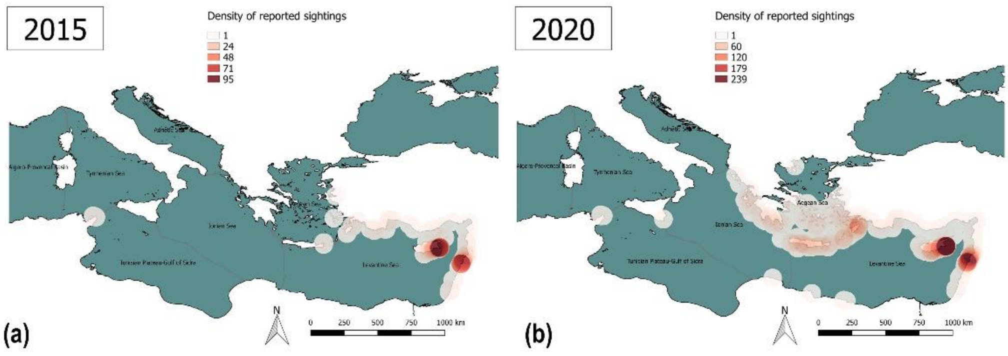

Figure 7.2. Heat map of the density of the reported lionfish sightings in the literature and authors' datasets (radius = 70 km) in (a) 2015 and (b) 2020 (the dataset is available in Appendix 4B).

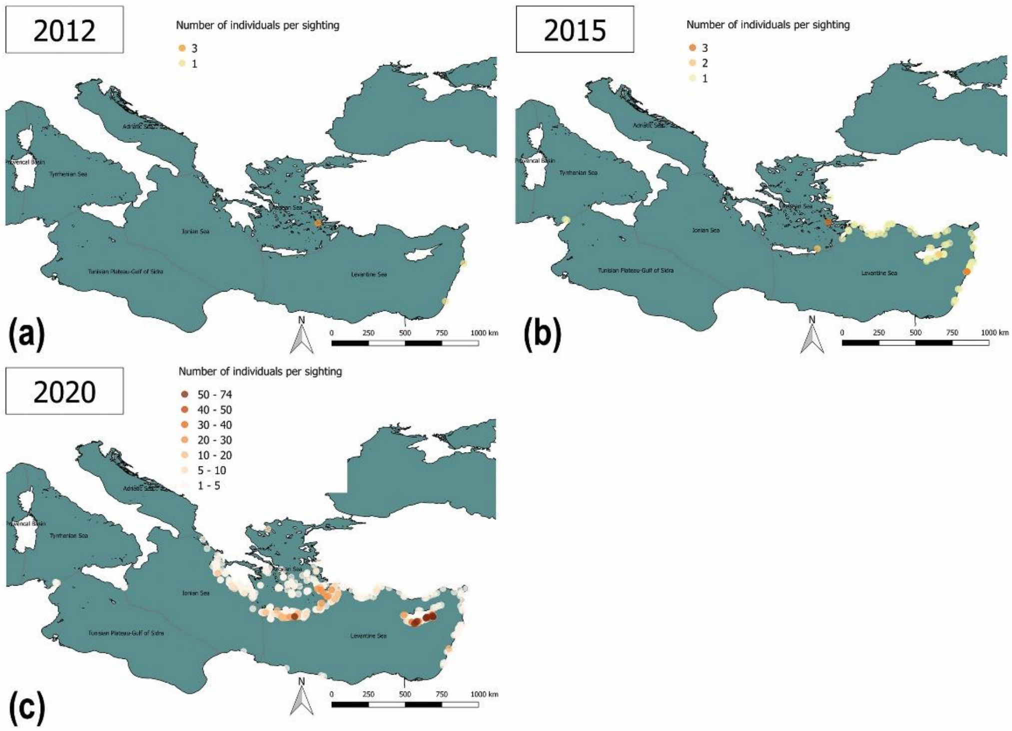

Figure 7.3. Number of individuals observed per sighting for (a) 2012, (b) 2015, and (c) 2015. The dataset is available in Appendix 4B).

In the Mediterranean, lionfish are mostly found on rocky substrata, followed by seagrass (*Posidonia oceanica*) meadows (Savva *et al.*, 2020), and they are also able to occupy deep-water habitats (Jimenez *et al.*, 2019) including *Dendrophyllia ramea* coral communities at 130-150 m depth (Orejas *et al.*, 2019). The biological studies conducted in the Mediterranean have shown that lionfish have characteristics that are typical of invasive success such as early maturity, rapid growth rates, generalist predation behavior, lack of natural predators, and naïve prey (Zannaki *et al.*, 2019; Agostino *et al.*, 2020; Savva *et al.*, 2020; Crocetta *et al.*, 2021).

The most relevant introduction pathways that were identified were (a) Corridor (Interconnected waterways/basins/seas - Suez Canal), (b) Release in nature (other intentional release – aquarium hobbyist), (c) Transport - Stowaway (Ship/boat ballast water). The Suez Canal, as confirmed by genetic studies, is the major pathway of lionfish introduction in the Mediterranean Sea (Bariche *et al.*, 2017; Stern *et al.*, 2019; Dimitriadis *et al.*, 2020). Natural dispersal of lionfish has been identified as the major pathway of spread within the Mediterranean, but other introduction pathways could enhance its genetic diversity and also facilitate its spread.

There is uncertainty about how far the species will spread under current and projected climate change. Species Distribution Models (SDMs) have been inaccurate in predicting lionfish Mediterranean hotspot areas (e.g. Poursanidis, 2016), likely due to climatic niche expansion (i.e. the environmental shift of species beyond their climatic limits in their native ranges) and the presence of a favorable climate in the invaded domain not yet occupied by the species (Parravicini *et al.*, 2015; Poursanidis *et al.*, 2020). Assessments of the future spread and impact of lionfish in the Mediterranean were conducted in two ways: (a) a conservative approach, based on an ensemble of Species Distribution Models, projected that lionfish will remain restricted to the eastern Mediterranean under projected climate change scenarios (D'Amen & Azzurro, 2020; Poursanidis *et al.*, 2020), and (b) assuming that lionfish are only limited by the winter isotherm of 15°C, as is the case in North Carolina (USA) (Whitfield *et al.*, 2014; Dimitriadis *et al.*, 2020). Using the latter method, lionfish were expected to spread to the western Mediterranean Sea and southern Iberian coast under current climatic conditions, and towards the Adriatic Sea, Bay of Biscay, and Macaronesia, according with the predicted climate change (Representative Concentration Pathway scenario 6.0) (see Ch2. in Appendix 4A).

The magnitude of impacts on biodiversity, ecosystem services, economy, and human health are thought to be 'major' to 'massive' but with medium confidence in the evidence used to underpin the assessment. Despite certainty about the impacts of lionfish on ecology, economy and human wellbeing in the Western Atlantic (Albins & Hixon, 2008; Lesser & Slattery, 2011; Green *et al.*, 2012; Côté *et al.*, 2013a; Layman *et al.*, 2014; Slattery & Lesser, 2014; Benkwitt, 2015; Ingeman, 2016; Kindinger & Albins, 2017), limited information was available about the effects of the invasion in the Mediterranean Sea. Therefore, most assessments about the potential impacts of lionfish at the European scale were scored with low confidence (Figure 7.4; Section 'Magnitude of Impact' in Appendix 4A). The assessments anticipate that lionfish impacts exacerbate under climate change scenarios (Appendix 4A).

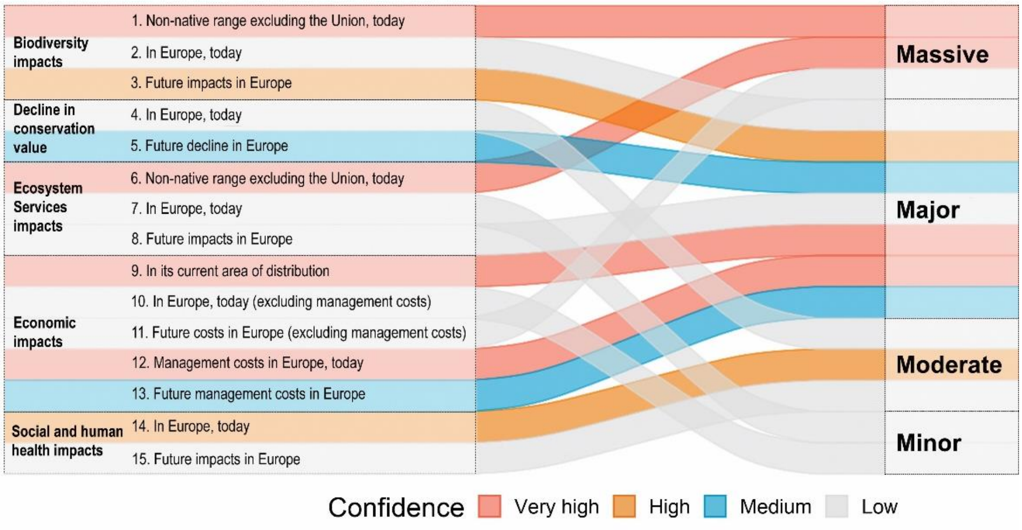

Figure 7.4. Assessment of lionfish current and future impacts on (i) biodiversity (at all levels of organisation, e.g. decline in native species, changes in native species communities, hybridisation), (ii) conservation value with regard to European and national nature conservation legislation, (iii) economy, (iv) ecosystem services

(provisioning, regulating, and cultural services), and (v) society and human health, using the evaluation scheme shown in Appendix 4A.

Options for Risk Management (Appendix 4C) identified three prevention, three eradication, and seven management measures that could be used to limit the ecological and socioeconomic losses caused by the lionfish invasion in the Mediterranean (Appendix 4C). The application of prevention measures could limit the genetic diversity of lionfish in the Mediterranean and prevent facilitation of lionfish spread within the region; thus they were promoted where cost-effective. Since the invasion is already well underway, eradication measures will have little success and could focus only in areas where lionfish are at a very early stage of invasion, and populations are still very limited. As regards to management/control measures, it was shown that diver-led culling can be effective to control lionfish in priority areas; however, legislative framework changes would be needed to allow removal events though scuba diving. Citizen science monitoring, dissemination of science-based knowledge, and market promotion of the lionfish were all found to be low-cost actions with a great potential for managing the lionfish invasion and they would deserve to be supported and properly coordinated at the regional or sub-regional level. Moreover, the implementation of these actions would offer important benefits (e.g. engagement of local communities, regular monitoring and adaptive management) for dealing with other invasive species too. New removal/fishery techniques such as lionfish specific traps (Harris *et al.*, 2020) and underwater robotics (Sutherland *et al.*, 2017) hold potential but need development and testing in Europe and potentially legislation changes to enable their use. Fishery reforms that could be used to tackle lionfish and other marine species in the Mediterranean were elaborated by Kleitou *et al.* (2021a).

The full risk assessment and risk management documents can be found in Appendix 4A and Appendix 4C, respectively.

7.7. Insights and Recommendations for the IAS Regulation

The process undertaken for the inclusion of lionfish on the Union list extracted many insights and highlighted limitations of the IAS Regulation, particularly with respect to marine species, justifying the disproportionately low presence of marine species in the list of IAS of Union concern (Tsiamis *et al.*, 2020). These include the need to demonstrate the threat in the absence of sufficient ecological and socioeconomic data, limited involvement by non-member states, unchallenged primary pathways of invasion (mainly through the Suez Canal), lengthy evaluation processes, and need for adaptive management of marine species (Table 7.1). Identifying the limitations in these first years of the IAS Regulation implementation are crucial towards an improved Post-2020 framework on IAS. In Table 1, we summarize the major challenges and recommendations that could be used to improve and streamline the EU legislation against IAS, and we discuss each point further below.

Table 7.1. Overview of challenges identified from the lionfish invasion in the Mediterranean and recommendations to improve EU Regulation and implementation against marine IAS.

Challenge	**Recommendation(s)**
Specificities of the marine environment, contradictory priorities and insufficient proactive action	(i) Horizon scanning exercises (ii) Pre-defined rapid response plans on the basis of species traits and initial spread patterns
Lack of information and absence of effective surveillance systems	(i) A more strategic and coherent monitoring in NIS hotspot areas (ii) Stationary monitoring stations and long-term ecological and socioeconomic data collection
Inadequate involvement of non EU Member States in prevention and control measures	(i) Synergies with established regional legally binding instruments (ii) Common strategies, protocols, and management activities
Adaptive management measures are needed	(i) Dead specimens of IAS of Union concern to be allowed (and promoted) in the food market in order to incentivize targeted fishery
Evaluation processes are slow	(i) All the steps of the invasive species evaluation for inclusion in the Union list need to be shorter in duration (ii) Peer-review to be conducted with strict deadlines or even not required in cases where risk assessments are conducted by more than three authors and at least two independent affiliations (iii) Use of the Article 11 provisions of the IAS Regulation for faster and regional response

7.7.1. *Specificities of the marine environment, contradictory priorities and insufficient proactive action*

The IAS Regulation encompasses all taxonomic groups and habitats within a single instrument, which does not acknowledge, nor address the fundamental differences between terrestrial and marine systems. Measures on banning sales and border controls on imported goods and travelers, while crucial for preventing terrestrial invasions (particularly traded plans and animals), and while indeed recognized as a key strength of the IAS Regulation, are meaningless for the marine environment. Importantly, the transport of organisms in the connective aquatic medium by the convective forces of ocean currents significantly surpasses, in magnitude and rate, the potential for propagule dispersal in terrestrial ecosystems (Carr *et al.*, 2003; Kinlan & Gaines, 2003). Indicatively, lionfish larvae are able to disperse across great distances for about 20-35 days before they settle to benthic habitats (Ahrenholz & Morris, 2010). Habitat corridors, natural barriers and discontinuities have little effect on marine organisms compared to their terrestrial counterparts, especially on those with a pelagic or biphasic life cycle (Carr *et al.*, 2003; Burgess *et al.*, 2016).

From an applied perspective, higher dispersal capacity increases the speed of changes, decreases the time available for rapid management response, and challenges the effectiveness of long-term management, necessitating faster reaction and stronger cross-border cooperation. Eradication of marine invasive species has rarely been achieved and only in restricted areas following early detection and rapid response (e.g. Willan *et al.*, 2000; Anderson, 2005).

The IAS Regulation acknowledges that prevention is more environmentally desirable and cost-effective than reaction after the introduction of an IAS, and should therefore be prioritized. Accordingly, priority is given to species that are not yet present in the Union or are at an early stage of invasion. Indeed, the control of marine invasive species is more likely to succeed if a species detection and management response is fast (Katsanevakis *et al.*, 2020a). However, IAS can be listed in the Union list only if they meet the criteria mentioned in Article 4 (Paragraph 3), including that “they are, based on available scientific evidence, likely to have a significant adverse impact on biodiversity or the related ecosystem services, and may also have an adverse impact on human health or the economy”, and that “it is likely that the inclusion on the Union list will effectively prevent, minimise or mitigate their adverse impact”. “An IAS should be considered to be of Union concern if the damage that it causes in affected Member States is so significant that it justifies the adoption of dedicated measures applicable across the Union.”

The criteria of the IAS Regulation can be viewed as contradictory to a proactive approach where prevention and/or early eradication are prioritized. They are compatible with a reactive approach, where countries need to first recognize the threats and show evidence that IAS policy can be turned into management actions (Early *et al.*, 2016). By the time that sufficient data are available to assess the potential impacts, marine species, as exemplified by the lionfish, can spread over a vast area, making eradication unfeasible and management attempts disproportionately costly (Kleitou *et al.*, 2019d; Booy *et al.*, 2020).

Horizon scanning exercises, to keep a continuous overview of IAS, along with rapid on-demand site-based assessments for a specific purpose (e.g. an IAS sighting), are useful in prioritizing species and guiding proactive measures (Peyton *et al.*, 2019; Peyton *et al.*, 2020; Tsiamis *et al.*, 2020). To further support rapid response after early detection, an improved IAS Regulation would necessitate pre-defined rapid response plans by member states, on the basis of species traits and initial spread patterns (see e.g. Giakoumi *et al.*, 2019a). This would allow rapid decision making on the appropriate actions for eradication immediately after detection, without the need of time-consuming species-specific evaluations. The rapid response plans will allow to identify where, how, on what, and when we should act, and first prioritize management actions rapidly at an early stage than can potentially control the population, and thus increase the likelihood of success (Kinlan & Gaines, 2003).

7.7.2. Lack of information and absence of effective surveillance systems

Despite the focus given to the Mediterranean Sea, as the most invaded marine region worldwide (Tsiamis *et al.*, 2018), there is still lack of standardized and harmonized monitoring throughout the basin (Boon *et al.*, 2020) and substantial knowledge gaps for marine invasions (Roy *et al.*, 2019). Information on marine species distributions, ecology, and evolution is often fragmented or non-existent (Bonanno & Orlando-Bonaca, 2019; Rilov *et al.*, 2019). The Delegated Regulation on risk assessments (EC/2018/968) acknowledges the possibility of incomplete knowledge about a species, and the need for risk assessments to "be able to account for such lack of knowledge and information and address the high degree of uncertainty as regards the consequences of an introduction or spread of the relevant species". Indeed, the knowledge gaps on the lionfish establishment, spread, and impacts were notable, albeit the coordinated effort for rapid data collection.

The IAS Regulation highlights the importance of surveillance systems for the IAS. Specifically, it states that, "surveillance systems offer the most appropriate means for early detection of new invasive alien species and for the determination of the distribution of already established species". In addition, Member States are obliged to establish a surveillance system of IAS of Union concern, or include it in their existing system, which collects and records data for IAS or other species (Article 14 of the IAS Regulation). According to the Article 19, the surveillance system should also be designed to monitor the efficiency of management interventions in minimizing the impacts of an IAS, as well as their impacts on non-targeted species.

The absence of effective surveillance systems from the lionfish-invaded areas was identified as a major bottleneck through the process to compile the risk assessment. The development of a (i) joint instrument for data and information of alien species through the European Alien Species Information Network (EASIN) (Katsanevakis *et al.*, 2012a; Katsanevakis *et al.*, 2015), and the (ii) monitoring conducted by Member States in the context of the European Union's Marine Strategy Framework Directive (Tsiamis *et al.*, 2019) are useful for providing distribution data, but lack of standardization, harmonization, and duration to enable understanding of species impacts (Tsiamis *et al.*, 2019; Murillas-Maza *et al.*, 2020). The emergence of participatory initiatives (Azzurro *et al.*, 2019a; Azzurro *et al.*, 2019b) and citizen science have been found effective mostly in monitoring the distribution of NIS and for early detection, particularly for conspicuous taxa such as the lionfish (Crocetta *et al.*, 2015; Carballo-Cárdenas & Tobi, 2016; Giovos *et al.*, 2019; Kleitou *et al.*, 2019b; Encarnação *et al.*, 2020; Katsanevakis *et al.*, 2020b). Other survey methods have been found able to capture different and complementary views of an ecosystem (Kelly *et al.*, 2017; Aglieri *et al.*, 2020). To understand mechanisms underlying ecological patterns and impacts by NIS, a targeted and hypothesis-driven research strategy is needed (Dickinson *et al.*, 2010). Fragmented efforts by Member States, without coordination and strategic implementation, might lead to gathering futile data that cannot enhance the understanding of interactions at relevant ecosystem levels (Ward *et al.*, 1986; Wilding *et al.*, 2017).

A more strategic and coherent monitoring plan could be promoted by the EU to optimize data collection and facilitate transparent, auditable and timely decision-making. The value of time-series ecological and socioeconomic data has been emphasized in conservation policy (García-Barón *et al.*, 2020), but no data were available to rapidly elucidate the impacts of lionfish in the Mediterranean ecosystems. Long-term data before and after the invasion could potentially enable a better understanding of the changes caused by the invasive species, together with well-designed comparisons between affected and unaffected sites. More EU effort can be strategically placed in areas where NIS are first recorded and by accounting dispersal and colonization processes, e.g. near NIS hotspots areas, in the Levant (e.g. Cyprus) which is the first area to be affected by Lessepsian immigrations, and in harbors and marinas for ship-mediated introductions.

7.7.3. Inadequate involvement of non EU Member States in prevention and control measures

The IAS Regulation highlights that "cross-border cooperation, particularly with neighbouring countries, should be fostered to contribute to its effective application". Article 22 of the IAS Regulation refers to the need for cooperation and coordination but only within the EU. Geopolitical borders do not affect the invasion of NIS and international cooperation is needed in management actions (Pyšek *et al.*, 2020; Rotter *et al.*, 2020). The Mediterranean Sea shares coastlines with 21 countries from which only seven are EU Member States. Isolative attempts from Member States to prevent introductions and/or manage IAS will likely be unsuccessful, particularly when dealing with species with high dispersal capacity.

The IAS Regulation obligates Member States to ban the intentional or negligent introduction of alive individuals of species of Union concern to avoid, as stated, situations where action taken in one Member State is undermined by inaction in another Member State. In addition, it requires all Member States to establish and implement one single action plan or a set of action plans to address the priority pathways of introductions. However, many IAS including lionfish, spread to the EU via secondary dispersal from non-EU Member States. The most important primary pathway for NIS introductions in the eastern Mediterranean is the Suez Canal in Egypt (Katsanevakis *et al.*, 2013). Propagule (e.g. larvae and eggs) pressure from neighbouring countries will persist in spite of the implementation of any IAS Regulation provisions at member state level. In our management assessment (Appendix 4C), we highlight the importance of cooperation and enforcement of biosecurity measures in the Suez Canal. This includes the installation of a high-salinity section in the Suez Canal, reinstating the former salinity barrier of the Bitter Lakes, and/or the establishment of locks that would additionally decrease current movements and dispersal of propagules drifting to the Mediterranean. Similarly, other legislation and effort, such as the ban from the market (aquarium) for species of Union concern or the legal framework to control translocations of non-native species in aquaculture (EC/708/2007), need to be promoted regionally (Galil *et al.*, 2015a; Galil *et al.*, 2017; Galil *et al.*, 2020).

The involvement of non-EU Member States could delay IAS establishment allowing more time for response, as well as enable a more consistent, multi-vector, and coordinated approach against IAS. Synergies with established, regional, legally binding instruments (e.g. Barcelona Convention and GFCM for the Mediterranean) can be promoted, voluntary codes of conduct can be implemented, and common strategies, protocols and management activities can be adopted at regional scales.

7.7.4. Adaptive management measures are needed

The IAS Regulation follows a hierarchy of management measures for prevention, early detection and rapid eradication, and lastly ongoing management. As demonstrated by the lionfish invasion, the level of quantitative data required for species to be placed in the Union list is barely available for marine species that are not already established and widespread. Therefore, measures for prevention and early response might not be adequate, and efforts are shifting to long-term management. For management measures, the IAS Regulation indicates that they shall be proportionate to the impact on the environment based on an analysis of costs and benefits. Raising public awareness and education, and encouragement of physical removal and commercial utilization have been recognized as few of the most low-cost but relatively effective management actions for marine IAS in the Mediterranean Sea (Giakoumi *et al.*, 2019a; Kleitou *et al.*, 2021a).

Article 7 of the IAS Regulation specifies that species of Union concern should not be intentionally placed on the market and that buying, selling, using, and exchanging the IAS shall be prohibited. The IAS Regulation needs to be adapted for dead specimens to be allowed (and promoted) in the food market in order to incentivize a targeted fishery and hence continuous removal from the natural environment (Kleitou *et al.*, 2019d; Kleitou *et al.*, 2021a). Time consuming and costly processes, and preconditions associated with derogations from the fishery market/trading restrictions of marine species (e.g. that species are widespread, inclusion of measures in member states management plan, obligations for monitoring and control of market) could be avoided to enable early and sustainable fishery pressure to IAS populations (Kleitou *et al.*, 2021a).

7.7.5. Faster evaluation processes are needed

The data collection, analyses of evidence, and the proposal of species to the Union list took years allowing lionfish populations to expand substantially (Figure 7.3). All the steps of the invasive species evaluation need to be shorter in duration for any rapid response to be possible. To achieve this, the Scientific Forum and stakeholders can deliver their opinions faster (e.g. a month rather than four months as experienced in our lionfish Risk Assessment), and examine the proposals for marine species more often thus allowing prompt (re-)submissions and minimizing the duration from the first sighting to the evaluation of the risk assessment. In addition, the Scientific Forum's final decision could be closer in date to the evaluation by the committee of representatives of the Member States. In the case of the recent lionfish risk assessment, significant time and an annual deadline of the Commission was misseddue to the need for peer-revision of the 129-page-long risk assessment. According to the Article 2 of the Delegated Regulation (EC/2018/968), a quality control process shall include at least a review of the risk assessment by two peer reviewers, and the author(s) of the risk assessment as well as the peer reviewers must be independent and have relevant scientific expertise, and not affiliated to the same institution. To limit costs, logistical difficulties and delays, we suggest peer-review to be conducted with strict deadlines or even not required in cases where risk assessments are conducted by more than three authors, at least two independent affiliations, and represented by two different Member States.

An alternative approach to avoid lengthy risk assessment processes for adding IAS to the Union list as well as Article 7 (market) restrictions would be the use of the Article 11 provisions of the IAS Regulation. Article 11 allows member states to identify from the national list of IAS, species that require enhanced regional cooperation and establish provisional measures (e.g. Articles 13, 14, 16, 17, 19, 20) with the support of the European Commission. The procedure is also linked to Article 22, which encourages cooperation/coordination among member states that share marine sub-regions, regarding marine species and may be enhanced through implementing acts. Although not used by any member state yet, Article 11 could offer an alternative, faster regional response and could be further promoted by the European Commission and member states.

7.8. Conclusions

The EU Invasive Alien Species Regulation is the core legislation for IAS management in Europe, and its importance is highlighted in the EU Biodiversity Strategy for 2030. However, marine species are under-represented despite posing a major socioeconomic and environmental threat in the region. Using the case of a current lionfish invasion in the Mediterranean Sea, we highlight some clear limitations of the basic Regulation 1143/2014 as well as the Delegated Regulation 2018/968 to manage the issue of marine bioinvasions in the Mediterranean region. The main issues originate from the intrinsic differences between terrestrial and marine systems, and the low consideration of marine bioinvasions in these regulations. This work identified and proposed several measures for improvement of the EU legislation.

The high connectivity of marine ecosystems necessitates a rapid approach. A lack of available information (both ecological and socioeconomic) emphasized the need for strategic, coordinated, and improved monitoring in sentinel locations of Europe. Efforts in the European marine sub-regions could be easily undermined by a lack of support from non member states, and their cooperation is even more important and should be further facilitated. It is in the best interests of the EU to proactively promote biosecurity in the Suez Canal, to work with Egypt and the international maritime industry, and address this fundamental threat to the Mediterranean socio-ecological system. Given the difficulties in eradicating established marine invasive species, adaptive management efforts should aim to promote public awareness and education, to incentivize targeted fisheries, and to promote continuous removal from the natural environment (Kleitou *et al.*, 2021a).

8. Chapter 6: Fishery Reforms for the Management of Non-Indigenous Species

8.1. Author contributions

P.K. conceptualized and designed the study with contribution from S.R. and I.G. All authors helped in refining its methodology and objectives. S.R. and J.M.H. supervised the study. P.K. wrote the manuscript and all authors contributed critically to the drafts and gave final approval for publication. This manuscript is published in the Journal of Environmental Management.

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8.2. Abstract

Marine ecosystems are undergoing major transformations due to the establishment and spread of Non-Indigenous Species (NIS). Some of these organisms have adverse effects, for example by reducing biodiversity and causing ecosystem shifts. Others have upsides, such as benefits to fisheries or replacing lost ecological functions and strengthening biogenic complexity. Stopping the spread of NIS is virtually impossible and so the societal challenge is how to limit the socioeconomic, health, and ecological risks, and sustainably exploit the benefits provided by these organisms. We propose a move away from the notion that NIS have only negative effects and suggest a turn towards an Ecosystem-Based Fishery Management approach for NIS (EBFM-NIS) in the Mediterranean Sea, the world's most invaded marine region. A structured, iterative, and adaptive framework that considers the range of costs and benefits to ecosystems, ecosystem services, and fisheries is set out to determine whether NIS stocks should be managed using sustainable or unsustainable exploitation. We propose fishery reforms such as multiannual plans, annual catch limits, technical measures for sustainable exploitation, and legitimization of unlimited fishing of selected NIS and introduction of a radical new license for NIS fishing for unsustainable exploitation. Depending on local conditions, investment strategies can be included within the EBFM-NIS framework to protect / enhance natural assets to improve ecosystem resilience against NIS, as well as fishery assets to improve the performance of NIS fisheries. Examples of the former include the enhancement of Marine Protected Areas, harvesting of invasive NIS within MPAs, and protection of overfished predators and key species. Examples of the latter

include market promotion and valorisation of NIS products, development of novel NIS products, and innovative/alternative NIS fishing such as fishery-related tourism (‘pescatourism’). The application of the suggested EBFM-NIS would create jobs, protect and enhance ecosystem services, and help to meet the United Nations Sustainable Development Goal 14: Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.

8.3. Introduction

Non-indigenous species (NIS, also known as alien, exotic, introduced, or non-native species) are species introduced outside of their natural past or present range, and outside of their natural dispersal potential (Pyšek *et al.*, 2009). The introduction and establishment of NIS is recognised as one of the major elements of ongoing anthropogenic global environmental change (Cassey *et al.*, 2018) and their number is increasing worldwide (Seebens *et al.*, 2017). Moderate increases in introductions of NIS are expected to cause major impacts on biodiversity in most global socioecological contexts (Essl *et al.*, 2020).

The Mediterranean Sea is a biodiversity hotspot containing ~7% of the known world marine biodiversity with many endemic and iconic species (Boudouresque, 2004; Coll *et al.*, 2010). This richness has offered valuable ecosystem services and supported human wellbeing for millennia (Theodoropoulou, 2019). However, the Mediterranean Sea is threatened by an intensification of human activities and various additional pressures, such as overfishing, eutrophication, habitat loss and climate change, which are impairing the structure, integrity, and functioning of marine ecosystems in the region (Claudet & Fraschetti, 2010; Coll *et al.*, 2010; Lacoue-Labarthe *et al.*, 2016; Liquete *et al.*, 2016). Synergistic effects of these drivers, coupled with increased global marine trade and recent enlargement of the Suez Canal, have rapidly increased the influx of Non-Indigenous Species (NIS) and reshaped local biocommunities (Galil *et al.*, 2018a; Galil *et al.*, 2019).

Invasion of NIS has four main stages: (1) arrival, (2) establishment, (3) dispersal or spreading, and (4) impacts (Kolar & Lodge, 2001). Major pathways for the arrival of NIS in the Mediterranean Sea include 'transport-stowaway' (the transport of species attached to ships, boats, and marine structures) and 'interconnected waterways/basin/seas' (Suez Canal), followed by aquaculture and aquarium trade (Kalogirou, 2011; Katsanevakis *et al.,* 2013; Hulme, 2015; Gewing & Shenkar, 2017). Management policies designed to avoid NIS introductions have only recently started to become widely acknowledged and mandatory (Galil *et al.*, 2018a).

Important advances towards the control of pathways that allow marine species to cross bio-geographical barriers include a) the European Union (EU) Regulation 1143/2014 on the prevention and management of the introduction and spread of invasive NIS, b) the enforcement of the Convention for the Control and Management of Ships' Ballast Water and Sediments in 2017 (BWM Convention), and c) the EU Regulation 708/2007 concerning use of alien and locally absent species in aquaculture. Any regulatory measure on the Suez Canal relies on policy coordination between Mediterranean EU and non-EU countries (Galil *et al.*, 2018b). As this joint effort is failing to tackle the introduction of NIS, mainly of Indo-Pacific origin through the canal, and given that early eradication is usually unachievable, efforts in the Mediterranean Sea are mostly focussed on adaptive management, monitoring, and limiting the secondary spread of NIS populations (Giakoumi *et al.,* 2019a).

Controlling the spread of marine NIS poses a number of challenges, such as incomplete and inaccurate data about species biology and impacts, and lack of concerted action to effectively control propagule pressure (such as eggs and larvae) (Carboneras *et al.*, 2018; Galil *et al.*, 2018b). By the time that NIS impacts are identified, species are typically well-established making management measures costly and eradication impossible. For such reasons, and the fact that the European Commission suggests avoiding disproportionate or excessive costs associated with the application of management measures, Plotosus lineatus (Thunberg, 1787) is the only marine species included on the EU priority list which has 75 terrestrial NIS (EC/2019/1262) (Tsiamis *et al.*, 2020).

A complete halt of marine NIS spread in the Mediterranean Sea is impossible and many species are continuing to spread in the region. In eastern and southern areas of the Mediterranean Sea, tropicalization (an increasing dominance of warm-water species) is happening at a significantly faster rate than in other regions of the world (Last *et al.*, 2011; Cheung *et al.*, 2013), with warm-water species increasing in abundance and expanding northwards, while temperate species decline (Kalogirou *et al.*, 2012; Givan *et al.*, 2018; Azzurro *et al.*, 2019b). Climate change may further diminish large-sized native fish populations in the Mediterranean, some of which with commercial interest, while pelagic, thermophilic, and generally NIS of Indo-Pacific origin will be increasingly favoured (Moullec *et al.*, 2019). Many NIS lead to ecosystem shifts and reduce the biodiversity that underpins ecosystem services. However, other NIS can provide benefits to humans by introducing novelty, replacing lost ecological functions, adding redundancy that strengthens resilience, and providing ecosystem services (Chaffin *et al.*, 2016; Sfriso *et al.*, 2020) (Figure 8.1). In parallel, many NIS have become targets for local fisheries, often helping to stabilize local fisheries catch (Michailidis *et al.*, 2019; van Rijn *et al.*, 2019; Saygu *et al.*, 2020).

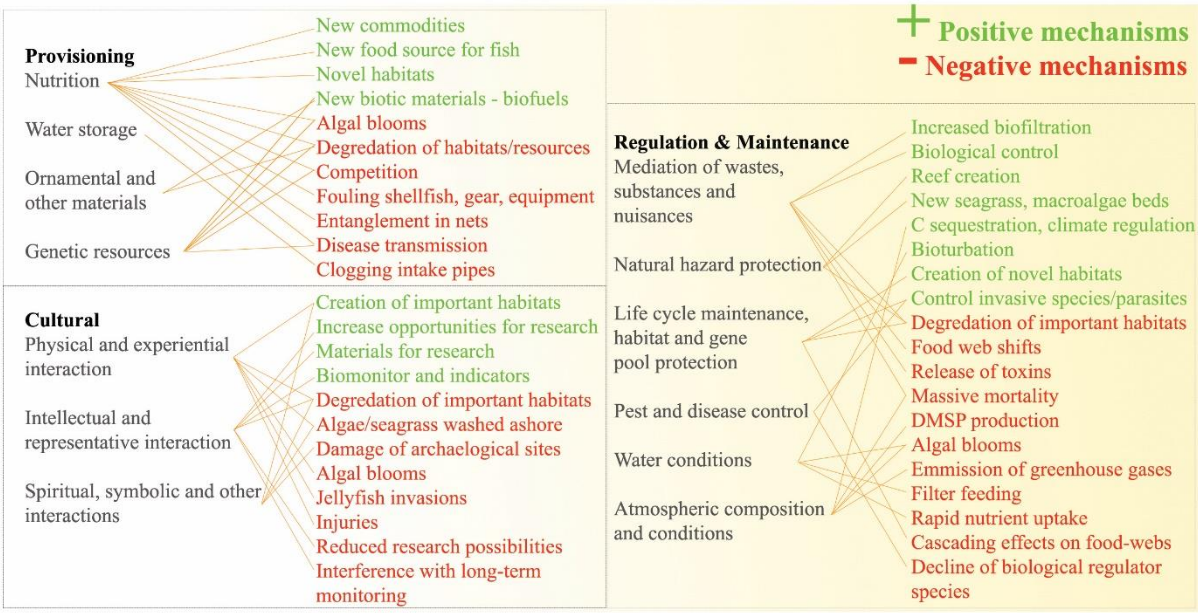

Figure 8.1. Main mechanisms through which marine Non-Indigenous Species (NIS) affect Ecosystem Services. Adapted from Katsanevakis *et al.* (2014b). Examples and details for each mechanism are presented in Katsanevakis *et al.* (2014b). For instance, NIS that cause algal blooms consume nutrients affecting ocean nourishment and consequently water conditions. Moreover, Dimethylsulfoniopropionate (DMSP) is produced by some marine algal NIS. DMSP can be enzymatically converted to the volatile dimethylsulphide (DMS) which could have a cooling effect on climate and help to compensate for warming from "greenhouse effect", but negative effects on air quality.

Society faces the considerable challenge of managing NIS to limit social and ecological damage as the Mediterranean Sea already has more than 600 of these species already established (Zenetos *et al.*, 2017; Giangrande *et al.*, 2020). Here, we suggest the application of a strategy where established NIS can become the target species of a fishery that is managed based on an ecosystem-based approach integrating ecological, economic, and social components.

8.4. Ecosystem-Based Fishery Management of Non-Indigenous Species

To date, NIS management has focused on single species monitoring and mitigation measures, an approach that does not consider the interactions of NIS within the ecosystem. This approach is problematic because it overlooks the fact that some of these species might provide useful ecosystem functions and that several Mediterranean fisheries have become dependent on economic returns from targeting NIS (Corrales *et al.*, 2018; Michailidis *et al.*, 2019).

Ecosystem-based fishery management (EBFM) was developed to move beyond single species management by incorporating ecosystem considerations such as habitat changes, bycatch, and ecosystem and human interactions (Pikitch *et al.*, 2004; Trochta *et al.*, 2018). Levin *et al.* (2018) define EBFM as "a holistic, place-based framework that seeks to sustain fisheries and other services that humans want and need by maintaining healthy, productive, and resilient fishery systems". Although there is no consensus on the best EBFM implementation and its wider adoption has been slow, EBFM is imperative for sustainable fisheries and livelihoods (Lloret *et al.*, 2018; Marshall *et al.*, 2018; Rees *et al.*, 2020).

In the case of NIS, the application of EBFM can help managers adapt current thinking and practices, and set clear goals and objectives. Not all NIS should be treated the same way, as some may have severe impacts, and others marked benefits. Given the interconnectivity of the Mediterranean, countries that surround this sea would benefit from having a consistent approach to the management of NIS. We propose the development of an Ecosystem Based Fisheries Management strategy for NIS (EBFM-NIS) for Mediterranean countries that will rely on a cost-benefit analysis to determine whether any fishery based on NIS should be managed as:

(i) an established ‘sustainable’ commercial activity, regulated with catch quotas (where appropriate) and gear restrictions to prevent pressure on local assemblages (Plan A);

(ii) in an ‘unsustainable’ manner, to facilitate overfishing of NIS populations (Plan B).

The EBFM-NIS strategy includes the local investment in capital assets (natural, physical, human, financial, and social capital) to increase the environmental and socioeconomic sustainability of NIS fisheries (Figure 8.2). The investment in capital assets should rely on a supplementary sustainability framework that accounts for the characteristics of each location.

We elaborate on the steps shown in Figure 8.2, including the decision-making process, and the implementation management measures that can be followed in a structured and iterative process by fostering social knowledge and learning through constant monitoring to improve human well-being and livelihoods (Allen & Garmestani, 2015).

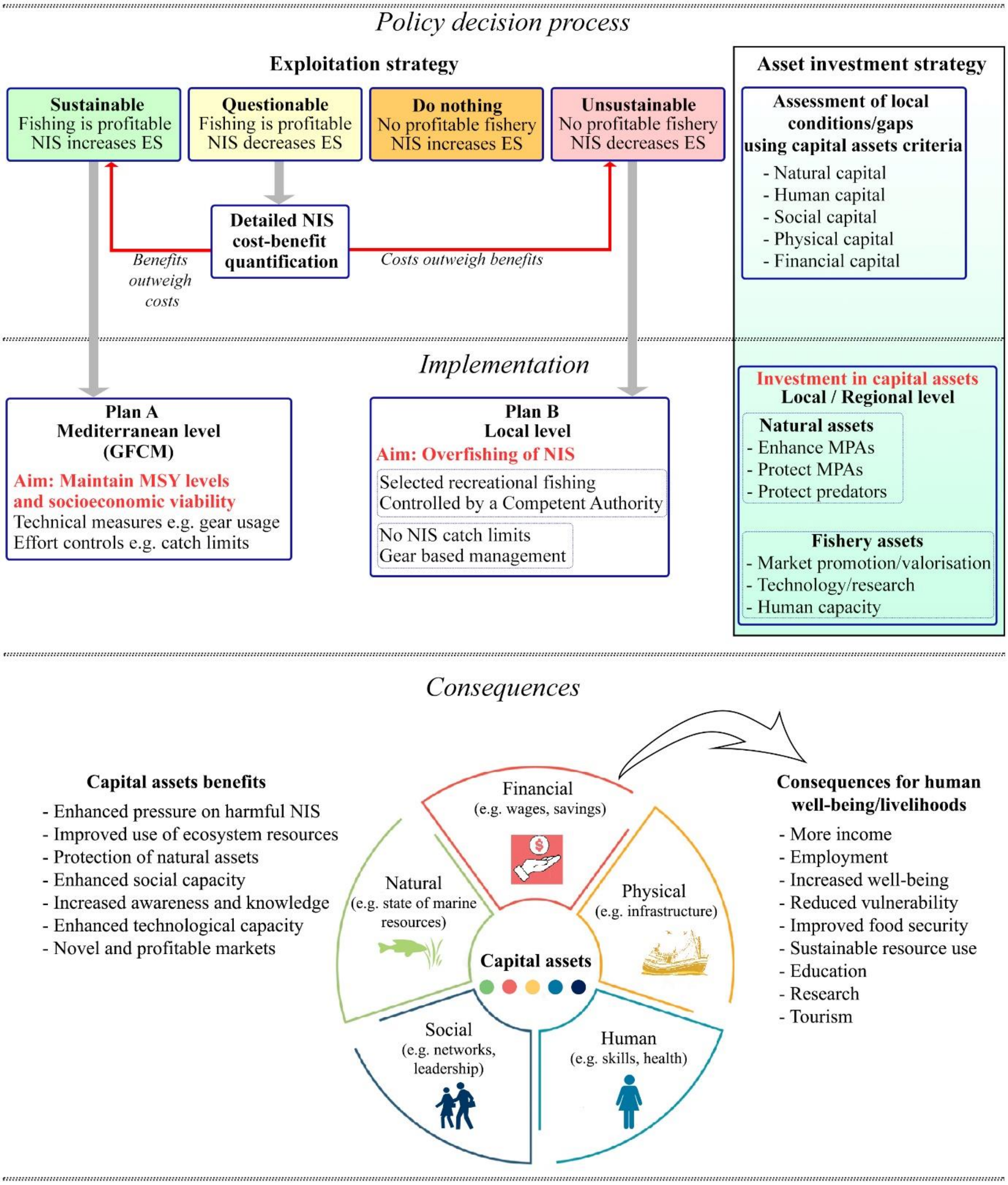

Figure 8.2. Proposed framework for Ecosystem Based Fishery Management of the Non-Indigenous Species (NIS) in the Mediterranean Sea (ES: Ecosystem Services, GFCM: General Fisheries Commission for the Mediterranean).

8.5. Policy decision – Guiding NIS fishery directions

The cost-benefit analysis of the EBFM-NIS should not only consider the environmental and human (social-cultural, economic, and institutional) dimensions from the fishery itself (hereafter referred as 'fishery performance') but should also look at the impacts of the NIS on the invaded environments. Any rare or recently established NIS may be excluded from consideration as their benefits and impacts will not be evident. Priority can be given to species which have been established for many years. Our proposed cost-benefit analysis includes a preliminary analysis using a decision matrix, and a detailed structured analysis for 'questionable' species.

A decision matrix can be applied where species impacts are clear and do not require detailed quantification of their costs and benefits (Figure 8.3). Invasive NIS whose negative impacts clearly outweigh potential socioeconomic benefits should be managed with the aim to prevent impacts on local marine biological assemblages (see Plan B in Fishery Reforms section) and to limit their populations (example species in 'Unsustainable', Figure 8.3). On the other hand, managers may decide that NIS which cause negative impacts but whose exploitation is beneficial for fisheries could be exploited at levels that maintain their stocks at Maximum Sustainable Yield (MSY) to improve the socio-economic viability of their fisheries (see Plan A in Fishery Reforms section) (example species in 'Sustainable', Figure 8.3). Many NIS that can/could provide significant benefits for Mediterranean fisheries have been associated with negative impacts on ecosystems (example species in 'Questionable', Figure 8.3). For those, a detailed quantification considering the full range of costs and benefits to broad ecosystem services should be followed.

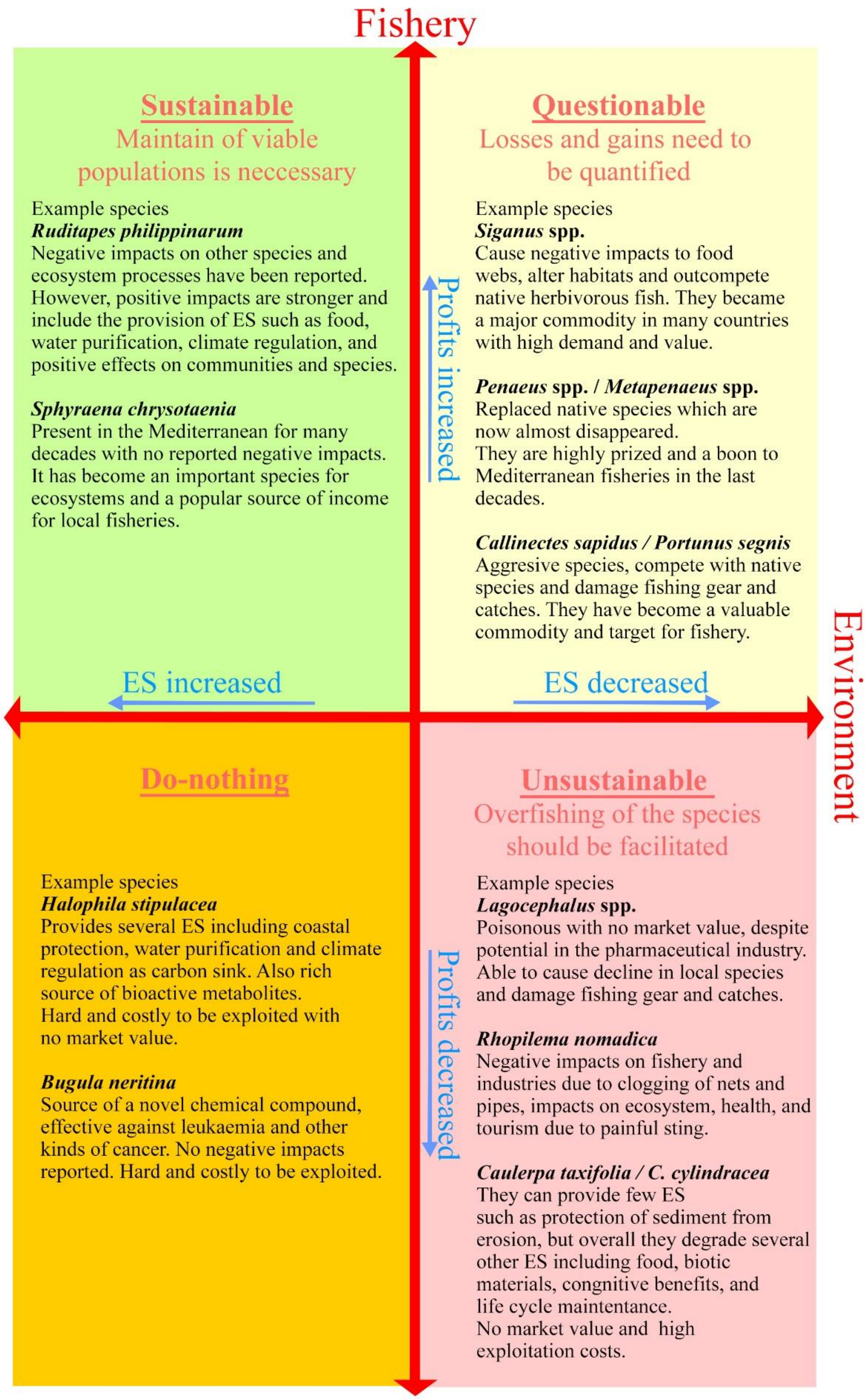

Figure 8.3. A decision matrix that can be used as a first step to decide an exploitation strategy based on the impacts of Non-Indigenous Species (NIS) on the ecosystem

services (ES) and the performance of their fishery (socioeconomic profitability). Profits of fishery are related to fishery & fleet (e.g. efficiency, catches, and sales), working conditions (e.g. job creation), and environmental (e.g. bycatch and damage to habitats). References for species impacts: (Streftaris & Zenetos, 2006; Katsanevakis *et al.*, 2014b; Corsini-Foka & Kondylatos, 2015; Kleitou *et al.*, 2018; Apostolaki *et al.*, 2019; Michailidis *et al.*, 2019; Bel Mabrouk *et al.*, 2020; Killi *et al.*, 2020).

Detailed quantification can be complex, particularly for parameters that are difficult to specify in monetary terms, such as impacts of NIS on cultural ecosystem services (Bonanno, 2016). Expert elicitation is a widely-used technique in science to overcome complexity, lack of data, and the urgent/imminent nature of many conservation decisions (Martin *et al.*, 2012; Roy *et al.*, 2020). This approach has been increasingly used in assessments to guide and implement policy making for NIS prioritisation and mitigation in the Mediterranean Sea (e.g. Roy *et al.*, 2015; Bacher *et al.*, 2018; Galanidi *et al.*, 2018; Peyton *et al.*, 2019). However, all previous assessments have been biased towards the negative effects of these species, as (potential) positive effects were often not taken into consideration. Martinez-Cillero *et al.* (2019) attempt to address these gaps by describing the INvasive Species Effects Assessment Tool (INSEAT) that enables expert elicitation and assessment using an ES framework scale that accounts for the magnitude and reversibility of both positive and negative impacts. In addition, INSEAT allows experts to highlight the level of confidence in each evaluation, thus enabling the identification of research gaps and/or conjectures. We suggest that INSEAT is adapted to include marine ecosystem services (mentioned in Figure 8.1). Emphasis could be given on the recent NIS history, as impacts reported in the past (e.g. replacement of a native congeneric species) might now be irreversible, with the NIS playing a critical role in maintaining ecological function in a different climate.

Although an important decision tool, expert elicitation is often subject to contextual biases and special precaution should be taken during the assessment processes. Experts might be prone to mistakes due to factors such as overconfidence, representativeness, groupthink, difficulties associated with communicating knowledge in numbers and probabilities, and inappropriate and ill-informed methods (Hemming *et al.*, 2018). Structured techniques to minimize uncertainty, identify experts, capture the level of knowledge, calibrate scores, aggregate experts' judgments, and validate responses, are strongly recommended (e.g. Martin *et al.*, 2012; Colson & Cooke, 2018; Hemming *et al.*, 2018).

To assess NIS fishery performance, several EBFM models have been developed and utilized (e.g. Atlantis, Ecopath with Ecosim, size-spectrum, MICE, Osmose, RAPFISH) (Pitcher & Preikshot, 2001; Plagányi *et al.*, 2014; Hornborg *et al.*, 2019) with high heterogeneity on purpose, scope, theoretical underpinning, processes, data input, and spatial extent (Tittensor *et al.*, 2018). Based on the ecosystem and societal considerations of the EBFM-NIS fishing, we selected a number of indicators that could be used (Table 8.1). The selection of indicators will depend on the fishery characteristics, such as location, technique, intensity, spatial extent, and species targeted. Some indicators can be assessed using ecosystem models while others using empirical data or input data by experts (e.g. working conditions, fishing effort). Fisheries modelling is often challenged by the lack of adequate fishery and ecological data (Coll *et al.*, 2015; Bevilacqua *et al.*, 2016), uncertainty in assessments (Natugonza *et al.*, 2020), and empirical evidence of impact of other environmental and human stressors (Chagaris *et al.*, 2019). To address gaps and ensure success of the analysis, recommendations and best practices can be followed such as utilization of fishers' and stakeholders' ecological knowledge to fill gaps in modelling (Bevilacqua *et al.*, 2016), use and intercomparison of multiple models to limit uncertainty (Tittensor *et al.*, 2018), continued communication and periodic review between stakeholders, modellers, and managers throughout the process to refine and ensure the utility and credibility of the model, and to avoid rejection of outcomes at a later stage (Rees *et al.*, 2013; Townsend *et al.*, 2019).

Table 8.1. Indicators to monitor the fishery performance.

Group	Indicator
Fishery & Fleet	Catch volume Revenue Profit Catch efficiency Fishing effort Exploitation rate Capital costs
Working conditions	Job creation Job seasonality
Environmental	Bycatch / Discards Damage to habitats Ghost fishing Compliance and monitoring

Expert elicitation of NIS fishery performance and NIS impacts can be useful in deciding the concerted approach (Plan A or B) of the Mediterranean countries against certain NIS. However, it cannot guide investment strategies, as it does not account for the local characteristics of each area. For that, a sustainability appraisal framework can be used, to consider all five capital assets (natural, physical, human, financial, and social) (DFID, 1999).

Example of local assets that can be taken into consideration include:

Natural capital:

(i) Health of marine habitats (e.g. species composition, richness, and diversity)

(ii) Health of commercial species populations (e.g. abundance, spawning stock biomass)

(iii) Level of protection of marine ecosystems

(iv) Profile and intensity of illegal activities that could affect natural resources

Human capital:

(i) Level of public education

(ii) Availability of data and systems that flow information which could affect knowledge, skills, and competencies

Social capital:

(i) Communication networks within the communities

(ii) Collaboration, participation, and engagement of the communities

Physical capital:

(i) Infrastructure available for NIS products preservation and processing

(ii) Availability of equipment related to NIS fishing that conforms to sustainability criteria

Financial capital:

(i) Financial capability of citizens to buy NIS products

(ii) Public demand for NIS products that could affect the potential sales (quantity and prices) of NIS products.

The aforementioned processes could be used to guide the development of a comprehensive, explicit, structured risk analysis framework after the engagement of all relevant stakeholders from policy makers to managers and fishers. In all our proposed evaluation frameworks, namely expert elicitation, fishery indicators, and sustainability appraisal, there are limitations which have been highlighted and should be carefully examined prior any decision on the approach to fishery reform. In addition, the complexity in managing species that have both positive and negative impacts can lead to inherent disagreements amongst stakeholders regarding the proposed management strategies. The behaviour of diverse stakeholders and the drivers of these behaviours must be taken into account to achieve success (Alter *et al.*, 2019). The decision processes should be transparent with enhanced stakeholders' engagement to minimize conflicts and limit wickedness. An emerging method of stakeholder engagement is the scenario based planning which enables stakeholders to bridge the gap by choosing the most agreeable solutions based on a limited number of proposed measures (Woodford *et al.*, 2016). Decisions should be subject of rigorous monitoring, constant adaptation to changing conditions and external stimuli, e.g. climate change and overfishing effects, and facilitate reflection and improvement.

8.6. Fishery reforms

8.6.1. Plan A: Sustainable exploitation of NIS

The exploitation and consumption of edible and conspicuous NIS has been increasingly promoted as a measure to increase pressure on NIS populations and turn these species into a food source and an economic benefit for local communities (Giakoumi *et al.*, 2019a; Kleitou *et al.*, 2019d). Despite this, managers have been reluctant to promote and develop strategies to exploit NIS in the Mediterranean Sea influenced by the widespread impression that all NIS have negative impacts.

Recently, the General Fisheries Commission for the Mediterranean (GFCM) listed the creation of adaptation strategies to cope with the potential effects of invasive species on fisheries as target outputs of the mid-term strategy (2017–2020) (FAO, 2017). Amongst the strategies developed, the most notable is the Recommendation GFCM/42/2018/7, following calls from Algeria, Tunisia, and the EU, which establishes a regional research programme to fill scientific and research gaps concerning the crabs *Callinectes sapidus* Rathbun, 1896 and *Portunus segnis* (Forskål, 1775). The goal of the recommendation is to maintain the Mediterranean stocks of blue crabs at MSY levels, as well as the socio-economic viability of the blue crab fisheries. An important risk connected to this strategy is the possible reliance of local fishery communities to an invasive NIS or a fishing technique that harms ecosystems and wider ecosystem services. For example, *C.*

sapidus is an invasive predator which according to both anecdotal reports and stable isotopes investigations, can impact benthic communities at multiple trophic levels (Carrozzo *et al.,* 2014; Mancinelli *et al.,* 2016), and damage fishing gears (Culurgioni *et al.,* 2020). A quantitative impact assessment on Ionian and Aegean fisheries in Greece using questionnaire surveys indicated considerable negative effects on fishing activities in areas where *C. sapidus* reached high abundances (Katselis, unpublished data in Mancinelli *et al.*, 2017). A thorough assessment of NIS impacts on ecosystem services to the wider Mediterranean region, including impacts on other fisheries, is needed before deciding to support the sustainable exploitation of 'questionable species' (Figure 8.2). Fisheries for NIS should be regulated by the GFCM and contracting parties would need to perform stock assessments and set catch limits. Current restrictions on fishing techniques should remain for fisheries that cause habitat destruction, have high bycatch rates of native species, or generally cause injuries and/or mortalities to the local biota. The example of blue crabs sets a good starting point for the management of NIS in the region, but a structured, adaptive and iterative management strategy that focuses on more NIS should be facilitated.

8.6.2. Plan B: Unsustainable exploitation of NIS

After detailed cost-benefit analysis, many NIS will likely fall into the 'unsustainable' category and fisheries for those NIS should be managed to reduce their impacts and populations. We suggest reforms to the current legal framework and the introduction of local permits for NIS fishing.

Reforms in the current fishery legislation

Management of NIS fisheries in Mediterranean countries is limited to national and regional legislation, with daily bag restrictions, spatio-temporal regulations of fishing activities, fishing gear deployment limits, and minimum size restrictions for certain species (e.g. EU/1967/2006, EU/1380/2013, EU/2019/982). These regulations were not designed with the invasive fisheries in mind and therefore require scrutiny and reassessment for selected invasive NIS. For example, the lionfish *Pterois miles* (Bennett, 1828) has recently become established in the Mediterranean and is likely to impact regional ecosystems (Kletou *et al.*, 2016; Poursanidis *et al.*, 2020; Savva *et al.*, 2020). Regulations such as daily bag restrictions can be adapted in order to allow fishers, using spearguns, to legally remove as many lionfish individuals as possible.

Turn recreational fishery to NIS targeted fishery

Recreational fishing pressure on certain species can exceed commercial pressure, especially if the exploitation is selective and intensive (Lloret *et al.*, 2018; Nillos Kleiven *et al.*, 2019). The total impact of the recreational fishery on fish stocks, and mostly on large and long-lived species with high reproductive potential, is very high and unsustainable for the fish stocks of many countries (Lloret *et al.*, 2008; Lindfield *et al.*, 2014). Recreational fisheries can also impact the trophic structure of coastal ecosystems (Lewin *et al.*, 2006; Lloret *et al.*, 2008). For instance, recreational fishing has had a significant impact on sea bass stocks, *Dicentrarchus labrax* (Linnaeus, 1758), in France (Rocklin *et al.*, 2014), (ICES, 2018), and triggered the EU to call for an 80% reduction in landings (Armstrong, 2014). In other cases, target species for recreational fisheries can threaten native species which are included in the IUCN Red List, e.g. *Pagrus pagrus* (Linnaeus, 1758) and species of the genus *Epinephelus* Bloch, 1793 (Unal *et al.*, 2010; Sbragaglia *et al.*, 2019). Driven by motivations other than making profits such as personal enjoyment, sense of freedom, and catch consumption, recreational fishers might continue targeting a NIS even when overfished (Kleiven *et al.*, 2019).

With the introduction of a NIS-specific fishing licence, recreational fishing could be transformed from a threat to biodiversity to an advantage. Local competent authorities (e.g. a governmental body or an MPA authority in collaboration with a not-for-profit national recreational fishery association) could i) guide and control NIS fishing intensity and area; ii) provide licenses; and iii); enable transparency and control of the market chain. Profits of such a scheme could sustain the licensing system, support monitoring, and be invested in the education and capacity of its members. Similar schemes already exist for terrestrial hunting in Mediterranean countries and could be used as examples (e.g. in Greece, the Hellenic Hunters Confederation with surveillance from the Government is responsible for the licensing system of hunters. Part of the revenues from the system is reinvested in supporting a third public monitoring scheme, research and awareness events).

The choice of licensed target species would depend on local conditions and perceptions. To avoid potential conflicts with commercial fishers, the target species may be NIS with low-moderate economic value, but with high socioeconomic and/or negative impacts on commercial fish stocks, or species that are difficult to target by commercial fisheries (e.g. species living in very shallow waters). Commercial and recreational fisheries often target the same resources; thus, directing the recreational fishery to other species will also likely promote acceptance and collaboration between them. This change can be conveyed by social norms, perceptions and beliefs, and information through a behavioural management approach (Battista *et al.*, 2018; Mackay *et al.,* 2018), which may constitute a low-cost and highly effective tool for recreational fisheries management (Mackay *et al.*, 2018).

Non-Indigenous Species (NIS) license conditions could include operator training in the marine environment, NIS impacts, as well as identification, safe harvesting, and handling of target species. Licence holders could benefit from indirect measures that promote NIS targeting, such as preclusion of selected areas/time periods for unlicensed recreational and commercial fishers. Finally, financial incentives (or similar incentives such as a free recreational fishery licence) can be given to NIS fishers who remove and deliver selected NIS, with authorities subsequently responsible to sell the specimens in the market, as a compensation for their expenses.

Such a scheme could: i) tackle invasive species using fishing gears with high species selectivity; ii) improve regulation of recreational fisheries while monitoring recreational fishing intensity by type and area, iii) enhance monitoring of NIS distribution, abundance, and ecology; iv) improve public awareness on NIS and other environmental issues, facilitating participation in marine conservation, collaboration, and public stewardship; v) decrease illegal, unreported, and unregulated (IUU) fishing activities by recreational fishers; and vi) improve the market potential of low-value species and generate extra motive even to commercial fishers.

8.7. Investment in capital assets

Prevention of introductions is widely accepted as the best approach to deal with NIS. This opinion is reflected in the Aichi Target 9 from the Convention for Biological Diversity (CBD) as well as the EU Regulation (1143/2014) which recommends a hierarchy of prevention, then rapid eradication, and lastly ongoing management. A fishery based on NIS is a type of ‘biodiversity offsetting’ that aims to reduce, halt, or reverse the losses of biodiversity (Niner *et al.*, 2017) from the introduction and spread of NIS caused by human activities. Within the context of protecting natural fishery resources, conservation measures such as rehabilitation of marine ecosystems through natural capital assets protection and/or restoration should be a priority.

Investments in fishery assets related to the manufactured/natural assets for improved NIS fishery efficiency, market for higher NIS products value, and human and social capital are also essential towards the sustainable NIS exploitation. To this end, we believe that EBFMS-NIS governance can be facilitated with investments in both the (natural) capital assets of the environment and of the fishery itself.

8.7.1. Environmental investment (natural capital assets)

The presence of a healthy functioning ecosystem has the potential to control the distribution and abundances of introduced species and dampen their induced trophic cascade (DeRivera *et al.*, 2005; Carlsson *et al.*, 2011; Papacostas & Freestone, 2019). Overfishing is ubiquitous in the Mediterranean Sea, with benthic ecosystems strongly depleted in finfish, especially in invertivores and top predators (Boudouresque *et al.*, 2017). Simulations have shown that fishing disturbance has been helping some NIS gain an advantage over native species through modifying predator-prey relationships (Saygu *et al.*, 2020).

We discuss three environmental investment measures that could be used to enhance ecosystems capacity, resilience, and resistance against NIS, namely:

- Enhancement of MPAs using Ecosystem Based Management (EBM) approach
- Harvesting of NIS within MPAs
- Protection of overfished predators and key species

Each location has its unique social and ecological context that influences the success of fishery conservation measures against NIS; thus, measures can be site-specific and locally implemented.

Enhance MPAs using an EBM approach

When properly managed, Marine Protected Areas (MPAs) are promoted as an essential tool for reversing the degradation of marine life, able to restore or maintain the ecosystem structure, function, connectivity, and integrity, protect important keystone species and habitats, restore the complexity of ecosystems, and improve ecosystem resilience to pressures such as NIS and climate change (Pieraccini *et al.*, 2017; Sala & Giakoumi, 2018; Laffoley *et al.*, 2019). Thus, enhancement of MPAs in all Mediterranean regions can be promoted in an EBM context where interaction among ecosystem components and activities is recognised (Katsanevakis *et al.*, 2011; Corrales *et al.*, 2018).

It is beneficial if MPAs cover a broad range of environmental conditions and niches to safeguard the functional processes that lead to adaptations due to climate change and other pressures. MPAs that cover habitat mosaics will enable wider ecosystem performance and recovery (Solandt *et al.*, 2020). No-take marine reserves (no fishing allowed) are considered as the most effective type of MPA able to significantly restore the biomass and structure of fish assemblages, and restore ecosystems to a more complex and resilient state (Sala & Giakoumi, 2018). In the eastern Mediterranean, however, higher biomass of NIS was recorded in no-take zones compared to adjacent unprotected areas and a lack of fishery pressure appeared as the most influential factor benefiting NIS populations within the MPA (Giakoumi *et al.*, 2019b). The high pressure of NIS in these areas can affect and deteriorate the potential benefits of a reduction in fishing effort and targeted harvesting of NIS has been suggested (see next section) (Corrales *et al.*, 2018; Giakoumi *et al.*, 2019b).

Targeted NIS removals within MPAs and at early stages of invasions

It has been shown that protected areas can offer refuge for invasive NIS to spread under climate change (Gallardo *et al.*, 2017). Under the propagule pressure of NIS, MPAs such as those located in the Levantine Basin might not perform as biodiversity conservation areas but as reserves and “seed banks” for NIS, inducing “spillover effect” to adjacent areas (Galil, 2017). Although NIS are a prevalent issue for MPAs and are the subject of some monitoring, management, and research, preventative measures for

NIS are largely absent (Iacarella *et al.*, 2019). Targeted species removals within MPAs have been suggested as a measure to effectively control NIS populations, even for species with high dispersal capacity (Giakoumi *et al.*, 2019a; Giakoumi *et al.*, 2019b). To this end, we suggest the introduction of special licenses for NIS targeted fishing into MPAs, directed both to professional and recreational fishers, with the use of specific techniques (e.g. spearfishing, line fishing with circle hooks, manual removal) depending on the targeted NIS. This could be done under the supervision of the MPA authority and in collaboration and coordination with local (e.g. port) authorities, and given that techniques used do not injure native species.

We draw from the experience of the RELIONMED LIFE project (www.relionmed.eu), which targets lionfish (*Pterois miles*) and successfully applies a similar scheme in the eastern Mediterranean (Cyprus). Similar schemes could be replicated in other areas of the region. Specifically, a group of >100 volunteer scuba divers (Removal Action Team) were motivated, trained, and equipped with the aim to remove the invasive and venomous lionfish P. miles from MPAs in Cyprus, and removal events, as well as competitions with awards, have been organised. Similar to all Mediterranean countries (Gaudin & De Young, 2007), harvesting of marine organisms with scuba gear is prohibited and a specific license has been provided which sets specific rules such as the attendance at educational seminars and training with specialized fishing equipment (e.g. Hawaiian slingshots), and the prerequisite that the participant has a 'white criminal record' (no records of criminal offenses) and is environmentally aware. Harvesting by scuba divers is supervised by scientists and controlled by a competent authority. Participants are informed about location, date, and time of upcoming removal events, depending on the capacity (of coastal police or organisers) to patrol and enforce. Participants must be highly (dive) qualified, sign a waiver for accidents and provide a medical fitness declaration. Participants are provided with specialized equipment, and can be fined and memberships terminated if illegal activities are conducted (e.g. the fishing of other species). Preliminary results have shown that removals can limit lionfish populations if applied in a consistent frequency and/or intensity (RELIONMED project unpubl. data). Similar results were found in another previous LIFE project (LIFE RES MARIS) (www.resmaris.eu) which used dark cloths underwater to kill species of the genus Caulerpa Lamouroux, 1809. Results were successful only for a short duration (Bacchetta *et al.*, 2018). Modelling studies can be useful in determining the threshold population levels at which invasive NIS cause damage to the ecosystem (e.g. Green *et al.*, 2014) and/or the removal effort required to deplete NIS populations (e.g. Usseglio *et al.*, 2017).

Removal events of NIS within MPAs may not only provide direct benefits to the marine environment but can also provide recreational benefits from the participation of recreational fishers in NIS harvesting. The engagement of sea users in NIS removals may also enhance their knowledge and awareness about invasive NIS and encourages responsible behaviour, increasing environmental stewardship, and participation in conservational efforts, improving public acceptance and compliance with management decisions. On another level, compulsory reporting of catches in the removal events could also help authorities and research centres to understand NIS distribution, abundance, and spread patterns.

In a similar manner, removal teams could prevent NIS from establishing after early detection. Early detection and response has been recommended as a more cost-effective control measure than post-establishment management, and is included in the priorities of management plans and programs (Finnoff *et al.*, 2007; Schulz & Della Vedova, 2014). To this end, established removal teams, coordinated by competent authorities, could support early detection and removal of organisms.

Protect and enhance overfished predators and key species

The dramatic decline of high trophic level predators has impacted entire food webs, leading to regime shifts and degraded ecosystem states (Estes *et al.*, 2011). Overfishing of top predators diminishes the resistance of Mediterranean ecosystems to NIS (Kimbro *et al.*, 2013). Some predators can feed on and potentially control NIS without requiring time to become accustomed to their new prey (Giakoumi *et al.*, 2019c). Therefore, it is important to strengthen high-level predators protection and conservation, especially for species that can have a major role in controlling introduced NIS (Mumby *et al.*, 2011; Kleitou *et al.*, 2018). Examples of such protection measures are that of France, which prohibited the commercial, spearfishing, and recreational hook-and-line fishing of groupers, *Epinephelus* spp. and *Mycteroperca rubra* (Bloch, 1793) until at least 2023 (Arrêté Arrêté n 2013357-0001 / n °2013357-0004), or of Israel, where commercial fishing of elasmobranchs is prohibited (Ariel & Barash, 2015).

8.7.2. Non-Indigenous Species fishery investment strategies

Access to capital assets (natural, physical, human, financial, and social capital) can determine the vulnerability or strength of communities engaged in NIS fisheries (Allison & Ellis, 2001); thus influencing the livelihood outcomes and sustainability of proposed management mechanisms. Strategies that leverage capital assets can establish the infrastructure and tools that will support fisher and wider community engagement in the EBFM-NIS. Decisions for investments should consider the local context, conditions, and trends that exist within communities by using an integrated ecological and socioeconomic framework. A range of topics for NIS fishery investment are proposed, from market to public awareness and fishery technology, some of which are interlinked (Figure 8.4).

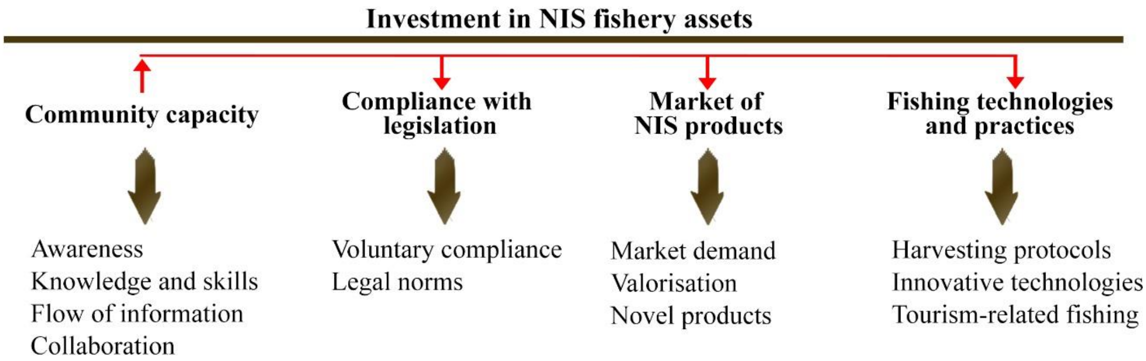

Figure 8.4. Investment strategies proposed that could improve the socioeconomic and environmental sustainability of the NIS fishery. Red arrows indicate that community capacity is impacting the rest of the topics but not the opposite. Strategies can be linked with more than one capital asset, e.g. fishing technologies and practices proposed are interlinked with physical capital, human capital, and social capital.

Community capacity

Our EBFM-NIS suggestion provides the opportunity for citizens to be involved in conservation-related activities and indirectly influence management and policy by improving stewardship, increasing awareness, and strengthening social license and community capacity to address environmental problems. Raising public awareness and developing skills and knowledge are integral components of an effective EBFM-NIS. Citizens/sea-users have been playing a critical role in monitoring NIS in the Mediterranean basin (Giovos *et al.*, 2019; Kleitou *et al.*, 2019b; Kleitou *et al.*, 2020), but have been largely excluded from mitigation efforts. Engagement of public and stakeholders through educational activities and campaigns can secure their acceptance and participation in management interventions such as the participation in NIS fishing and harvesting within MPAs (Kleitou *et al.*, 2019d), in line with the EU Directive (2003/35/EC). Fishers' engagement and representation in management decisions has also been recognised as few of the major attributes fostering Mediterranean MPAs success in achieving healthier ecosystems and social acceptance (Di Franco *et al.*, 2016).

Public awareness and education are top priorities for NIS management in the Mediterranean (Giakoumi *et al.*, 2019a). Citizens can be motivated to consume NIS rather than native species, harvest NIS, and participate in mitigation activities. As several Mediterranean NIS are venomous or poisonous (Galil, 2018), public campaigns and training of sea users are important to avoid accidents related to touching, handling or consumption of these species. In the EU RELIONMED-LIFE project, all fishers and divers participating in lionfish removals are trained in safe handling and equipped with specialized equipment such as lionfish boxes and puncture-resistant gloves.

Finally, information flow can be improved through systems that facilitate open sharing of marine research outputs, best practices, and knowledge related to NIS and their fishery, providing equitable access to ocean knowledge. Similar initiatives have been running in the EU FARNET network, which brings together local communities such as managing authorities, citizens, and experts, and aims *inter alia* to improve the knowledge and capacity, identify and disseminate successful responses to key challenges, ensure flow of information among stakeholders and support cooperation. Recognizing that marine NIS are a regional inter-connected issue, transboundary collaboration between Mediterranean countries is imperative.

Compliance with legislation

A behavioural management approach can be promoted to increase awareness and ensure voluntary compliance with legislation (Battista *et al.*, 2018; Mackay *et al.*, 2018). Indeed, our EBFM-NIS proposals embed high risks of Illegal, Unreported and Unregulated (IUU) fishing, particularly within MPAs. Thus, an increase of fishing activities is likely to increase the need for patrols, especially for the recreational-related fishing activities which are already a big proportion of illegal fishing activities, e.g. in a case study analysing Greek fisheries, almost half of the infringements were conducted by recreational fishers (Moutopoulos *et al.*, 2017). The problem gets even more complicated when considering the various duties of the control authorities (e.g. border control and marine safety and security), and this may limit their operational effectiveness especially during summertime when tourist and marine recreational activities are intensive.

Indirect suggestions or reinforcement (i.e. nudges) through a behavioural approach represent a potential inexpensive and highly-effective tool for recreational fisheries management (Mackay *et al.*, 2018). Examples include prohibition of areas for recreational fishers but not for NIS fishers, or even prohibition of recreational fishing on certain days/seasons of the year but not for NIS fishers, and/or an involuntary and cheaper (than normal recreational licenses) license to NIS fishers. An indicative cost for the license can be attributed to subscription to conservation efforts against NIS and accompanied with education material to (re)inform participants about the purpose of their license. Behavioural measures to promote NIS might be easier in areas where NIS are abundant such as in the eastern Mediterranean.

Legal norms that set the conditions to facilitate social capital changes can also be established. These include the obligation of reporting, membership terminations in cases of violations, and prohibitive penalties. Small penalties encourage illegal fishing and enhance a sense of impunity (Andrews-Chouicha & Gray, 2005). In this context, fines should be dissuasive compared with the economic income generated from the black market. Other consequences for the culprits, such as temporal/permanent ban of access to public assistance, subsidies, liability insurances, vessel confiscation, and even jail sentences (Le Gallic & Cox, 2006; Moutopoulos *et al.*, 2016; Soyer *et al.*, 2018) can be applied to anyone involved in the trade of illegal, unreported, and unregulated products of the present activities, such as fishers, dealers, processors, and sellers.

Market potential

Market promotion and exploration of valorisation opportunities (e.g. Hamdi *et al.*, 2018; Jiménez-Muñoz *et al.*, 2019) are imperative to build incentives and ensure the sustainability of NIS fisheries. Similar efforts have already been initiated in the Mediterranean. For example, an important action of the RELIONMED-LIFE project is the exploration of lionfish known uses to make removals sustainable. The project specifically explores the market potential of lionfish as a delicacy at the Cyprus restaurant business industry, and its fins in the jewellery and artwork industry. A similar approach is followed by another project ('Pick the Alien', www.isea.com.gr/pick-the-alien-2) in the Cyclades islands in Greece, where the consumption of NIS is promoted through the creation of a recipe e-book, public events with renowned chefs cooking NIS fishes and discussions with key stakeholders for the development of pilot market chains in the islands.

Through such marketing, local communities may be triggered to protect NIS (Nuñez *et al.*, 2012). To avoid this, control, education, and awareness building would be needed. In addition, people can become aware of which NIS products are edible and develop a preference over native overfished species. Countries with utilization and high demand for a specific NIS could share experiences and recipes with other (e.g. *Siganus* rabbitfish are highly valued fish market products in countries such as Cyprus, Israel, and Lebanon, but at the same time are discarded in most parts of Greece).

Research can play a critical role in valorisation and marketing of inedible or novel NIS products for economic profit. For instance, the GoJelly project (gojelly.eu), funded by the EU Horizon 2020, aims to develop protocols for handling, preserving, and processing jellyfish to make commercial products (animal feed, fertilizers, cosmetic and nutraceutical, and human food), and promising results can be used for the exploitation of the non-indigenous jellyfishes in the Mediterranean. *Caulerpa cylindracea* Sonder, 1845 holds potential to become one of the alternatives for the production of bioplastics, and for the development of functional foods for human nutrition, aquaculture, and/or drugs for treating chronic diseases (e.g. diabetes, obesity, atherosclerosis) (Stabili *et al.*, 2016; Vitale *et al.*, 2018). The seagrass *Halophila stipulacea* (Forsskål) Ascherson, 1867 has bioactive metabolites with promising activities against obesity and biofouling (Bel Mabrouk *et al.*, 2020). The exoskeleton of the spider crab *Libinia dubia* H. Milne Edwards, 1834 can be used to extract bioactive molecules (Rjiba-Bahri *et al.*, 2019), carotenoid compounds from the blue crab *Portunus segnis* have potential in food or pharmaceutical industries (Hamdi *et al.*, 2020), and the tetrodotoxin, a neurotoxin present in many invasive and abundant pufferfish such as *Lagocephalus sceleratus* (Gmelin, 1789) and *Torquigener flavimaculosus* (Hardy & Randall, 1983) (Katikou *et al.*, 2009; Kosker *et al.*, 2018), could be used as analgesic, e.g. to safely relieve severe, treatment-resistant, cancer pain (Hagen *et al.*, 2008).

Fishing technologies and practices

i) Fishery equipment for NIS

Developing fishery techniques that reduce bycatch, eliminate discards, and minimize ecological impacts are primary aims of ecosystem-based fishery management (Chopin & Suuronen, 2009). Within the non-indigenous species context, fishery techniques need to be optimized to improve NIS catches, reduce by-catch, and allow fisheries for NIS in areas where this was previously not possible. For example, the GoJelly project developed protocols to allow jellyfish biomass collection during jellyfish blooms. Many of the jellyfish blooms consist of NIS and, particularly in the eastern Mediterranean Sea, they characterize recurrent jellyfish outbreaks (Ghermandi *et al.*, 2015; Gravili, 2019).

Climate change and a recent enlargement of the Suez Canal is allowing thermophilic species to establish viable populations and spread into vulnerable habitats (Galil *et al.*, 2019). A lack of fishing pressure on NIS populations can undermine marine conservation management efforts (Andradi-Brown *et al.*, 2017). In the Western Atlantic, innovative harvest technologies have been proposed to remove lionfish from deeper waters using spiny lobster traps (Pitt & Trott, 2013; Harris *et al.*, 2020) or weaponized remotely operated vehicles (Gittings, 2019). Development of technologies for selective harvesting of NIS can provide an alternative source of income and lower the impacts of highly invasive NIS.

ii) Tourism-related fishing

Fisheries-related tourism is rapidly developing in many Mediterranean regions, , creating new sources of employment and income, and linking local fishing traditions with education and recreational activities (Nicolosi *et al.*, 2016; Kyvelou & Ierapetritis, 2020). Fishery-related tourism covers a wide array of activities such as excursions in professional fishing vessels (known as 'pescatourism'), recreational fishing from a boat (e.g. charter boat) or the shore, learning about fishing, and exploring the marine environment and its biodiversity.

Recently, the EU adopted a resolution on the role of fisheries-related tourism in the diversification of fisheries (2016/2035(INI)), following a procedure which acknowledged the yet untapped potential of fishery tourism and the importance of its promotion. Benefits include diversification of fisheries and tourism, greater awareness of fish species and how to cook them, and conservation of fish stocks and marine ecosystems, particularly through reduced catches and physical and mental well-being of fishermen and their families through reduced working hours at sea and higher involvement of women (Report A8-0221/2017).

In the fishery-related tourism activities sector, the primary source of income usually derives from the tourists and not from the catches; thus, tourist excursions for NIS fishing would ideally be used to catch low- or no-value species such as poisonous pufferfish (Tetraodontidae). Such activities are already taking place in Cyprus and Greece where charters provide tourists the experience of catching pufferfish using hand and pole-line-fishing techniques. Fishery-related tourism activities that focus on NIS could be further promoted with incentives by the managers such as sharing of protocols, best-practices, or even financial support. An integrated approach at each location could be performed, making sure that tourism development does not by-pass and affect the interests of the fishery communities, ensure support of the relevant stakeholders, and identify opportunities for maximum sustainable impact.

8.8. Conclusion

In the eastern Mediterranean, non-indigenous species have become an integral part of fishers' livelihoods. Ecosystem Based Fisheries Management of NIS (EBFM-NIS) would help limit the socioeconomic and ecological impacts of established NIS populations. This approach may have many benefits such as protecting natural capital, creating new markets, promoting collaboration, and reducing management costs. It could improve both the viability of fisheries as well as securing improvements in ecosystem function. Thus, the proposed EBFM-NIS strategy can help to achieve several of the interconnected goals of the 2030 Agenda for Sustainable Development, particularly Sustainable Development Goal 14, that aims to conserve and use oceans in a sustainable way, achieve sustainable development of fisheries, and maintain natural marine resources (UN, 2019). In addition, it can help Mediterranean countries to comply with policies, regulations, and conventions related to the NIS and/or the protection of marine resources, such as the goals for the 'Descriptor 2' of the European

Marine Strategy Framework Directive: ‘Non-Indigenous Species introduced by human activities are at levels that do not adversely alter the ecosystems’ (2008/56/EC).

9. Conclusions

9.1. Overview

Marine ecosystems face increasing alteration due to stressors such as climate change, NIS, pollution, fisheries, eutrophication, and habitat loss. (Coll *et al.*, 2010; Kletou & Hall-Spencer, 2012; Chatzimentor *et al.*, 2022). These stressors often co-occur in time and space and act synergistically reducing the local biodiversity and ecosystem functioning. The 21st century faces a global challenge; understanding the ecosystem changes and regulating fish resources is essential to provide food for mankind and to preserve the oceans (Perissi *et al.*, 2017). With numerous fish stocks collapsing globally over the past 20^{th} century due to overexploitation, an increased demand for more sustainable management tools and strategies have been demanded. However, fishery production has been stagnant since the 1990s, while fishery resources continue to decline, posing challenges to achieving Sustainable Development Goal 14 in the 2030 Agenda (FAO, 2022). Depletion of marine resources can jeopardize goods and ecosystem services and cause cascading impacts on economic systems and human societies (Figure 9.1). Reforming fisheries and NIS impacts in ways that offset negative impacts and fix current potentially maladaptive responses is essential (Gaines *et al.*, 2018; Kleitou *et al.*, 2021a).

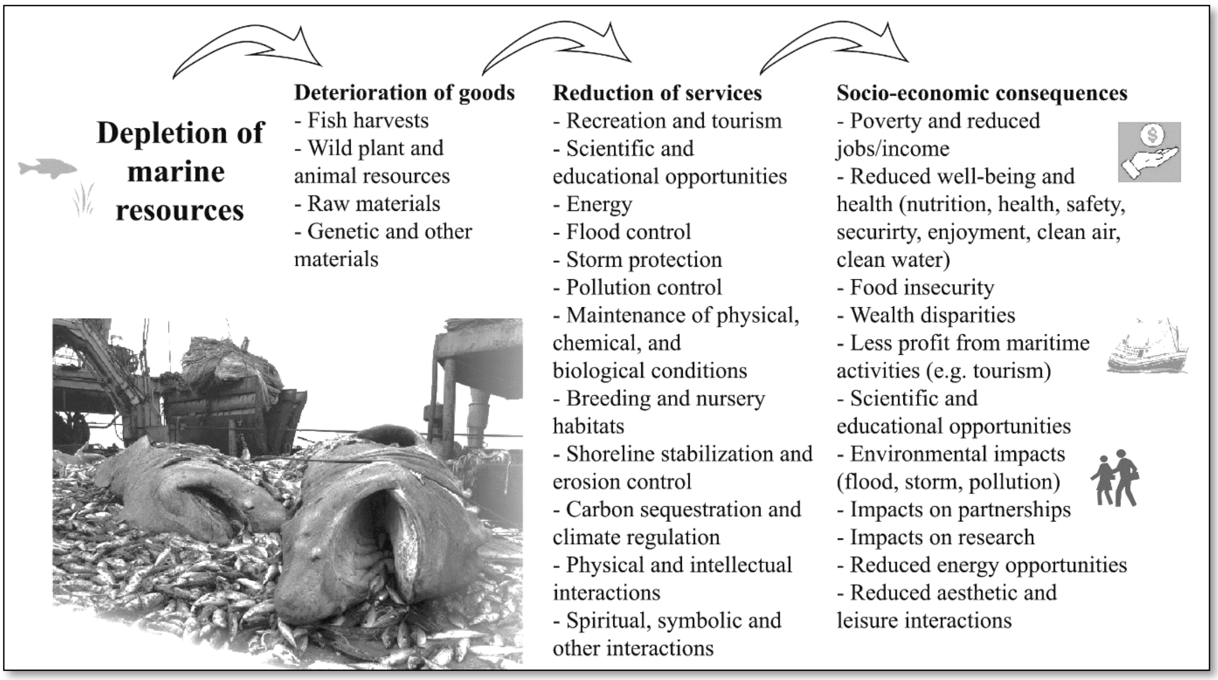

Figure 9.1. Example consequences of marine resources depletion in relation to goods, ecosystem services, and socio-economic systems.

Existing legislation for invasive species management in the EU lacks specific control measures for marine IAS. Focusing on species' detection and distribution monitoring (e.g. as part of the Marine Strategy Framework Directive, see Galanidi & Zenetos, 2022) might be more relevant to regions where NIS numbers are small, while it does not consider the multifaceted interactions of NIS within the ecosystems neither mitigating their negative impacts (Kleitou *et al.*, 2021a; Tiralongo *et al.*, 2022).

9.2. Do nothing is a dangerous management option

Insufficient understanding about the multifaceted impacts of NIS in the Mediterranean ecosystems has driven scientists to consider the option of "doing nothing" and letting the ecosystem recover by itself as a cheap, possible, and easy solution (Giakoumi *et al.*, 2019a). This solution however poses several dangers since introductions of novel species can further reduce the ecosystems' resilience and increase their vulnerability to regime shifts that can lead to undesirable social and ecological effects (Chaffin *et al.*, 2016). In addition, it fails to recognize the emerging contribution of many NIS (Kleitou *et al.*, 2021a) where they have become members of a complex system of interactions between physical, chemical, and biological processes that underline the ecological functioning. In situations where controlling invasive species through management efforts is deemed economically expensive, irrelevant, or ineffective, such as with certain taxonomic groups, it is still important to monitor the distribution, spread, and impacts of the species in question.

"You can also commit injustice by doing nothing (Marcus Aurelius)"

This PhD project has shown that 'do nothing' is a dangerous option for established NIS since many of them are now interlinked with the environment, society, and economy of Mediterranean countries (Kleitou *et al.*, 2022b). Negligence to take actions could also diminish conservation efforts such as the promotion and establishment of MPAs (Chapter 2). As Tricarico (2016) mentioned, there is still vast amount of biodiversity to protect and the significance of aquatic ecosystems is too enormous to 'throw in the towel' and do-nothing. On the contrary, now is the time to promote and consolidate knowledge and efforts for stronger management of NIS (Tricarico, 2016). Through the outputs of this PhD, it was evident that management of marine NIS needs to recognize the complexity and interconnectedness of marine ecosystems and involve multidisciplinary expertise and stakeholders to ensure effective, sustainable, and beneficial management for both the environment and the people who depend on it.

The PhD Chapters 1-4 produced substantial knowledge regarding the examined priority management actions, i.e. (i) Education and awareness; (ii) Rehabilitate the environment; (iii) Commercial or recreational utilization; and (iv) Mechanical removal of species. Chapters 5-6 used the knowledge to guide major reforms in the management and policy frameworks of NIS in the Mediterranean Sea that could be utilized to improve legislations, adapt, or control to NIS spread, limit the socioeconomic, health, and ecological risks, and sustainably exploit the benefits provided by these organisms.

9.3. Management Action 1: Education and public awareness

Public awareness was identified as the highest priority for management of invasive species in the Mediterranean Sea (Giakoumi *et al.*, 2019a). The importance of public participation in bringing effective and timely action to tackle invasive species has also been recognized by the European Regulation on IAS (EC/1143/2014). Insufficient consideration of stakeholders and public perspectives can lead to divergent opinions and actions that lose support at the local management level (Barney & Tekiela, 2020; Oficialdegui *et al.*, 2020). Furthermore, strategies to commercialize non-indigenous species could be dangerous and generate perverse incentives to maintain or expand the NIS populations, if not supported with adequate educational and engaging processes of the public and stakeholders (Pasko & Goldberg, 2014; Kourantidou *et al.*, 2021). The participation of citizens and volunteers was essential in managing lionfish populations in the Western Atlantic either through the development of commercial fisheries or their participation in monitoring and removal attempts (Malpica-Cruz *et al.*, 2016; Clements *et al.*, 2021). In this region, scientists discovered that understanding perceptions, behaviours and socioeconomic interactions is necessary to build effective management strategies (Estévez *et al.*, 2015). They also concluded that in this unprecedented crisis, fishers and sea users could be important allies if they are properly informed and involved in collaborative and communicative management processes (Morales-Nin *et al.*, 2017). Furthermore, close collaboration and engagement of fishers with the conservation sector increased awareness, created new opportunities, and fishers took an active role, positioning themselves as conservation leaders in the lionfish invasion rather than perversely incentivized to collapse fish stocks (Quintana *et al.*, 2023).

Chapter 1 (Kleitou *et al.*, 2019d) conducted a telephone survey and stakeholder meetings to assess public and stakeholder awareness of lionfish. There was a significant discrepancy between stakeholders and the public in terms of awareness and knowledge. More educational and communication activities were needed to increase public awareness and support for lionfish fisheries. Scientists and managers' encouragement was the preferred incentive for stakeholder involvement in management activities (Quintana *et al.*, 2023).

Chapter 3 (Kleitou *et al.*, 2021c) demonstrated that involving volunteers in lionfish management activities positively impacted their knowledge and motivation for marine conservation. Close cooperation between scientists and divers (volunteers) enabled the acquisition of citizen science data using logbooks that were filled by the divers. The data yielded sufficient information about the spatiotemporal variation in lionfish densities, a detail that can be lacking from established and official citizen science programs in the Mediterranean Sea which record only the presence of species (e.g. MedMIS of IUCN or EASIN of the European Commission). Engaging volunteers in citizen science initiatives leads to increased stakeholder knowledge and awareness and enhance participation and support for conservation and management actions (Tricarico, 2022). Close cooperation with fishers, divers and other sea users, and use of log-books (Kleitou *et al.*, 2021c) could be further promoted by established and official citizen science programmes.

Chapter 4 revealed fishers’ lack of knowledge and awareness regarding the origin and impacts of several NIS. Positive perception of high-priced NIS and misunderstanding of ecological impacts emphasized the need for collaborative and communicative management processes to harmonize stakeholder views (Morales-Nin *et al.*, 2017).

9.4. Management Action 2: Rehabilitation of the environment including protection and restoration of marine areas

Accumulating evidence suggests that protection of marine areas can enhance their resilience against stressors like climate change (Duffy *et al.*, 2016; Roberts *et al.*, 2017; Gaines *et al.*, 2018).

In the eastern Mediterranean however, the spread of invasive species in MPAs has been alarming since they are sometimes found in higher densities compared to adjacent unprotected areas (Giakoumi *et al.*, 2019b); raising calls that MPAs might not perform as biodiversity conservation areas but as reserves and 'seed banks' for IAS, inducing negative effects to the surrounding areas (Galil, 2017). With plans for future protection of at least 30% of our oceans (HAC, 2022), understanding how MPAs influence invasive species' spread is crucial.

The eastern Mediterranean area exhibits higher seawater warming (Marbà *et al.*, 2015) and the successful establishment of thermophilic NIS is expected to be further favoured (Corrales *et al.*, 2018; Moullec *et al.*, 2019). Monitoring of MPAs response to Lessepsian species in the Levantine, could provide opportunities for adaptation and adaptability of species, ecosystems, and management measures before impacts are detectable across the entire region.

Chapter 2 demonstrated that lionfish densities were favoured by the fishery restriction measures at an MPA of eastern Cyprus. Lionfish densities and sizes increased significantly faster in areas where fisheries were regulated/prohibited and were found at substantially higher densities compared to adjacent unprotected (fished) areas, especially compared to areas where targeted removals were applied. The study emphasized the need for comprehensive ecosystem-based management approach of MPAs considering all habitat pressures, including invasive species

The MPA was recently established while it has been estimated that an area would need in the best scenario (without considering increasing pressures) about 20 years to reach 90% of its undisturbed baseline level (Duarte *et al.*, 2020). In a mature ecosystem where ecological niches are occupied, novel species are expected to find more resistance in occupying available niches. Various predators, such as groupers (*Epinephelus* spp.) and common octopus (*Octopus vulgaris*) have been recorded to prey on lionfish in the Mediterranean Sea (Crocetta *et al.*, 2021; Ulman *et al.*, 2022) and rebuilding and protection of their populations prior the establishment of a strictly protected MPA could be prioritized prior the establishment of an MPA in a degraded/impacted area.

A study in Israel indicated that fishery restrictions benefit fish populations even in warm waters and when faced with marine invasions (Frid *et al.*, 2022). On the other hand, a Mediterranean study indicated that MPAs will not be able to tolerate larger-scale biotic alterations and biomass decreases associated with climate change (Frid *et al.*, 2023). The presence of long-term and robust monitoring can clarify the holistic ecosystem interactions of invasive species within recent or old MPAs.

9.5. Management Action 3: Encourage the commercial and/or recreational utilization

The history of fisheries has shown that many fish stocks can be harvested at a faster rate than they can be replenished, leading to a widespread population decline (Perissi *et al.*, 2017). Commercial fisheries are considered as a strategy to incentivize invasive species removal and ensure sustainable population controls(Pasko & Goldberg, 2014; Chapman *et al.*, 2016).

Chapter 2 confirms the potential contribution of fisheries in long-term invasive species management, as lionfish densities were lower in fished areas compared to fishery restricted MPA zones., The results agree with simulations which found that fisheries can significantly reduce lionfish biomass in Cyprus (Michailidis *et al.*, 2023). However, there are controversial opinions about whether commercialization of NIS is a win-win solution as local communities might become dependent on their exploitation to the point of aiming for sustainable fishing; since depletion of invasive species populations might damage their revenues and sustainability (Nuñez *et al.*, 2012; Quintana *et al.*, 2023). Non-indigenous species are gradually becoming a source of revenue in the eastern Mediterranean (van Rijn *et al.*, 2019) and understanding fishers perspectives and priorities is necessary for the design of effective management strategies that account for the multi-faceted costs and benefits of NIS.

Chapter 4 (Kleitou *et al.*, 2022b) analysed the socio-economic dimensions of NIS in commercial and recreational fisheries in eastern Cyprus. Six NIS contributed to a significant portion of the commercial fishery catch, comprising over half of total landings and value in the summer. Some NIS caused economic damages, like destroying nets or depredating catches. A comprehensive framework aligning fisheries management with ecological systems and changing social dynamics is needed(Kleitou *et al.*, 2021a) (Chapter 6).

Recreational fishers were not catching common NIS, possibly due to motivations beyond economic, such as targeting larger keystone top-predators (Giovos *et al.*, 2018a; Mackay *et al.*, 2018; Michailidis *et al.*, 2020a; Sbragaglia *et al.*, 2021). Frequently, these keystone predators are large fish with the slowest biological reproduction and lowest natural mortalities that are likely to be more vulnerable to overexploitation (Kuparinen & Merilä, 2007; Maggs *et al.*, 2013; Perissi *et al.*, 2017). On the other hand, invasive species usually exhibit life history traits that aid their ability to thrive in new conditions such as rapid growth and high fecundity (Pasko & Goldberg, 2014). Reforming fisheries in ways that adapt to productivity changes can potentially lead to a future with higher profits and yields compared to what is produced today (Gaines *et al.*, 2018). Future strategies for NIS management need to challenge social norms and motivations of recreational fishers to enhance pressure to nuisance NIS and alleviate pressure from native keystone species like groupers (Kleitou *et al.*, 2021a).

Official fishery data had significant gaps, such as misreporting, misidentification, and lack of data from recreational fishers. These data deficiencies need improvement for reliable and accurate monitoring and impact assessments.

9.6. Management Action 4: Targeted physical (mechanical) removal of species

Targeted physical removal of species is considered an applicable control mechanism, but its effectiveness, feasibility, and cost depend on species and environmental characteristics(Giakoumi *et al.*, 2019a). Traits of the invasive species (biology, population spread and dynamics, impacts on local biota, cryptic behaviour, defensive systems such as venomous spines or poisonous tissues) and their interactions with human health, ecological, biological, and socioeconomic factors are important underlying criteria which if not considered, can result in ill-used time and resources (Pasko & Goldberg, 2014).

In Chapters 2 and 3, competitions (derbies) and small-targeted removals of lionfish with volunteers were organised. This strategy was identified in the Western Atlantic as the most viable management strategy for controlling lionfish populations below levels that cause damage to the surrounding biota (Côté *et al.*, 2014a; Green *et al.*, 2014; Ulman *et al.*, 2022). The removals were found effective in suppressing lionfish populations, especially in hotspot sites (Chapters 2 and 3). However, the trade-off varied among sites; interconnected rocky areas showed more rapid recovery, while isolated sites required more intense and frequent efforts to achieve depletion effects.

The involvement of volunteers in the removals enhanced their participation in conservation activities and monitoring of lionfish using citizen science and had a strong positive impact on knowledge about lionfish and motivations – the divers were even willing to pay extra to remove lionfish. Management reforms should capitalize on this societal motivation and enable effective lionfish removals coordinated by competent authorities. Western Atlantic jurisdictions have allowed removals with SCUBA and targeted spearfishing with MPAs, with high costs offset by social and environmental benefits, such as ecotourism opportunities (Ulman *et al.*, 2022; Rahman *et al.*, 2022).

9.7. Recommendations and management impact

The last Chapters summarized lessons learnt from the management applications and research projects, identified challenges, and translated them into recommendations for management and policy in two Chapters (Chapters 5 and 6) and one regional guide (Appendix 5) (Kleitou *et al.*, 2021a; Kleitou *et al.*, 2021b; Kleitou *et al.*, 2022a).

➢ The Invasive Alien Species (IAS) Regulation (Chapter 5)

The IAS Regulation (EC/1143/2014) established in 2014, represented a major advance towards a coordinated and harmonized procedure for IAS. Species included in the Union list are subject to stringent provisions for prevention, early detection and rapid eradication, and management by all EU Member States. The first years of its implementation offered critical insights and opportunities for improvement.

Chapter 5 (Kleitou *et al.*, 2021b) presented efforts to collect early-invasion data and propose lionfish *Pterois miles* for inclusion to the Union list of the IAS, documented challenges encountered, and provided recommendations on the basic IAS Regulation and the Delegated Regulation on risk assessments (EC/2018/968) that could be applied to improve relevance, coverage, effectiveness and management of marine IAS at a European and regional level.

The risk assessment concluded with high confidence that there is a high degree of risk (social, ecological, and economic) associated with the future spread of lionfish in the Mediterranean and the European Union, being one of the fastest fish invasions ever reported in the eastern Mediterranean Sea. Important challenges associated with the species inclusion in the Union List were identified and included insufficient proactive action especially since introductions from Suez Canal irrelevance of legislation to the marine environment, lack of information and absence of effective surveillance systems, low involvement of non-EU regional countries, absence of adaptive measures possibilities, and slow evaluation processes (Kleitou *et al.*, 2021b).

Recommendations included the establishment of horizon-scanning exercises and pre-defined rapid response, promotion of mitigation measures at the Suez Canal, development of strategic and coherent monitoring for the EU for faster response driven by scientific knowledge, synergies with established regional legally binding instruments and development of common strategies for concerted action within the Mediterranean, utilization of dead specimens to allow market-based management approaches, and steps that could increase the speed of peer-review of the risk assessment or provisionally allow faster regional responses to the invasive species. (Kleitou *et al.*, 2021b). The development of long-term, standardized, and consistent monitoring methodologies was identified as priority for Cyprus, as in Peyton *et al.* (2022), since absence of robust data might not enable rapid impact assessments and understanding of management actions' efficiency.

The results of this Chapter were strongly considered during the most recent review of the IAS Regulation by the European Commission (EC, 2021).

➢ Fishery reforms for non-indigenous species management in the Mediterranean Sea (Chapter 6)

Non-indigenous species are establishing and occupying important ecological niches within the ecosystem but not considered in fisheries management leading to further pressure on native stocks (Kleitou *et al.*, 2021a). To move beyond current problematic management approaches that do not adapt to the presence of non-indigenous species, Chapter 6 (Kleitou *et al.*, 2021a) proposed major fishery reforms and an Ecosystem Based Fisheries Management strategy that could direct a concerted and harmonized approach against NIS and limit the socioeconomic and ecological damages of NIS within the Mediterranean Sea. The EBFM process would guide whether each species should be managed sustainably or unsustainably depending on the environmental and human (social-cultural, economic, and institutional) performance of the fishery and the impacts of the NIS on the invaded environments. Depending on local conditions, investment strategies are suggested for the EBFM-NIS framework to protect / enhance natural assets to improve ecosystem resilience against NIS, as well as fishery assets to improve the performance of NIS fisheries.

Some recommendations of this Chapter (Kleitou *et al.*, 2021a) have potentially influenced legislations and management of Mediterranean countries. For example, EU Member States (e.g. Cyprus and Greece) are now under consultations to explore amendment of their legislation and allow recreational fishers to catch as many lionfish as possible. Furthermore, authorities amended the fishery legislation for recreational fishers of Cyprus in 2022 and each fisher (or fishery vessel) is now allowed to fish only one individual of dusky grouper (*Epinephelus marginatus*) or common dentex (*Dentex dentex*) per fishing trip instead of two that was allowed before. "*The man who moves a mountain begins by carrying away small stones"* – Confucius.

- Mediterranean Management Guide of Lionfish (Appendix 5)

Drawing from the summarized results of the PhD Chapters and supplemented with knowledge from the RELIONMED project (Kleitou *et al.*, 2022a), a tailored-regional lionfish management guide was produced, designed to inform all key stakeholders in the region. Key topics included (a) lionfish removals (Chapters 2 and 3), (b) development of markets (Chapters 4 and 6), (c) outreach (Chapter 1), (d) research and monitoring (Chapters 1, 2 and 3), and (e) regional cooperation (Chapter 5). Challenges and opportunities for each topic were discussed, and a strategy combining cost-effective management approaches was promoted.

The guide recommended frequent removal actions due to the rapid reproduction and metapopulation dynamics of lionfish (Chapter 3). Targeted removals in priority locations and functional eradication were suggested, while traditional or alternative fisheries could be promoted in other areas (Chapter 6). Market opportunities were identified, with restaurant owners needing a steady supply of lionfish and a streamlined supply chain (Chapter 6).

Conventional fishing gears were found ineffective for targeting lionfish, and specialized gears like traps and harvesting robots could be investigated (Chapter 4). Biological control was considered a sustainable option, but the protection of natural predators was crucial (Chapter 6).

Increasing public awareness through education and communication methods was deemed fundamental for effective lionfish management (Ulman et al., 2022). The guide recommended involving sea users and the public in removal programs and market exploitation to promote responsible behavior and compliance with legislation (Chapters 1, 3, and 4). Citizen science data was highlighted for monitoring lionfish invasion and population dynamics (Chapters 3 and 5).

The guide emphasized the need for effective surveillance systems in lionfish-invaded areas and promoted ecological monitoring protocols and sentinel locations (Chapter 5). Regional cooperation with all affected parties in the Mediterranean region was deemed vital, calling for lionfish inclusion in the list of IAS of Union concern (Chapter 5).

Endorsed by the Prince of Monaco Albert II, the guide was shared widely with media, the European Commission, fishery bodies of the Mediterranean Sea, and national authorities.

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List of relevant publications produced during period of study

(additional to the ones listed on Author's Declaration page)

1. **Kleitou P**., Hall-Spencer J.M., Rees S.E., Kletou, D. (2022) Guide to lionfish management in the Mediterranean. University of Plymouth, 62 pp. https://doi.org/10.24382/kyck-j558

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11. Appendices

11.1. APPENDIX 1. Chapter 1 supplementary material(s)

(A) Questionnaire used to assess stakeholders and public perceptions.

Topic	#	Questions	Answers provided	Group interviewed
Part A: Perception of the threat of lionfish as an invasive species	1	Have you ever heard of lionfish?	Yes; No; if no, continue to Part B	Stakeholders and Public
	2	Would you recognize a lionfish in a picture, live or on TVs?	Yes; No	
	3	Are you aware that lionfish is edible?	Yes; No	
	4(i)	Lionfish can damage the environment	Likert-type scale: 0-10	
	4(ii)	Lionfish can negatively impact the economy	Likert-type scale: 0-10	
	4(iii)	Lionfish pose a risk to human health	Likert-type scale: 0-10	
Part B: Perception on future strategies	5(i)	It is necessary to undertake research to understand the potential effects of lionfish on local environment, economy and human health	Likert-type scale: 0-10	Stakeholders and Public
	5(ii)	It is necessary to develop a management strategy for lionfish in Cyprus	Likert-type scale: 0-10	
	5(iii)	I support management measures to limit the numbers of lionfish in Cyprus's marine environment	Likert-type scale: 0-10	
	5(iv)	I support management measures for the complete eradication of lionfish from Cyprus's waters	Likert-type scale: 0-10	
	5(v)	I would consume lionfish	Likert-type scale: 0-10	

Topic	#	Questions	Answers provided	Group interviewed
	5(vi)	I would buy products made from lionfish	Likert-type scale: 0-10	
Part C: Abundance of lionfish	6	Have you ever seen a lionfish in Cyprus's waters?	Yes; No; if no go to Part D	Stakeholders
	7	When was the first year that you saw a lionfish?	Year and details	
	8	What is the maximum number of lionfish that you have seen (or captured) in a group?	Number and habitat	
	9	Since your first sighting has the lionfish population increased/decreased/stayed the same?	Increase; Decrease	
	10	In your direct experience from the previous years has the lionfish population increased / decreased / stayed the same?	Increase; Decrease; Same	
Part D: Effects from lionfish	11	Have you ever experienced any direct effects (positive and negative) of lionfish in Cyprus's waters (personal, economic, environmental)?	Yes; No; if yes please describe the effects	Stakeholders
	12	In the last year have you ever experienced any direct effects (positive and negative) of lionfish in Cyprus's waters (personal, economic, environmental)?	Yes; No	
Part E: Management of lionfish	13	In your opinion, should lionfish be managed in Cyprus's waters?	Yes; No	Stakeholders
	14	What management measures are the most effective?	Open-ended question (i.e. No possible answer provided)	
	15	Would you be willing to get involved in lionfish removal activities?	Yes; No; if no go to Part F	
	16(i)	Would you willing to participate in lionfish removal initiatives for personal consumption?	Likert-type scale: 0-10	
	16(ii)	Would you willing to participate in lionfish removal initiatives for trophy or sport?	Likert-type scale: 0-10	
	16(iii)	Would you willing to participate in lionfish removal initiatives due to the market demand?	Likert-type scale: 0-10	

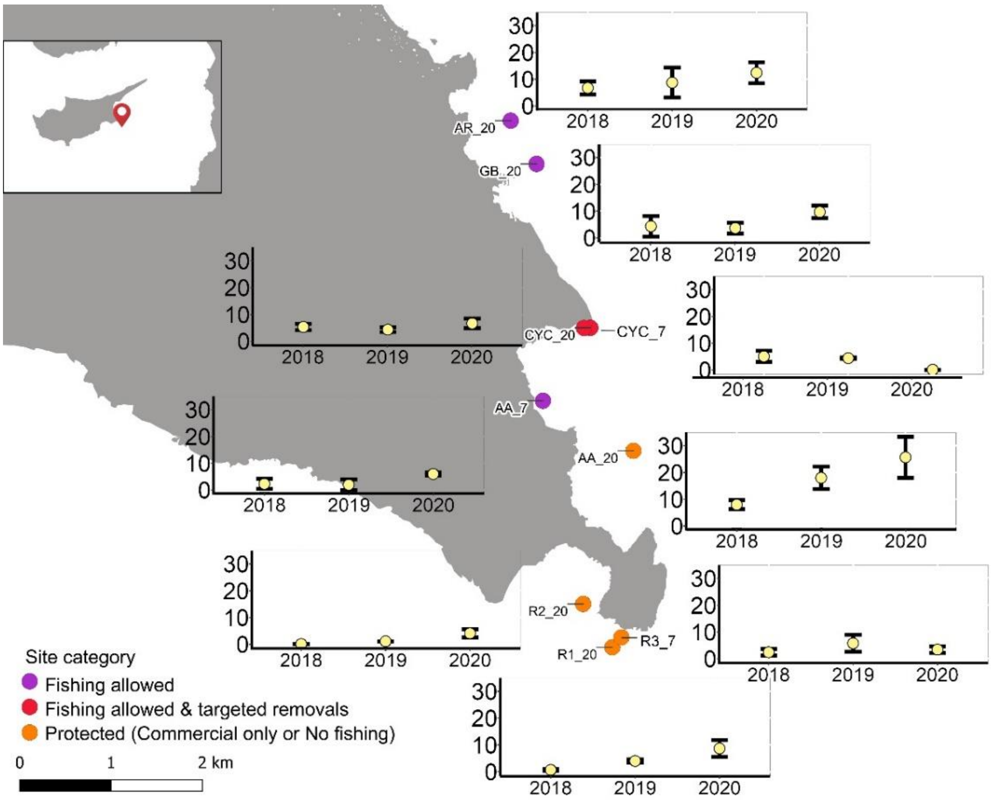
Topic	#	Questions	Answers provided	Group interviewed
	16(iv)	Would you willing to participate in lionfish removal initiatives because of encouragement from scientists and managers?	Likert-type scale: 0-10	
	17	What are the barriers to getting involved in lionfish removal activities?	Open-ended question (i.e. No possible answer provided)	
	18	What are the enablers for getting involved in lionfish removal activities?	Open-ended question (i.e. No possible answer provided)	
Part G: Socio-demographic	22	Gender	Man; Woman	Stakeholders and Public
	23	Age	Open-ended question (i.e. No possible answer provided)	
	24	Marital status	Married; Not married; Other	
	25	Education	Read and write; Elementary school; Higher school; Lyceum; College; University; Postgraduate education	
	26	Occupation	Full time; Part time; Housekeeping; Student/soldier; Pensioner; Unemployed (less than 12 months); Unemployed (more than 12 months); Public worker; Private worker; Self-employed; Land-owner	
	27	If you are a pensioner, record your previous occupation	Open-ended question (i.e. No possible answer provided)	
	28	Residence city	Nicosia; Limassol; Larnaca; Famagusta; Paphos	
	29	Area of residence	Urban; Rural	
	30	Post code of residence	Open-ended question (i.e. No possible answer provided)	
	31	Date of interview	Open-ended question (i.e. No possible answer provided)	

11.2. APPENDIX 2. Chapter 2 supplementary material(s)

(A) Details regarding the removal events carried out by volunteer divers at the sites CY_7 and CY_20 between 2018 and 2020.

Removal event date	Number of divers participating	Lionfish removed	CPUE (caught individuals / per diver)	Lionfish missed	Catch efficiency (%)
30/04/2019	2	19	9.5	5	79.17
26/05/2019	18	72	4	38	65.45
06/06/2019	8	37	4.63	19	66.07
29/09/2019	42	44	1.05	21	67.69
30/11/2019	14	67	4.79	26	72.04
02/02/2020	16	44	2.75	27	61.97
22/04/2020	5	13	2.6	8	61.9
17/05/2020	6	20	3.33	30	40
05/07/2020	8	79	9.88	35	69.3

(B) Changes of lionfish densities (individuals/500 m2) between 2018 to 2020 at the nine sampling stations of the temporal monitoring survey.



(C) Information criteria for log likelihood, ΔAICc, and Akaike weight for Poisson zero-inflated generalized mixed effects models (GLMMs) for lionfish densities. GLMMs evaluated different combinations of the covariates of habitat, protection zone, depth, predators, and prey. The same covariates used in the count component were also used in the zero-inflated component with the exception terms from the zero-inflated part which had high multicollinearity or simplified for the models to converge.

Response variable	Model		Log likelihood	ΔAICc	Weight
Lionfish density	1.	Count component: habitat + depth + protection zone + prey density Zero-inflated component: depth + protection zone + prey	-149.49	0.00	0.642
	2.	Count component: protection zone + depth + habitat Zero-inflated component: habitat + depth + protection zone	-151.68	1.93	0.244
	3.	Count component: protection zone + depth + habitat + predators Zero-inflated component: habitat + depth + protection zone	150.50	2.10	0.168
	4.	Count component: habitat + depth + protection zone + prey density + predators Zero-inflated component: depth + habitat + protection zone	149.70	2.90	0.108
	5.	Count component: depth + protection zone + prey Zero-inflated component: depth	-156.29	4.00	0.087
	6.	Count component: prey + protection zone + predators Zero-inflated component: prey + protection zone	155.20	6.50	0.180
	7.	Count component: prey + protection zone Zero-inflated component: prey + protection zone	-156.83	7.42	0.016
	8.	Count component: protection zone Zero-inflated component: protection zone	-157.70	9.20	0.005
	9.	Count component: depth + protection zone Zero-inflated component: protection zone	-158.91	9.24	0.006
	10.	Count component: habitat + protection zone + predators Zero-inflated component: habitat + predators	-158.10	9.90	0.003
	11.	Count component: habitat + protection zone Zero-inflated component: habitat + protection zone	-158.70	11.16	0.002
	12.	Baseline model	-164.38	11.18	0.002

(D) Results of the generalized mixed effects model (GLMM) (#2 in Appendix 2C) used for the illustration of the lionfish spatial distribution in Figure 4 of the main text. Model #2 was the best-fitted model combination after excluding the prey density (which was not representative for areas with soft substrate as transects were placed only in rocky substrate and Posidonia oceanica meadows).

Factor	**Oddsratio**	**95% CI**	**z-value**	**p-value**
Conditional fixed effects				
(Intercept)	0.1	0.01-1.1	-1.88	0.06
protection zone (Commercial only)	1.92	0.58-6.34	1.07	0.29
protection zone (No fishing)	**8.11**	**1.93-34.12**	**2.86**	**<0.001**
depth	1.03	0.93-1.13	0.6	0.57
habitat (rock)	3.27	1.07-9.95	2.07	0.04
Conditional zero-inflation effects				
(Intercept)	12.25	0.01-10676.43	0.73	0.47
habitat (rock)	1	0.01-73.32	0	1
depth	0.73	0.49-1.09	-1.55	0.12
protection zone (Commercial only)	0.15	0.01-3.81	-1.15	0.25
protection zone (No fishing)	10.11	0.21-487.35	1.17	0.24

11.3. APPENDIX 3. Chapter 4 supplementary material(s)

(E) Non-indigenous species questionnaire used to assess fishers' knowledge and perceptions.

Demographic data

1. Sex: Male Female Prefer not to say

2. Age: ___________ Prefer not to say

3. What is your educational level?

a. I have not finished primary school b. Primary school c. Gymnasium

d. Lyceum e. Student f. College / University

g. Postgraduate / Doctoral h. Prefer not to say

4. Do you own a vessel? Yes No

5. Do you own a fishery licence? If yes, Please specify

6. Please specify the gear(s) that you use for your fishing:

Knowledge and perceptions for non-indigenous species (NIS) in general

1. Do you know what is a 'non-indigenous' or 'alien' species? Yes or No (If not, explain)

2. Using a scale - 2 to +2, whereas -2 = very negative, 0 = neutral and +2 = very positive, to what degree do you think that alien species affect your fishery? ____________

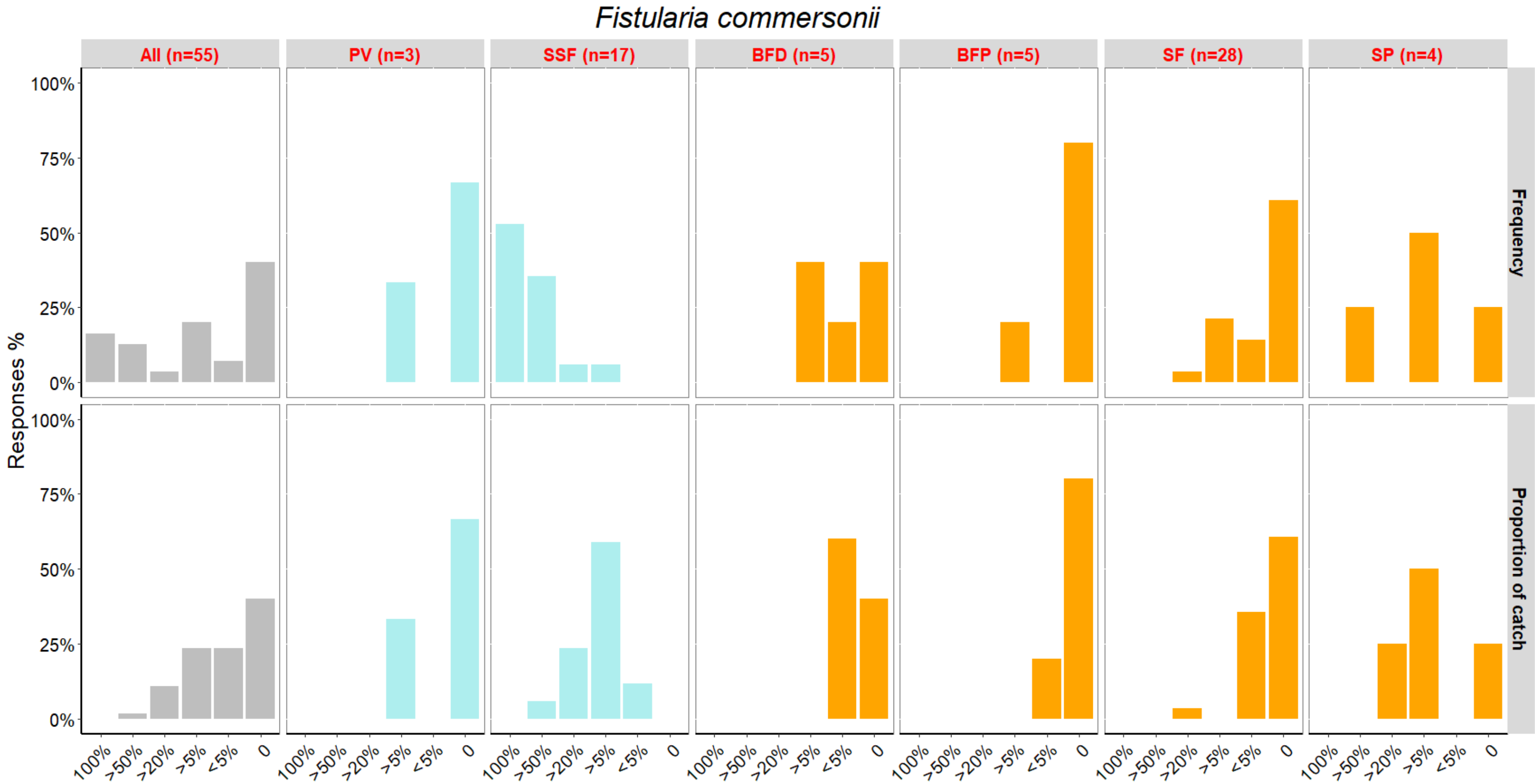
3. Do your increase the duration of your fishing as a result of NIS catches? If so, please quantify (minutes/trip):

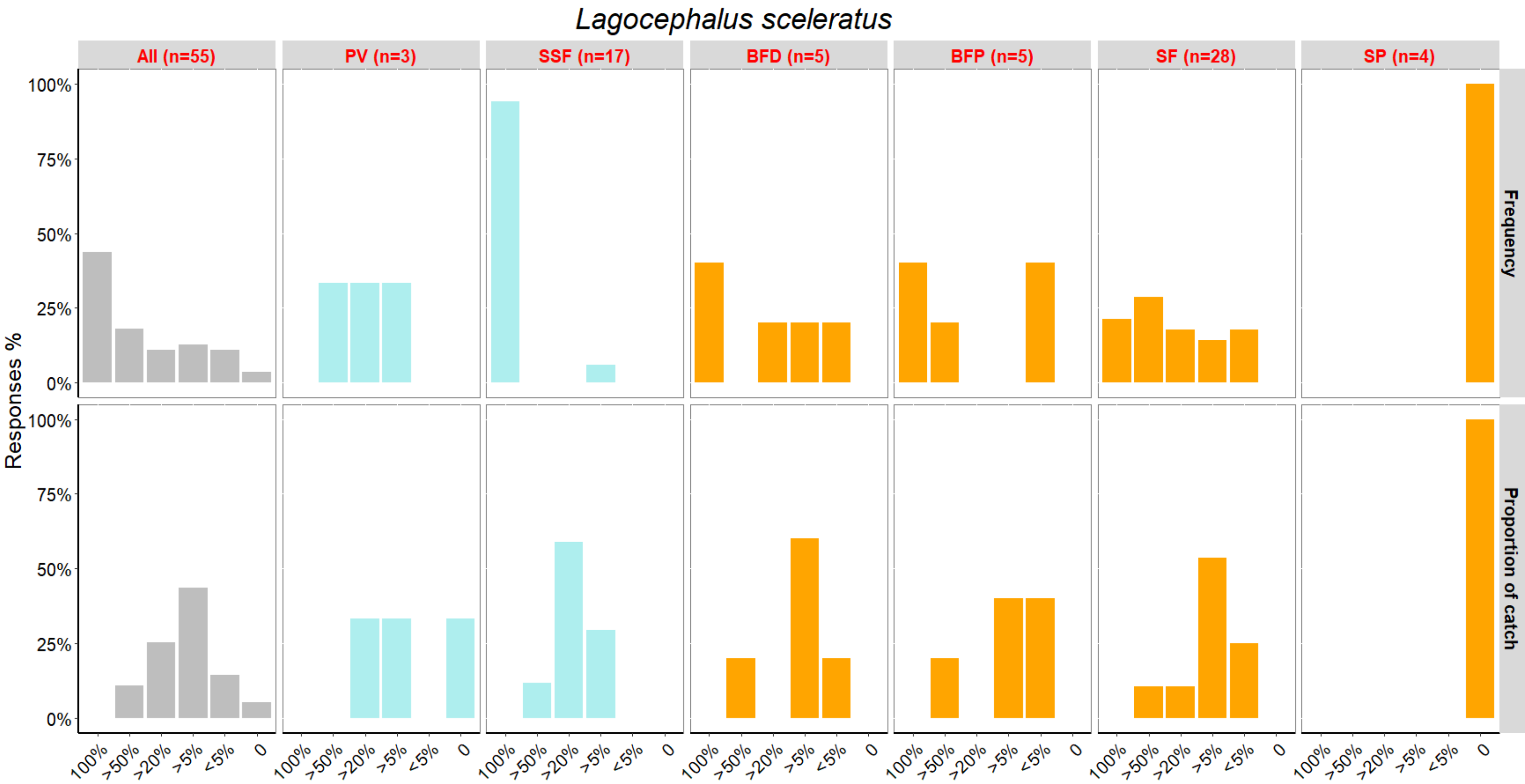
Knowledge and perceptions for selected non-indigenous species (NIS)

1. To be completed for each species (a picture was shown for each species):

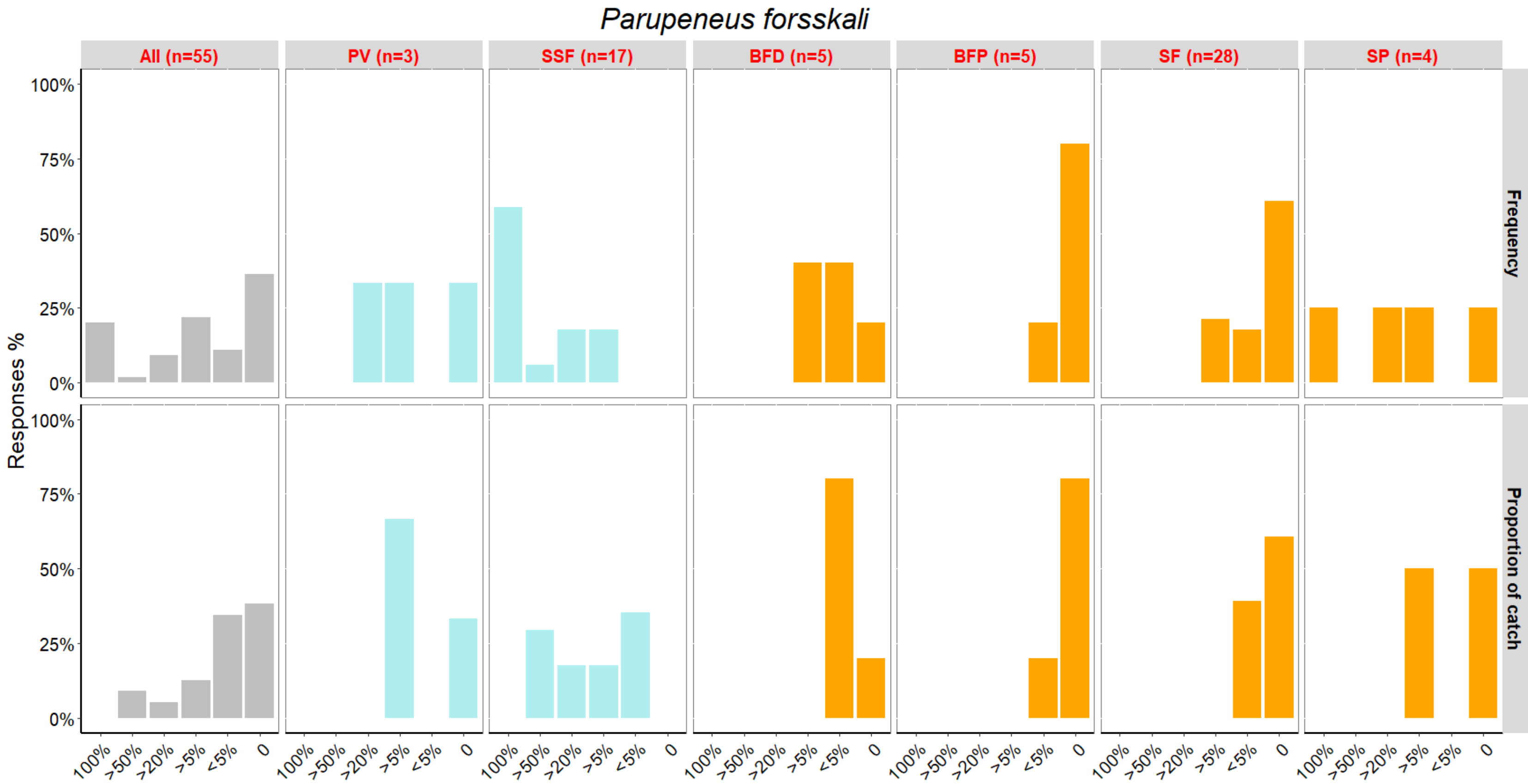
Species	Common name	Alien to the Mediterranean (Yes or No)	Positive (+), Negative (-), Neutral (/) or I don't know (IDK)	Discarded (Yes or No)	Fishing frequency 100% 50-99% 25-49% 5-24% 1-4% 0%	Proportion of catches 100% 50-99% 25-49% 5-24% 1-4% 0%	Damages in catches/tools: (cost / year)	Injuries (injuries / year)	Caused change of fishing (1) tools, (2) location (3) duration
Lagocephalus sceleratus	Silver-cheeked toadfish								
Torquigener flavimaculosus	Yellowspotted puffer								
Parupeneus forsskali	Red Sea goatfish								
Pterois miles	Devil firefish								
Fistularia commersonii	Bluespotted cornetfish								
Sepioteuthis lessoniana	Bigfin reef squid								
Sargocentron rubrum	Redcoat								
Siganus luridus	Dusky spinefoot								
Siganus rivulatus	Marbled spinefoot								
Sphyraena chrysotaenia/flavicauda	Yellowstripe barracuda								
Pempheris sp									
Saurida lessepsianus									

(F) *Frequency and proportion of catch of each non-indigenous species based on the fishers responses. SSF: Small-scale fishers, PV: Polyvalent, BFD: Boat fishing demersal, BFP: Boat fishing pelagic, SF: Shore fishing, SP: Spearfishing. Grey colour shows all responses, blue colour indicates commercial fishers, and yellow colour indicates recreational fishers.*



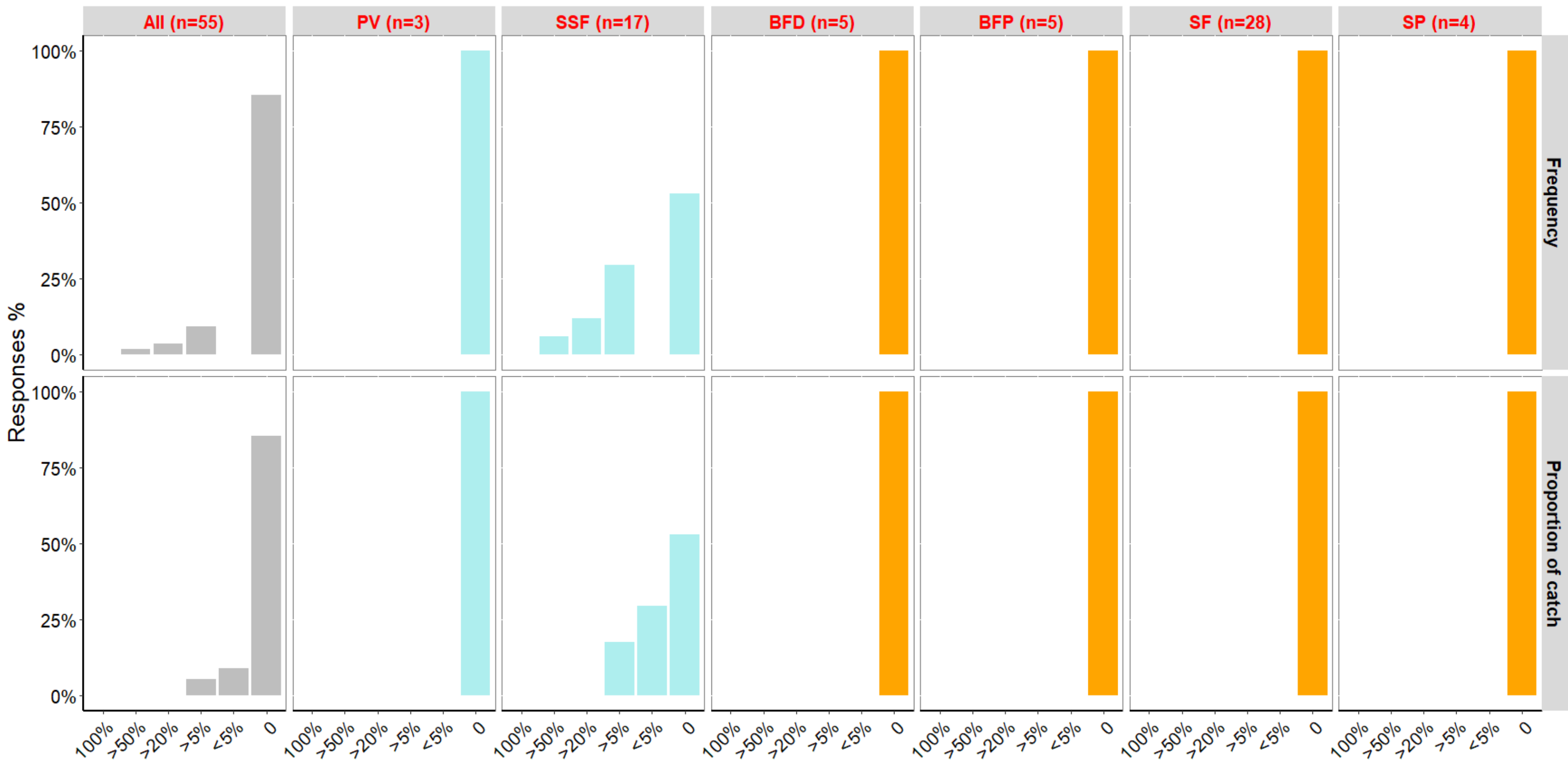


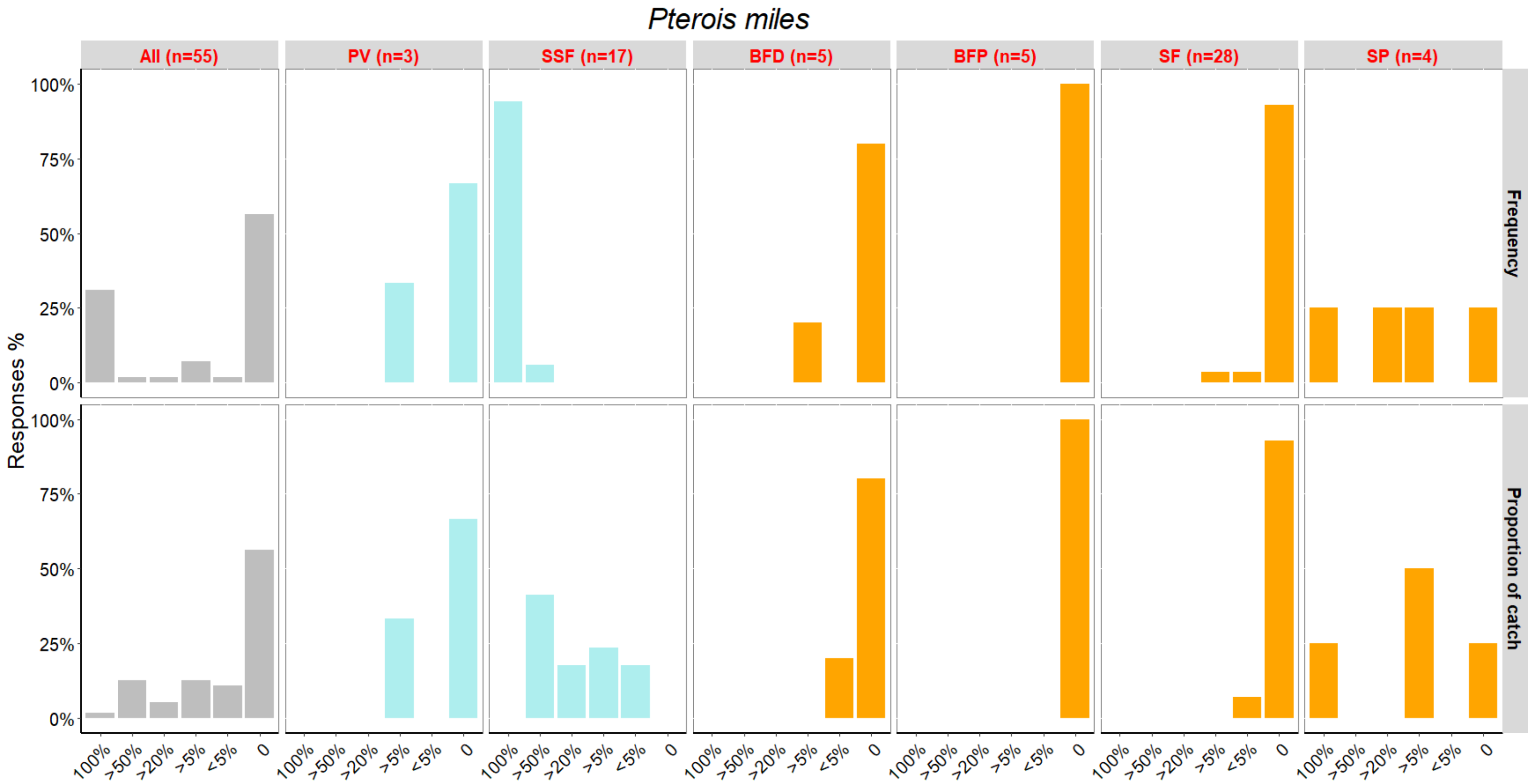
Lagocephalus sceleratus
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
>5%
<5%
0



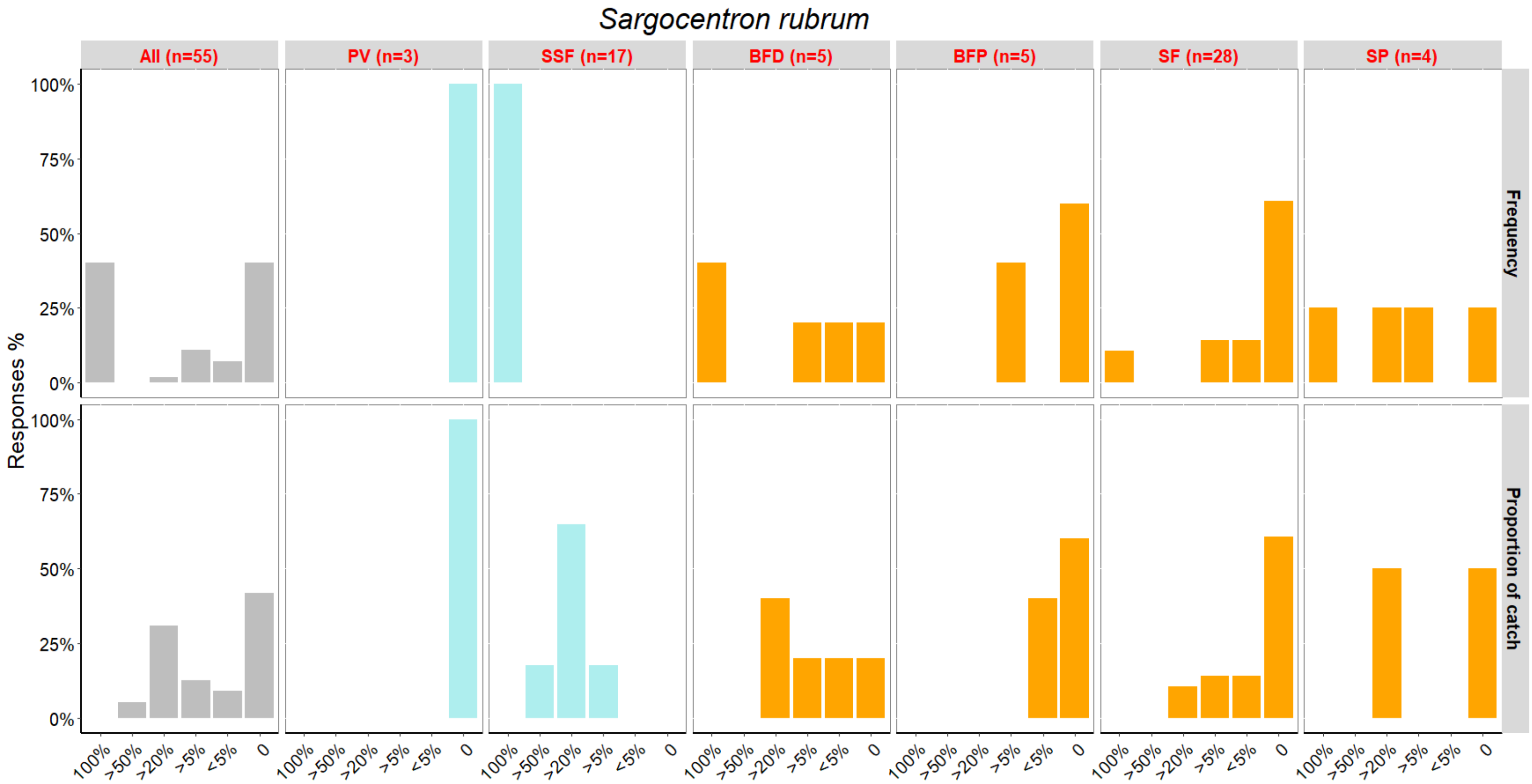
Parupeneus forsskali
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
>5%
<5%
0

Pempheris sp.





Pterois miles
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
>5%
<5%
0


Sargocentron rubrum
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
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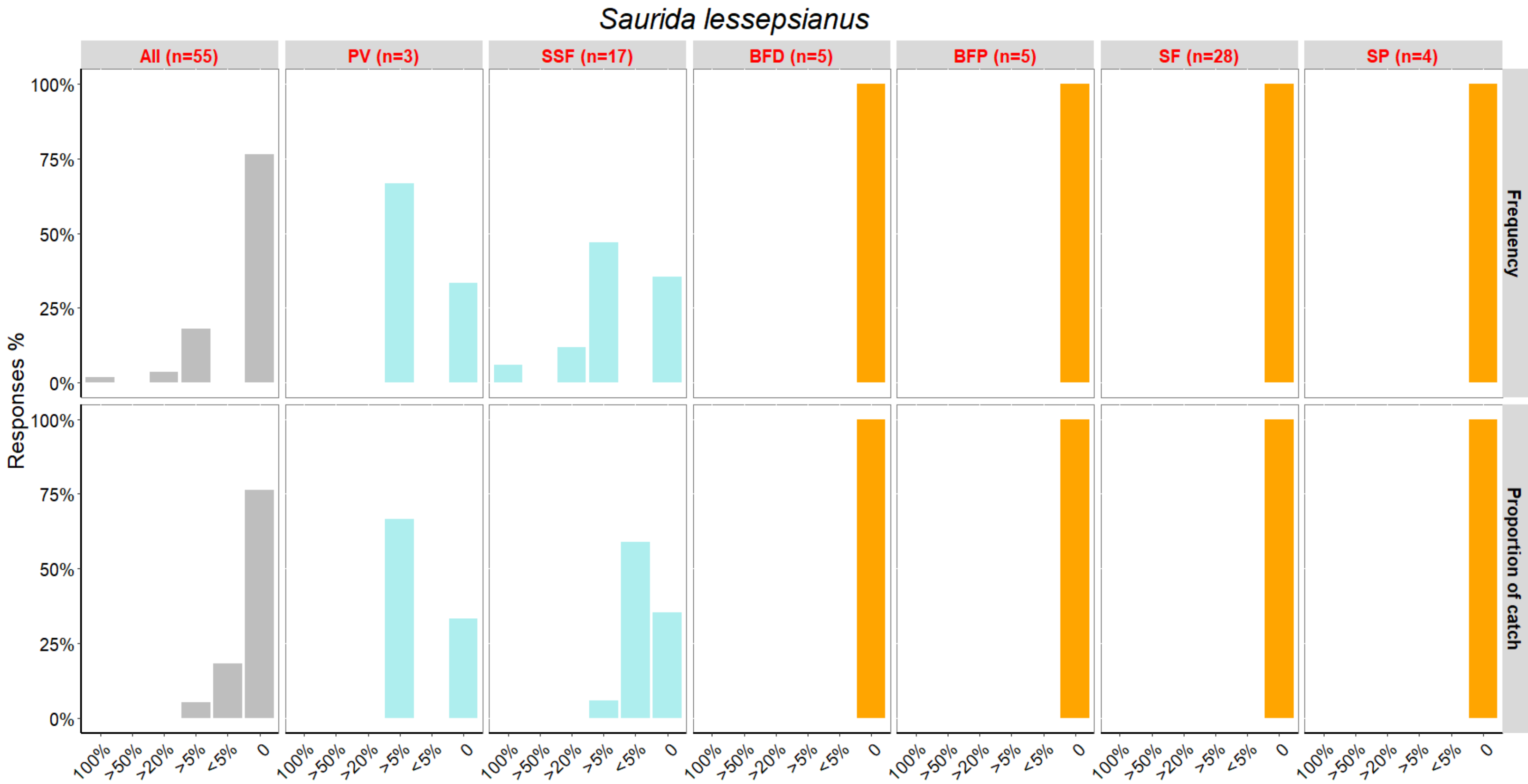
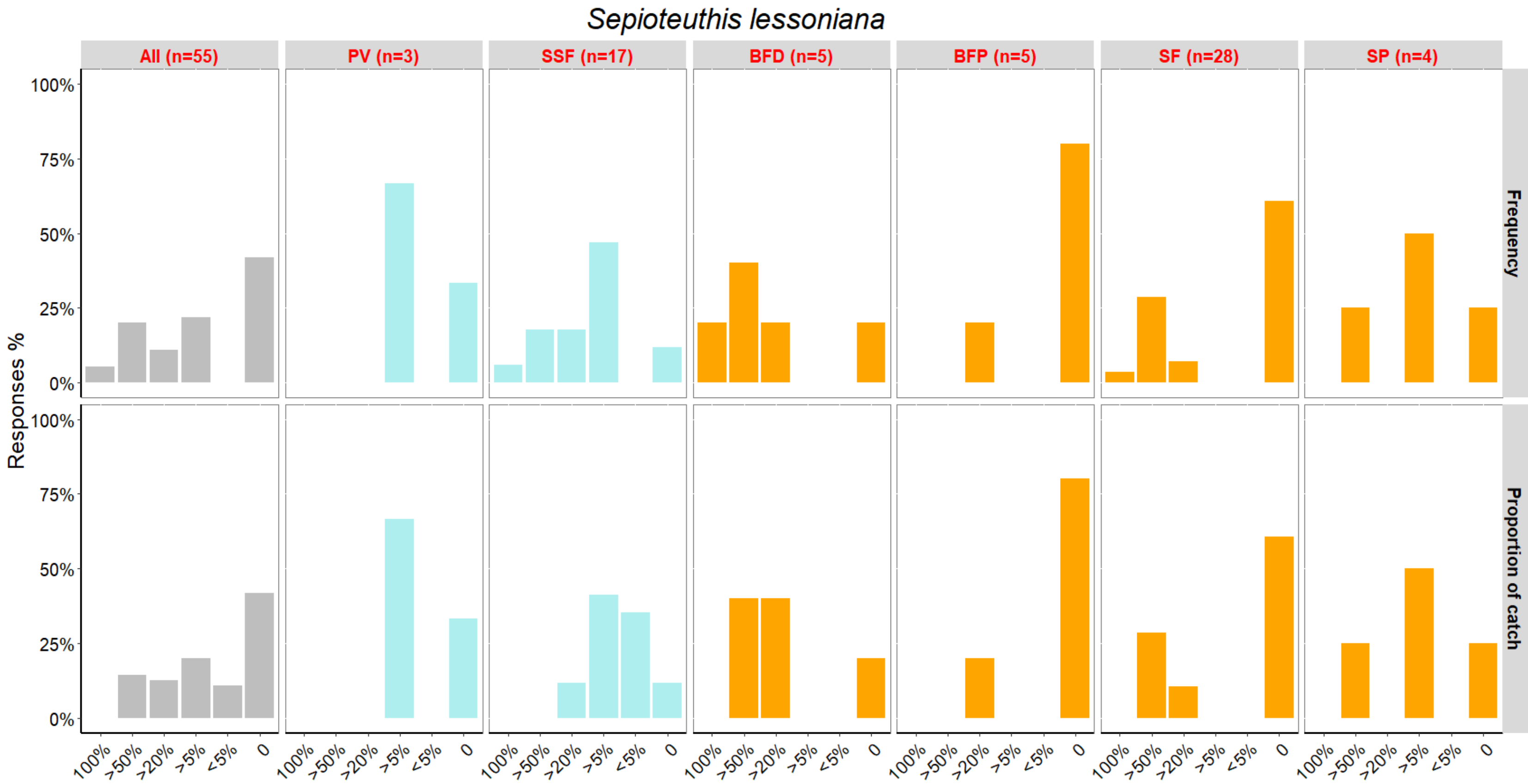
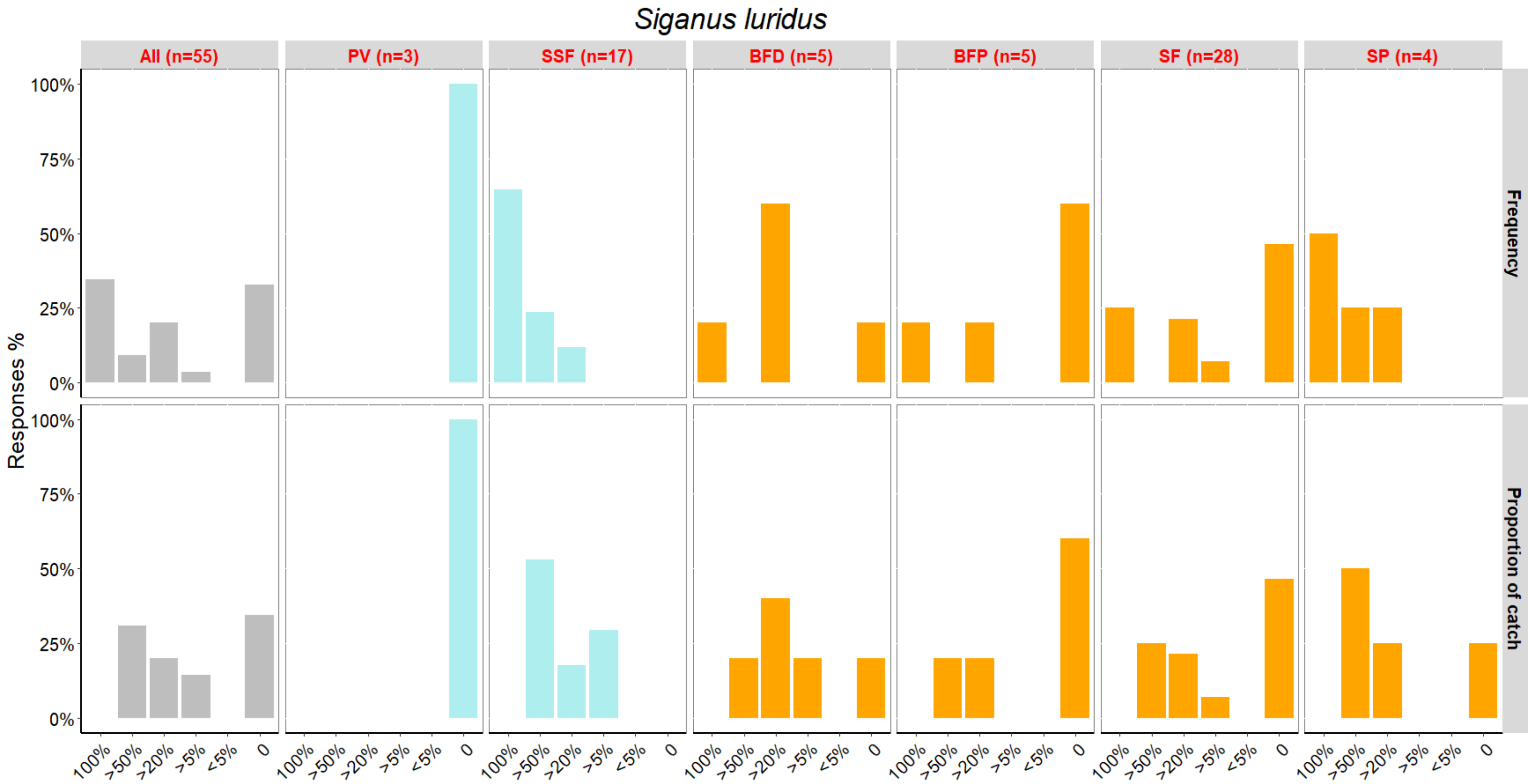

Saurida lessepsianus
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
>5%
<5%
0



Sepioteuthis lessoniana
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
>5%
<5%
0


Siganus luridus
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
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25%
0%
100%
>50%
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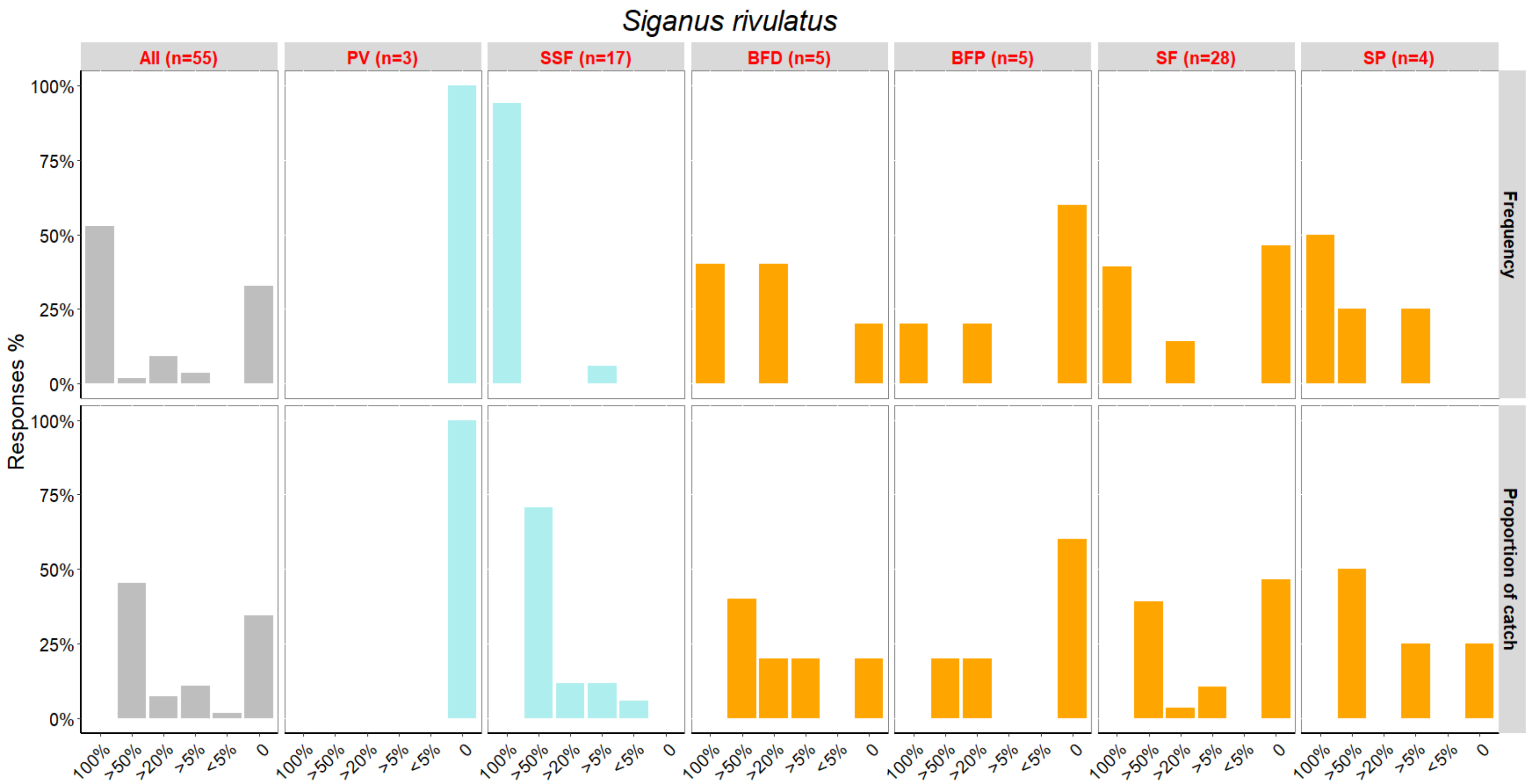
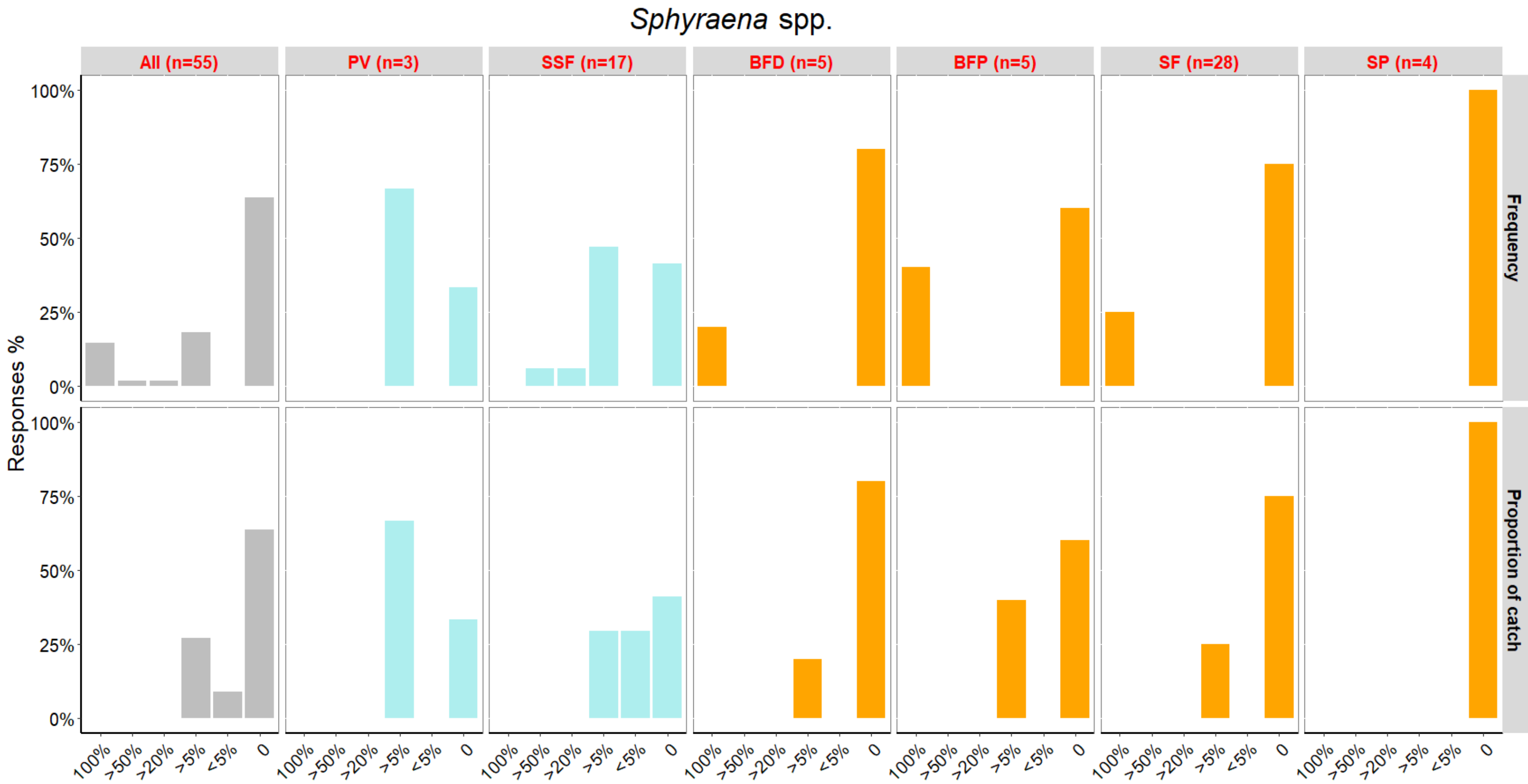
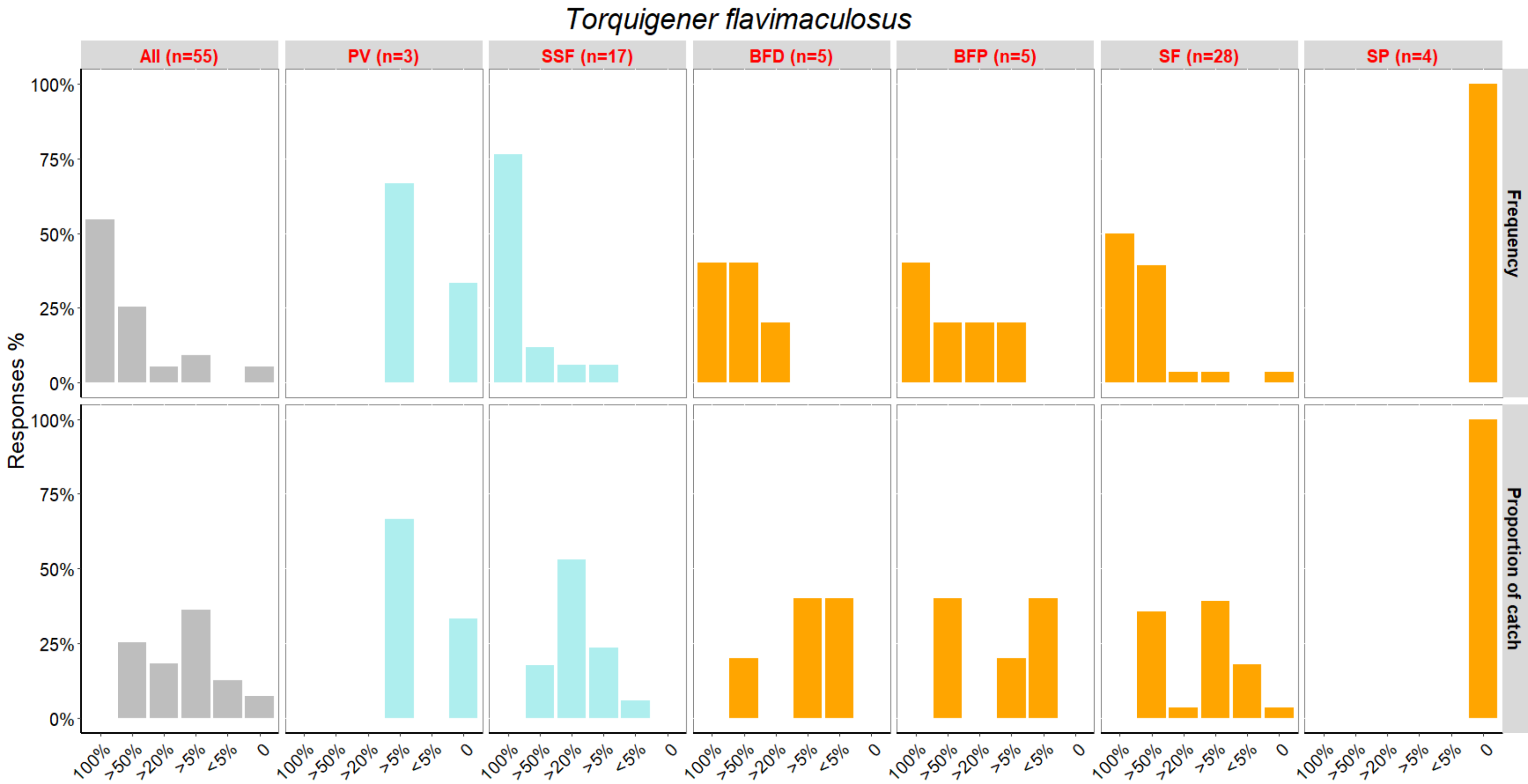
<5%
0


Siganus rivulatus
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
>5%
<5%
0

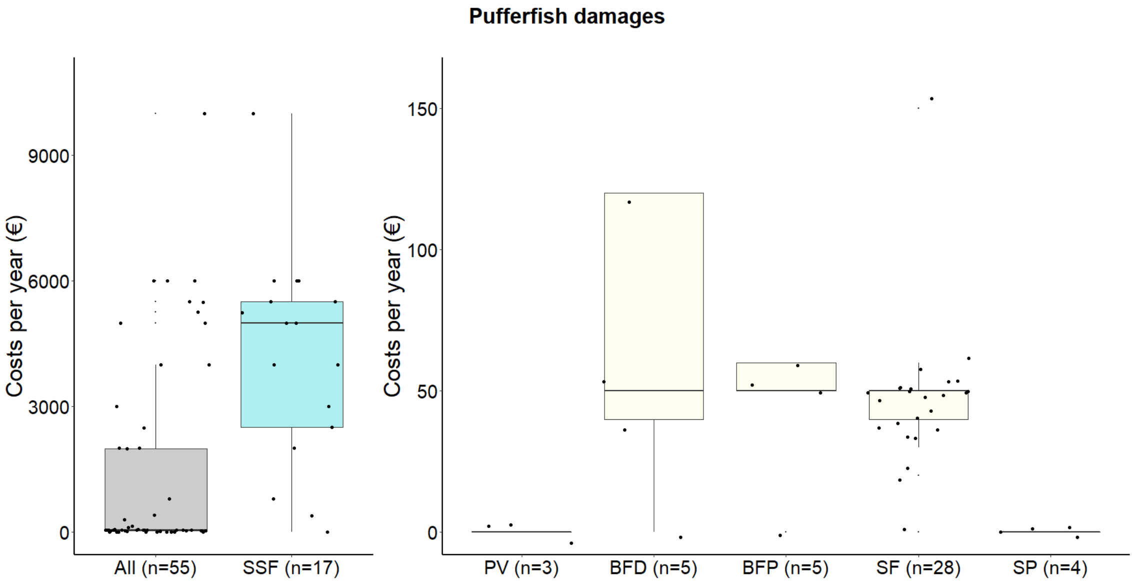


Sphyraena spp.
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
>5%
<5%
0

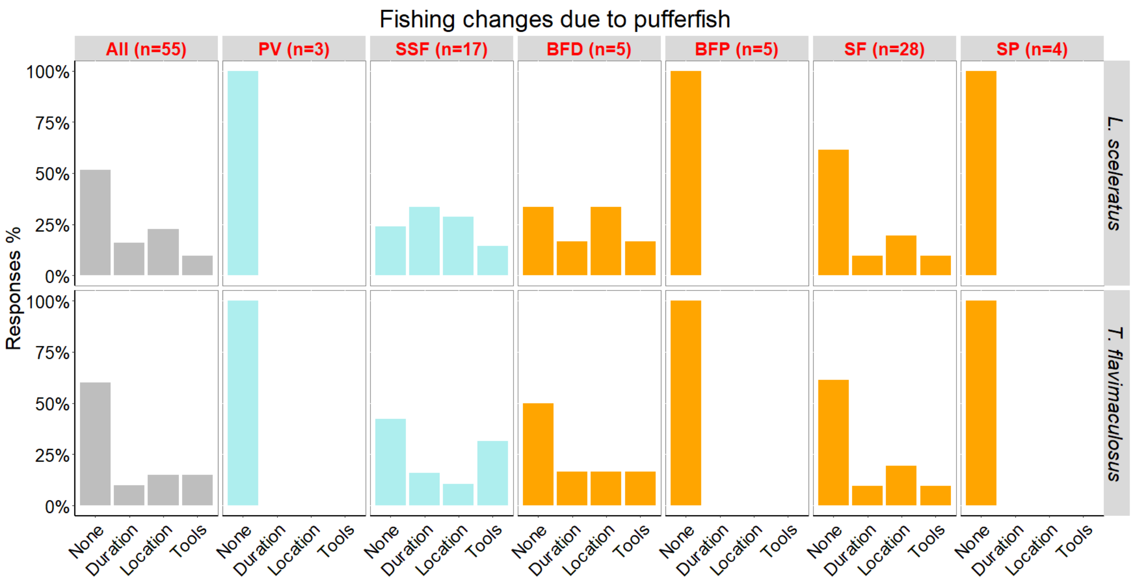


Torquigener flavimaculosus
All (n=55)
PV (n=3)
SSF (n=17)
BFD (n=5)
BFP (n=5)
SF (n=28)
SP (n=4)
Frequency
Proportion of catch
Responses %
100%
75%
50%
25%
0%
100%
>50%
>20%
>5%
<5%
0

(G) Costs (in €) per year caused by direct damages of pufferfish according to the fishers' responses. Commercial fishers (SSF: Small-scale fishers; PV: Polyvalent) and recreational fishers (BFD: Boat fishing demersal; BFP: Boat fishing pelagic; SF: Shore fishing; SP: Spearfishing). Grey colour shows all responses, blue colour indicates commercial fishers, and yellow colour indicates recreational fishers.



(H) Percentage of fishers who reported changes in the duration, location, and/or tools due to the presence of pufferfish (Lagocephalus sceleratus and Torquginer flavimaculosus). Commercial fishers (SSF: Small-scale fishers; PV: Polyvalent) and recreational fishers (BFD: Boat fishing demersal; BFP: Boat fishing pelagic; SF: Shore fishing; SP: Spearfishing). Grey colour shows all responses, blue colour indicates commercial fishers, and yellow colour indicates recreational fishers.



11.4. APPENDIX 4. Chapter 5 supplementary material(s)

(A) *Risk Assessment for the lionfish Pterois miles (Bennett, 1828) that was submitted to the European Commission for inclusion of the species in the Union List of the Invasive Alien Species*

The document can be found attached (as pdf) or online from the following link:

https://circabc.europa.eu/ui/group/98665af0-7dfa-448c-8bf4-

e1e086b50d2c/library/10ac3565-b3f8-4263-9185-3f58a1f32d5b/details

(B) Dataset of lionfish sightings that was used to develop the maps of the Chapter (attached as Excel file).

(C) Risk Management for the lionfish Pterois miles (Bennett, 1828) that was submitted to the European Commission as complementary to the Risk Assessment for inclusion of the species in the Union List of the Invasive Alien Species.

Annex with evidence on lionfish (*Pterois miles)* measures, their implementation cost and cost-effectiveness

Species (scientific name)	*Pterois miles* (Bennett, 1828)
Species (common name)	Common lionfish (GB), Devil firefish (GB), Rotfeuerfisch (DE), Pez león soldado (ES), Pez fuego diablo (ES), Pez escorpión (ES), Pesce diavolo di fuoco (IT), Λεοντόψαρο (CY), Λιονταρόψαρο (GR)
Author(s)	Periklis Kleitou, Sian Rees, Demetris Kletou, Ioannis Savva, Jason Hall-Spencer
Date Completed	10.02.2020

Summary
Several measures can be implemented to mitigate the lionfish invasion in the Mediterranean. Hereby, we chose to present the most cost-effective and/or important options based on our expertise and opinion for each of the categories (i) Prevention, (ii) Eradication and (iii) Management. Measures for prevention analysed include: P1. Barriers to the Suez Canal P2. Awareness campaigns for the aquarium trade P3. Trade prohibition of *Pterois miles* by including it in the EU priority list (EU 1143/2014) Measures for eradication analysed include: E1. Early surveillance systems E2 Scientific monitoring E3. Targeted removal for early eradication Measures for management analysed include:

M1. Diver-led culling with hand spears
M2. Citizen science monitoring
M3. Awareness and participation
M4. Regional action
M5. New removal/fishery techniques
M6. Market (consumption and jewel-crafting) promotion
M7. Scientific monitoring

Since the invasion of lionfish in the basin is at a mature level with high population levels in many areas (including EU countries), its introduction to suitable habitats of the EU cannot be prevented. However, prevention measures can limit the genetic diversity of lionfish in the Mediterranean and prevent facilitation of lionfish spread within the basin. At a time when Egypt is investing significant developments in the area of the Suez Canal (including mega desalination plants), it might be prudent to collaborate and explore prevention measures that can be used for the lionfish and other Lessepsian invasions in the basin. Trade prohibition of lionfish in the aquarium trade and awareness campaigns are cost-effective ways to prevent further spread and new introductions of lionfish through this pathway. Measures for eradication should be limited to targeted areas where lionfish is next anticipated since it is very highly unlikely to eradicate the species from locations where lionfish is established. The measures for management that we propose are cost-effective and all important towards lionfish (and other alien species) management in the basin. We elaborate on the experience gained from the RELIONMED project to analyse each measure. We show that diver-led culling can be effective to control lionfish at priority areas; however, legislative framework needs to adapt to allow removal events with scuba diving. Citizen science monitoring, awareness measures, regional action, and market promotion are all very useful tools for management of lionfish and their promotion will offer important benefits (e.g. increased citizen science participation, better monitoring, consumption, etc.) for other invasive species too. New removal/fishery techniques hold potential but need development and potentially legislation changes. We highlight the importance of scientific monitoring at sentinel locations to better understand lionfish (and of other invasive species) interactions, impacts and to offer data vital for early response and management.

To guide implementation cost and cost effectiveness of each measure, we used the following categories:
For the costs (Euros) of each measure:
>5,000,000 = very high
500,000- 4,999,999 = high
10,000 – 499,999 = moderate
500 - 9,999 = low

<499 = very low

- For the effectiveness of the approach towards the goals of the management measure:
  Low – negligible effect
  Moderate – Moderate effect
  High – Likely to minimise introduction or spread or invasive effects of lionfish

- For the social acceptability:
  High, Moderate, Low

- For the duration:
  Permanent, Temporary

Detailed assessment			
	Description of measures	**Assessment of implementation cost and cost-effectiveness (per measure)**	**Level of confidence**
Measures to achieve prevention (P1-P3)	**P1**. **Barriers to the Suez Canal** Installation of a high-salinity section in the Suez Canal (Goren & Galil, 2005) / Reinstating the former salinity barrier of the Bitter Lakes (Galil *et al*., 2017). Long-term management of invasive species introductions is viable only if taken in tandem across the region. A concerted action at a regional level through the Barcelona Convention is necessary.	As mentioned in the risk assessment undertaken for the Striped Eel Catfish *Plotosus lineatus* (Galanidi *et al.*, 2017), reinstating a high salinity section in the Suez Canal requires international co-operation. This would avoid continued introductions of lionfish and other Red Sea species into the Mediterranean. To tackle the spread of lionfish that are already in the	Moderate

	The Suez Canal is the major pathway of invasive species in the Mediterranean and its impact will likely increase as climate change continues; favouring thermophilic species of Indo-Pacific origin. The much lower rate of species introductions through the Panama Canal, which includes a freshwater section (consisting partly of the natural Gatun Lake) and the increase in species introductions through the Suez Canal after the salinity changes in the Bitter Lakes and the Nile estuary provide evidence that a salinity barrier could be an effective solution for the canal pathway (Gollasch, 2011; Galanidi *et al.*, 2017). Apart from the salinity change, establishment of locks would additionally decrease current movements and limit the dispersal of propagules (e.g. larvae and eggs) drifting to the Mediterranean.	Mediterranean other measures are needed. Although biosecurity measures in the Suez Canal are of paramount importance to tackle non-indigenous species introductions and impacts in the Mediterranean, they cannot prevent the spread of those lionfish that are already in EU waters. They can limit the genetic diversity of lionfish in the Mediterranean. The costs are high but could be decreased if they are combined with other construction initiatives on the Suez Canal. The Egyptian government is in fact building some mega desalination plants in the vicinity of the Suez Canal and their hypersaline effluent could be strategically used to re-establish the salinity barrier in the Bitter Lakes. Collaboration with Egypt and other countries of the Mediterranean basin are needed to develop prevention measures at the Suez Canal at a critical time when several developments have been planned for the area. Costs = high to very high (potential to be combined with other construction initiatives on the Suez Canal will reduce construction costs) Effectiveness = high (to cut off a source route into the Mediterranean)	

		Social acceptability: high Duration: permanent Other benefits from such measure can be massive; preventing future introductions of new invasive species and subsequent costs, while preventing genetic and propagules pressure from the Red Sea to the Mediterranean for the species that already invaded.	
	P2. Awareness campaigns for the aquarium trade To prevent intentional release from domestic aquaria: awareness campaigns to educate the public about the threats posed by *Pterois miles* to the environment, ecosystem services and human well-being. Lionfish are imported into many Mediterranean countries by the aquarium trade from the Indo-Pacific. RELIONMED surveys indicate that many pet-shops in Cyprus are selling lionfish and the situation is similar in other Mediterranean countries such as Turkey (Gülenç, 2019), Lebanon (Bariche, pers. communication), and Italy (Tiralongo, pers. communication).	The costs of awareness and educational campaigns vary depending on the target group and platform used (e.g. media, social platforms, personal communication) and public events (e.g. workshops, info days, etc.). Nevertheless, a large number of people can be reached and educated with relatively little effort and cost. Advancement of education and awareness has been considered as the first priority measure for managing invasive species in the Mediterranean (Giakoumi *et al.*, 2019). Such activities will not only enhance knowledge and improve perceptions about lionfish, but they will also improve knowledge about invasive species and potentially stimulate the interest of the public for other environmental issues.	High

	Awareness campaigns among citizens of the EU and non-EU countries should be also promoted to deactivate this potential pathway for lionfish introductions. Countries such as Turkey are already using lionfish captured in their coasts to sell them in the aquarium/petshop trade (Gülenç, 2019). In Cyprus, lionfish captured alive by free divers were sold on numerous occasions to pet shops (Jimenez unpublished data). To prevent further introductions of lionfish to already invaded or as yet uninvaded areas of Europe, it is important that precautionary measures are implemented and for people to become aware and environmentally conscious enough to avoid intentional release of individuals to the marine ecosystem through campaigns and educational material.	RELIONMED project organised several workshops and participated in many events in Cyprus; directly involving and engaging thousands of people in RELIONMED events with few thousands Euros cost. Educational and training events for divers and fishers were organised in all cities of Cyprus while RELIONMED was disseminated in local and international channels (e.g. The Guardian, BBC, Euronews) and reached millions of people. Posts on mass media was achieved with the collaboration and interest of stakeholders with almost no cost at all. The improvement in education and awareness about lionfish was reflected in surveys with a representative sample from the public of Cyprus. Indicatively, surveys in 2017 (beginning of project) has shown that approximately 25.70% of the public was aware about lionfish while in July 2019, approximately 58.40% was aware. From those, 76.70% disagreed that lionfish can damage the environment in 2017 and this percentage dropped to around 49% in 2019. Only 15% would consume lionfish in 2017 while 25% would consume it in 2019.	

		Even if education and awareness campaigns prevent future intentional releases via the aquarium trade, the measures will not be effective to prevent introduction to the EU as the species is already established in the basin and is spreading naturally. Prevention of future releases will prevent genetic increases of lionfish and potential speed up of the spread that could be caused by a release to a suitable habitat where lionfish hasn't yet established. Costs= very low to low (can be combined with other measures, e.g. see M3). Effectiveness = Moderate. This will prevent intentional releases via the aquarium trade, However, this must also be combined with measures to prevent the spread of lionfish species already established Social acceptability: high Duration: temporary	
	P3. Trade prohibition of *Pterois miles* by including it in the EU priority list (EU 1143/2014)	If *P. miles* is listed as an IAS of Union Concern (Regulation 1143/2014), then its trade into and within EU will be banned. Costs= very low	High

		Effectiveness = high (to prevent future introductions via the aquarium trade) Social acceptability: high Duration: permanent	
Measures to achieve eradication (E1-3)	**E1. Early surveillance systems** Several national and regional collaboration platforms on invasive/alien species (e.g. EASIN, ESENIAS, ELNAIS, Sea Watchers) and citizen science programmes have been established (for a review of initiatives see Giovos *et al.*, 2019). These initiatives have been proved effective for the early detection of Lessepsian invasive species. In collaboration with RELIONMED project, MedMIS has established a platform specific for lionfish (http://www.iucn-medmis.org/?c=LionFish/show) aiming to promote and motivate users across the entire Mediterranean.	Almost all *P. miles* records in the Mediterranean that have been published in the literature originate from a record provided by a citizen-scientist; particularly those which represent the first records of the species in a country (e.g. see Turan *et al.*, 2014; Bariche *et al.*, 2013; Dailianis *et al.*, 2016; Ali *et al.*, 2017; Azzurro *et al.*, 2017; Al Mabruk & Rizgalla, 2019). Surveillance systems are already in place so they don't require substantial resources apart from maintenance and running costs. Promotion of the systems through the media and campaigns can enhance participation and success of the platforms. Such promotion activities are currently being implemented by the RELIONMED project and we expect that the number of citizens recording lionfish in the MedMIS platform will increase. Given the distinctive and spectacular appearance of lionfish, citizens can easily identify it. Promotion of surveillance systems can be combined with other management	Moderate

		measures such as M3. Surveillance systems with citizen-science support can be considered as the most effective method to achieve early detection of lionfish in new locations. Costs= low Effectiveness = high (to detect lionfish at an early stage of their invasion in new locations) Social acceptability: high Duration: permanent The systems also offer other benefits as they increase awareness and motivate the public to report alien species to researchers.	
	E2. Scientific monitoring Utilization of existing survey programmes and/or targeted scientific monitoring in areas where lionfish is next anticipated to invade (and establish) can be implemented to early detect lionfish invasion. Targeted monitoring could be implemented in countries such as Albania, Italy and Tunisia close to areas where lionfish have established.	Cost effective methods such as the utilisation of existing survey programmes (e.g. MEDITS International bottom trawl survey in the Mediterranean Sea) can be used. Targeted scientific monitoring can also be utilized in areas where lionfish is anticipated to next invade. However, their effectiveness is doubtful. For instance, the area of Cavo Greco in Cyprus (hotspot of alien species) was monitored under a national scheme using visual census by	Moderate

		scientists. After more than 2100 transects (× 25 m) and 450 random photoquadrats during day light in different habitats (i.e., *Posidonia* meadows, and rocky and soft substrates), no new records of alien species were obtained (Kleitou *et al.*, 2019). On the other hand, six new alien species were sighted and reported for the first time based on the volunteered contributions of citizen-scientists (Kleitou *et al.*, 2019). Cost= very low to low (if combined with existing survey programmes) Effectiveness = moderate (to detect lionfish at an early stage of their invasion in new locations) Social acceptability: high Duration: temporary	
	E3. Targeted removal for early eradication Rapid eradication of lionfish after its detection.	Early detection and rapid response for early eradication of marine species has been achieved only rarely and in restricted areas. Examples include the eradication of the black-striped mussel *Mytilopsis sallei* in Darwin Harbor, Australia (Willan *et al*., 2000) and of the alga *Caulerpa taxifolia* in Agua Hedionda Lagoon and Huntington Harbor, California (Anderson, 2005). Eradication attempts of the lionfish in the Carribean have also demonstrated that	Moderate

		complete eradication is unlikely (Barbour *et al*., 2011; Frazer *et al*., 2012, Green *et al.*, 2014). Early response (e.g. spearfishing a lionfish after its detection in a new area) should be promoted since its costs will not be high and despite low chances of avoiding the invasion in the new area, it might delay it until EU and Mediterranean countries are more prepared to challenge the invasion. Eradication in areas adjacent (e.g. <5 km) to infected by lionfish sites will be labour intensive. For example, Cyprus sunk a new artificial reef (wreck) in a sandy area and three lionfish colonized the wreck just one week after its placement while two more colonized in the later week. Any attempt to eradicate lionfish from such areas should need to be consistent and frequent. Cost= low Effectiveness = moderate (if combined with management that will reduce source input) Social acceptability: high Duration: temporary	
Measures to achieve management	**M1. Diver-led culling with hand spears**	In the Western Atlantic invasive range, lionfish culling by divers has been an	Moderate

	Current lionfish management in the Atlantic invasive range relies on diver-led culling with hand spears (Barbour *et al.*, 2011; Harms-Tuohy *et al*., 2018).	effective control practice at local scales able to reverse the declines in native reef fish (Green *et al.*, 2014). Multiple removals off Little Cayman Island at irregular intervals over a seven month period, restricted the size frequency distribution towards smaller individuals, which allowed decreased predation on ecologically and economically important fish (Frazer *et al.,* 2012). Furthermore, a study on Bonaire and Curaçao, in southern Caribbean, revealed significant reduction in both lionfish densities and biomass compared to sites that were not targeted for culling (de León *et al.*, 2013). Similar results were observed in Puerto Rico. The removals decreased the lionfish densities and re-colonization to the targeted area at the initial densities was gradual and took about 9 months (Harms-Tuohy *et al*., 2018). According to Barbour *et al.,* (2011) and (Morris *et al.,* 2011), if 15- 65% per year or 25% per month, respectively of adult population is eliminated, then it would be enough to drive population declines. Preliminary results after removals of lionfish in the Mediterranean, as part of the RELIONMED LIFE project, have shown	

		that habitat features of a site play a major role in the success of removals. Specifically, small removals with 2-3 divers and visual census surveys using transect replicates have shown little success in sites where lionfish were widespread over rocky reefs (Figure A.1). On the other hand, 2-3 divers did decrease the lionfish populations from sites with prominent erosional features (e.g. crevices, depressions, ridges) were lionfish were aggregated along those features (Figure A.1). Success of lionfish removals from extensive rocky reefs seems possible when removals take place on a larger scale (i.e. more people). After RELIONMED organised large removals (>10 divers) from two extensive rocky reef sites, lionfish populations declined. Nevertheless, recolonization of lionfish was rapid (maximum two months) and for removals to be effective they need to frequent. Control via removals is not feasible within the current legal framework and that a model involving citizen divers is necessary. Currently, scuba diving and spearfishing is prohibited in all Mediterranean countries apart from	

		Cyprus in which small teams gather permits to remove lionfish under strict criteria. Such initiatives are cost-effective and similar programmes can be implemented at a wider scale. The approximate cost for organising a removal event with citizen divers in the framework of the RELIONMED project ranged between 500 and 960 Euro (mean 730 EU) (Table A.1). Nevertheless, a removal event with divers and a responsible authority/individual could also be organised at far less expense given that only 1 responsible person could supervise the event. To assess whether removals could become sustainable with the support of the divers, we asked removal participants whether they would pay extra fee to participate in lionfish removals, lionfish observation, or to support others in lionfish removals. Most divers reported that they would pay at least 2 Euro extra fee to participate in removals while more than 40% reported that they would pay more than 6 Euro extra fee to participate in lionfish removals. The health and safety issues due to the venomous spines of lionfish can be a	

		concern for divers who want to participate but they can be tackled with correct awareness strategies and campaigns (see M3). Cost= low Effectiveness = high (able to decline lionfish populations in levels that do not cause damage to the other communities) Social acceptability: high Duration: temporary (need to be applied consistently) This measure offers additional benefits such as increasing public participation, motivation and knowledge about invasive species. Major issue for its implementation is the current legislation and specifically the absence of coordination and specialized framework for divers to be allowed to remove lionfish using SCUBA.	

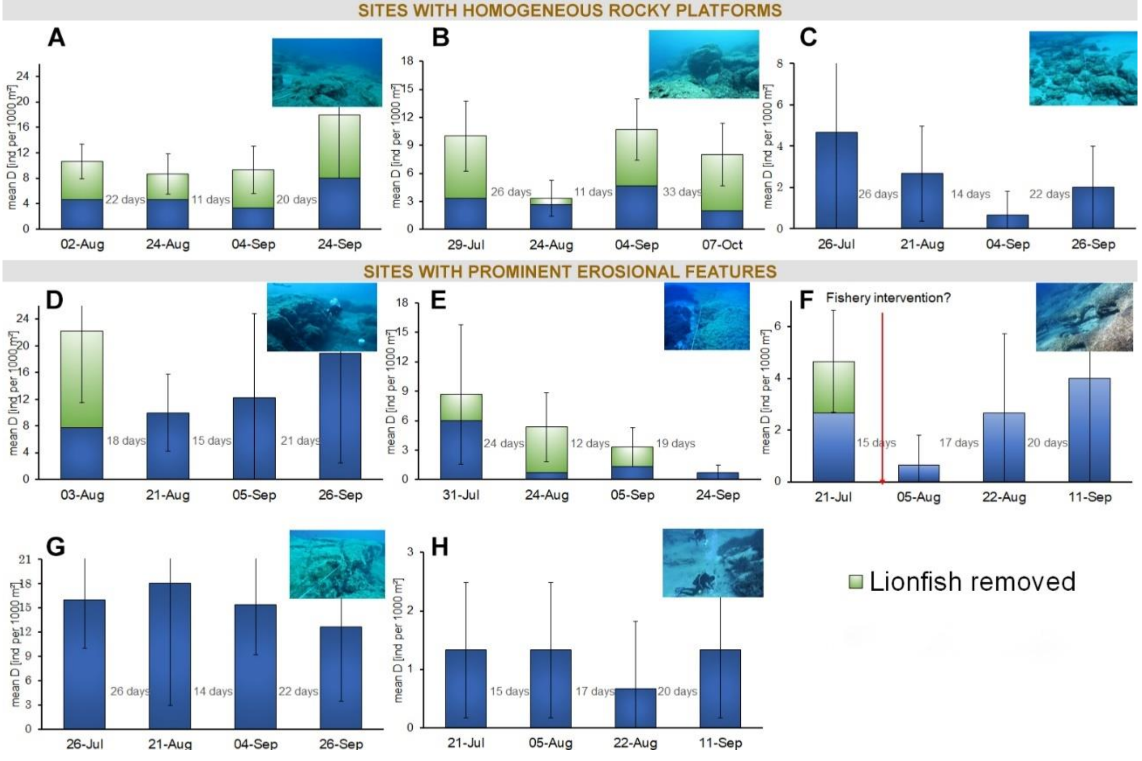


Figure A.1. Lionfish abundance in sites with extensive rocky reefs (A-C) and prominent erosional features (D-H) monitored using visual census at Cavo Greco Area, Cyprus (RELIONMED data; Kleitou et al. in prep.). Removals of lionfish were conducted by small teams 1-3 divers.

Table A.1. Indicative costs for organising a lionfish removal with citizen-divers based on the experience of the RELIONMED LIFE project.

Costs of organising lionfish removals with citizen-divers in Cyprus as part of RELIONMED project				
Parameter	**Minimum scenario €**	**Maximum scenario €**	**Mean €**	**Explanation**
Personnel participation in the competition day (2-3 researchers)	260	390	325	Using an average 130.00 EU per day for each researcher
Competition preparation: 1 day (1 person/researcher)	130	130	130	
Boat rental and fuel (0-1 boat)	0	250	125	250.00 EU for each boat use
Car fuel (2-3 cars)	80	120	100	40.00 Euro for each car transferring personnel and boats
Consumables (snacks and beverage)	30	70	50	
Total	**500**	**960**	**730**	

	M2. Citizen science monitoring Citizen science has proved very useful in monitoring lionfish populations. Monitoring requires regular efforts, to raise awareness, with good organization, citizen participation and stakeholder engagement.	Citizen science data complement official surveillance systems, and can be particularly useful in contributing to the early warning of the IAS of European Union concern. Such projects can additionally increase awareness and empower citizens (Cardoso *et al.*, 2017).	Moderate

		RELIONMED project established a surveillance system together with MedMIS, with the aim to detect and identify hotspots of lionfish to guide removal action. Citizens' data can be used to understand trends and lionfish densities. The citizen science data were used in RELIONMED to guide removals when lionfish numbers were high, and also prove that removals were effective in lowering the lionfish numbers. In addition, citizens can provide useful background information (i.e. water temperature) to better understand lionfish invasion. Cost= low (can be implemented along with other management measures such as E1) Effectiveness = high (able to identify priority areas under invasion and trends of lionfish population) Social acceptability: high Duration: permanent This measure offers other benefits such as increased public participation, motivation and knowledge about invasive species.	

	M3. Awareness and participation To mitigate social impacts and stimulate stakeholders interest (mainly fishers and divers), awareness events can be carried. During the events, stakeholders can be informed about the venomous sting of the species, trained on safe handling and first-aid, and get equipped with removal equipment.	Similar activities and with high success are implemented in Cyprus as part of the RELIONMED project. For the removals, equipment is provided by the project to the divers including needle proof gloves, specialized lionfish containment unit, Hawaiian slingshots, and heat packs. Professional fishers are provided with needle proof gloves. Although little expensive (100-200 EU), containment	High

	To raise public participation, competitions (lionfish removals with awards for winners) can be organized.	units could be provided to spearfishers to allow easy removal of lionfish from spearguns and facilitate their involvement. Participation of divers in removal events including competitions appear to have strong social benefits. After a questionnaire survey, participants strongly indicated that their involvement in removal activities enhanced their support towards potential management measures against invasive alien species (IAS), their collaboration with scientists and authorities, their participation in conservation activities while at the same time enhanced their knowledge about impacts and edibility of lionfish. Indicative costs of organising a lionfish removal competition with awards for divers are shown in Table A.2). Cost= low (can be implemented along with other management measures such as P2) Effectiveness = high (able to stimulate citizen science participation and improve monitoring and management of lionfish) Social acceptability: high Duration: temporary (needs to be applied consistently)	

Table A.2. Indicative costs for organising a lionfish removal competition with divers based on the RELIONMED project experience (RELIONMED data).

Costs for organising a lionfish competition with citizen-divers in Cyprus as part of RELIONMED project				
Parameter	**Minimum scenario**	**Maximum scenario**	**Mean**	**Explanation**
Personnel participation in the competition day (4-6 researchers)	520	780	650	Using an average 130.00 EU per day for each researcher
Competition preparation: 2 days (2-3 people/researchers)	520	780	650	
Safety diver during the competition	0	150	75	
Boat rental and fuel (1-3 boats) for safety/control during the competition	250	750	500	250.00 EU for each boat use
Car fuel (3-5 cars)	120	200	160	40.00 Euro for each car transferring personnel and boats to the competition
Ambulance stand-by in the competition area	0	100	50	
Consumables (snacks and beverage)	150	250	200	
Prices/Awards	500	1000	750	
Total	**2060**	**4010**	**3035**	

	M4. Regional action Regional co-ordination and policy integration with non-EU countries bordering the Mediterranean where *P. miles* is already present or expected to arrive.	This would be important both for monitoring and for containment efforts between introduction "hotspots" and surrounding populations. *P. miles* is already included in the priority list of non-indigenous species for monitoring in relation to fisheries in the East Mediterranean in a pilot study by FAO/GFCM (UNEP/MAP, 2017). The proposal is that the species is monitored through the Data Collection Reference Framework (DCRF) (CFP requirement) of EU Member States and the discards monitoring program of the GFCM (GFCM – UNEP/MAP, 2018). Further regional collaborations should be promoted across the entire Mediterranean. RELIONMED project plans to invite relevant experts and managers to Cyprus to transfer good practices and knowledge gained through the project. Cost= low Effectiveness = high Social acceptability: high Duration: temporary	High
	M5. New removal/fishery techniques With the logistical, financial, and safety challenges of diving deep, alternative ways should be explored (lionfish has been	Early lionfish removal via trapping represented bycatch in existing fisheries of the Western Atlantic (e.g. lobster traps) but there has been an effort for trap refinement	Low

	reported to invade areas deeper than 300 m). Adapted methods can also be used to create a targeted lionfish fishery. New techniques include use of adapted lionfish traps and utilization of new computer-vision technology and underwater robotics.	to reduce bycatch and increase lionfish catches (Pitt & Trott 2015; Gittings *et al.*, 2017). Trapping holds great promise as a low-cost method to allow lionfish removal from depths below diver limits but its development has not yet reached an optimum level. Computer-vision technology and underwater robotics that are able to stun and collected lionfish are being tested with promising results in the Western Atlantic (Sutherland *et al.*, 2017). Technological advancements could significantly increase our ability to tackle the growing range of problematic invasive species across the world in the future. However, the costs of this approach are currently high and might be prohibitive in many circumstance (Sutherland *et al.*, 2017; Andradi-Brown, 2019). In the RELIONMED project, divers used Hawaiian slingshots for lionfish removals. However, slingshots were not very successful in catching the small individuals (Figure A.6) and adaptations or alternative techniques or gears should be used.	

		Cost= high Effectiveness = moderate Social acceptability: high Duration: permanent The major issue is that the methods described are not yet available in the EU and specific licences might be required if adopted at a commercial level.	

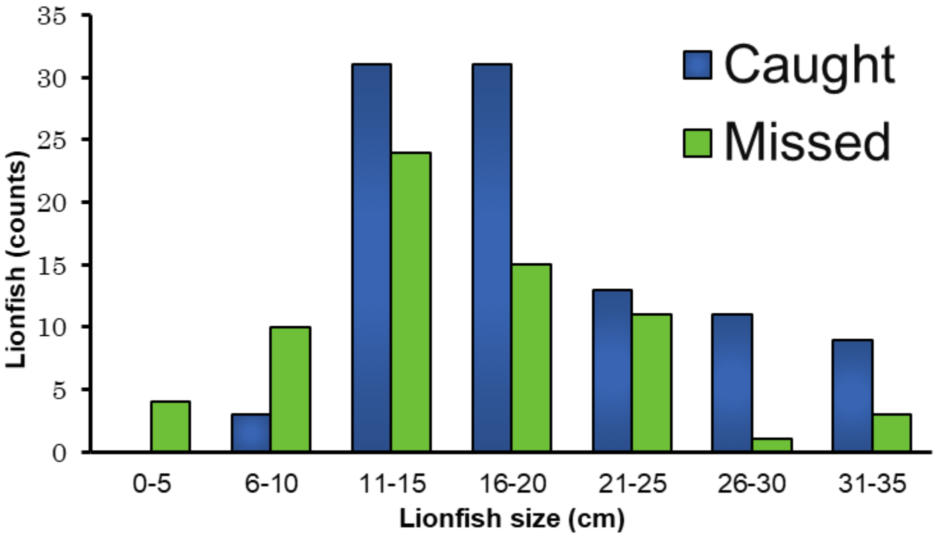


Figure A.6. Caught and missed lionfish for each size-range during the removal expeditions (RELIONMED data)

	M6. Market (consumption and jewel-crafting) promotion In the Western Atlantic, local authorities established management strategies to counteract the threat and to create localised benefits linked to control mechanisms. Exploring and initiating commercial market niches is a current management strategy among the seafood industry, distributors, chefs, researchers, fishers and conservationists in the Atlantic invasive	Enhancement of lionfish market value will sustain targeting and removal actions in the wider region of the Mediterranean. The RELIONMED project is exploring and will demonstrate and assess the feasibility of small market niches for lionfish exploitation market such as the potential for jewellery and artwork market and/or for food market.	High

	range. Artists also take advantage of the unique; ornate beautifully patterned spines, rays and tails of lionfish to make and/or sell an assortment of jewellery from them (Ali, 2017). Profitability of the small-scale fishery of several eastern Mediterranean countries (e.g. Cyprus, Israel, Lebanon, Turkey) now strongly relies on some NIS catches, such those of rabbitfishes (*Siganus* spp.) and goatfishes (*Upeneus* spp. and *Parupeneus forskalii*) while trawlers are extensively exploiting the non-indigenous penaeid shrimps *Penaeus pulchricaudatus*, *Penaeus semisulcatus*, and *Metapenaeus affinis*. The lionfish edibility and good taste should be used to advertise and promote the consumption of specimens captured either through coordinated removal programmes or through opportunistic capture by citizens.	Promotion of lionfish value will significantly improve participation of recreational fishers (i.e. spearfishers) in tackling the lionfish invasion. Cost= low Effectiveness = high Social acceptability: high Duration: permanent This measure incurs some costs for its development but on the long-term it will provide both socioeconomic and environmental benefits.	
	M7. Scientific monitoring Scientific monitoring at sentinel locations can advance knowledge about the lionfish invasion, its impacts and interactions within the basin.	Data inadequacy is a major issue to enable rapid and robust assessment of invasive species potential under the EU Regulation 1143/2014.	

	Monitoring an initial establishment location (e.g. ports for species that are likely to be introduced via ballast waters, or hotspot areas of Lessepsian immigrants near the Suez Canal) could be used to delay the buildup of an invasive species (and assist E3). As the easternmost point of EU in the Mediterranean, Cyprus offers an ideal position for monitoring Lessepsian species at an early stage of their invasion before the impacts are felt to the rest of the EU.	Stationary monitoring stations could be established in the basin to provide early response data to fulfil the requirements and guide the implementation of the Regulation. With stationary monitoring stations, a BACI (Before-After-Control-Impact) design could be used to understand impacts and interactions caused by an invasive species such as the lionfish. For instance Cavo Greco area (a hotspot of alien species) was monitored for two years prior and during when lionfish started expanding, as part of a national-programme of Cyprus. If monitoring is repeated constantly, then useful information about the changes observed in the ecosystem and lionfish impacts can be delineated. Other existing surveys (e.g. MEDITS) could also be used as an additional measure. Cost = moderate (but can be increased depending on its duration, interval, and targeted taxa – e.g. if monitored a large array of species with different traits macroalgae, pelagic species, sessile invertebrates, etc.) Effectiveness = high Social acceptability: high	

		Duration: permanent The benefits of such a measure can be manifold as it will provide vital information about lionfish interactions and impacts, lionfish migratory and foraging behaviour, and understand lionfish threshold densities that cause damage. At the same time, it can provide useful data for other taxa and act as an early station for the EU (Measure E1).	

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11.5. APPENDIX 5. Guide to Lionfish Management in the Mediterranean

The document can be found attached (as pdf) or online from the following link:

https://doi.org/10.24382/KYCK-J558