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Management priorities for marine invasive species

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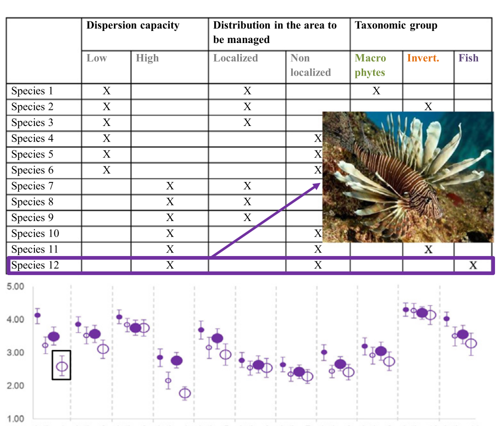
HIGHLIGHTS

- None of the actions was considered ideal for the management of invasive species.
- Public awareness and commercial use of invasive species were highly prioritized.
- Biological control actions were considered the least applicable.
- "Doing nothing" ranked high but should be considered with great caution.

GRAPHICAL ABSTRACT



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ABSTRACT

Managing invasive alien species is particularly challenging in the ocean mainly because marine ecosystems are highly connected across broad spatial scales. Eradication of marine invasive species has only been achieved

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when species were detected early, and management responded rapidly. Generalized approaches, transferable across marine regions, for prioritizing actions to control invasive populations are currently lacking. Here, expert knowledge was elicited to prioritize 11 management actions for controlling 12 model species, distinguished by differences in dispersion capacity, distribution in the area to be managed, and taxonomic identity. Each action was assessed using five criteria (effectiveness, feasibility, acceptability, impacts on native communities, and cost), which were combined in an 'applicability' metric. Raising public awareness and encouraging the commercial use of invasive species were highly prioritized, whereas biological control actions were considered the least applicable. Our findings can guide rapid decision-making on prioritizing management options for the control of invasive species especially at early stages of invasion, when reducing managers' response time is critical.

1. Introduction

Managing invasive alien species is one of the greatest challenges for the conservation of terrestrial, freshwater, and marine native biodiversity (Pyšek and Richardson, 2010). Invasive species have been reported as the second most common cause of species extinctions (Bellard et al., 2016) while their ecological impacts can propagate along the food web and affect ecosystem functioning (Gallardo et al., 2016). Invasive species also often have important socio-economic and health impacts (Vilà and Hulme, 2018) and can cause important loss of ecosystem services (Walsh et al., 2016). Consequently, their management is crucial for biodiversity conservation and human wellbeing. International institutions have explicitly recognized the need to control and eradicate biological invasions and have set relevant targets (e.g. the Aichi Target 9 set by the Convention on Biological Diversity).

To date, management strategies have been developed mainly for the control of terrestrial invasive species. The application of such strategies has led to many successful eradications (i.e. the permanent removal) of populations especially from small islands but also at large scales (Robertson et al., 2016). For example, six alien mammals that are highly influential consumers (such as the red fox *Vulpes vulpes* and the feral cat *Felis catus*) have been gradually eradicated from more than 45 islands off the Western Australian coast (Burbidge and Morris, 2002). Lately, sophisticated cost-effective approaches have been developed for the prioritization of management actions for controlling invasive species on land (e.g. Helmstedt et al., 2016). Conversely, the development of methods for the prioritization of management actions with respect to marine invasive species lags (Giakoumi et al., 2016).

In the marine environment, high environmental connectivity through the water medium fosters the dispersal of species, rendering efforts to control biological invasions more challenging. The larger the invaded area and the higher the dispersion capacity of the invader, the more challenging it is to control the invader's population (Williams and Grosholz, 2008; Ojaveer et al., 2015). Hence, when selecting the best approach to control a biological invasion, it is crucial to consider the size of the invaded area and the species' dispersion capacity.

Eradication of marine invasive species has been achieved in rare cases characterised by early detection and rapid response in restricted areas, e.g. 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). Realistically, for established invasive populations, eradication is unlikely, and the aim of management is generally to reduce their populations to levels that exert lower impacts considered as acceptable (Usseglio et al., 2017). The suppression of invasive populations below densities that cause significant environmental harm can be beneficial for native ecosystems and secure their resilience (Green et al., 2014).

Commonly, invasive control strategies in the marine environment follow a species by species approach (e.g. Anderson, 2005; Coutts and Forrest, 2007). However, trait-based prevention and management could result in more efficient conservation outcomes as a set of management actions could benefit multiple invasive species sharing common traits (Williams and Grosholz, 2008). Moreover, a comprehensive approach to invasive species management should consider: the expected impacts of these species on native ecosystems, the available technical intervention options, their expected likelihood of success and their cost, the risks associated with management, and the extent of public support and stakeholder support for the proposed interventions (Hulme, 2006). In this study we aimed to provide guidance to decision-makers on how to prioritize management actions for the control of marine invasive species based on the species' dispersal capacity (an important trait for which information is often available) and their distribution in the area to be managed. Unlike previous studies, the aim was not to prioritize the invasive species for which management should be applied (e.g. McGeoch et al., 2016; Booy et al., 2017) but to prioritize management actions for groups of invasive species that share similar characteristics.

2. Methods

2.1. Model species and management actions

The range of most marine invasive species was represented by 12 model species, distinguished by differences in: their dispersion capacity (low vs high), their distribution in the area to be managed (localized vs non-localized), and their taxonomic identity (macrophyte, invertebrate, or fish) (Table 1). For the control of these 12 model species (examples in Fig. 1 and Table 1) the following 11 management actions were identified:

- **Action 1**: Physically (mechanically) remove the species.
- **Action 2**: Rehabilitate the environment (e.g. protect and/or restore marine areas).
- **Action 3**: Encourage the targeted removal and commercial and/or recreational utilization of dead specimens (trading live specimens for use in aquaria is not included).
- **Action 4**: Deploy biocides in the sea, tactically applied.
- **Action 5**: Promote native consumers (predators or grazers) that feed on the invasive species (e.g. by restocking predator populations).
- **Action 6**: Encourage native diseases and/or parasites that affect the invasive population.
- **Action 7**: Apply biological control, using alien parasites and/or diseases.
- **Action 8**: Apply biological control, using alien consumers (predators or grazers).
- **Action 9**: Apply genetic approaches that affect only the invasive.
- **Action 10:** Education and public awareness.
- **Action 11**: Do nothing.

By 'control', we refer to the reduction of the population to such levels that their ecological impacts are substantially mitigated. The formulation of the range of prospective management actions (1 to 9: hard

Table 1
Categorization of species based on their dispersal capacity, distribution in the area to be managed, and taxonomic identity. A species can fit into more than one model depending on its distribution in the invaded area (see example in Fig. 1).

	Dispersion capacity		Distribution in the area to be managed		Taxonomic group			Species Examples
	Low	**High**	**Localized**	**Non localized**	**Macrophytes**	**Invert.**	**Fish**	
Species 1	✓		✓		✓			*Halimeda incrassate* (Mallorca Island, Spain), *Kappaphycus alvarezii & K. striatum* (Hawaii, USA)
Species 2	✓		✓			✓		*Cassiopea andromeda* (Mediterranean), *Terebrasabella heterouncinata* (successfully eradicated in California, USA)
Species 3	✓		✓				✓	*Parablennius thysanius* (Hawaii, Turkey), *Omobranchus punctatus* (Turkey)
Species 4	✓			✓	✓			*Stypopodium schimperi* (Mediterranean Sea), *Undaria pinnatifida* (New Zealand)
Species 5	✓			✓		✓		*Oculina patagonica* (Mediterranean Sea), *Nematostella vectensis* (West coast of the USA)
Species 6	✓			✓			✓	*Pempheris rhomboidea* (Eastern Mediterranean Sea), *Apogonicthyoides pharaonis* (Eastern Mediterranean Sea)
Species 7		✓	✓		✓			*Caulerpa taxifolia* (successfully eradicated in California, USA), *Dictyota cyanoloma* (Mediterranean Sea and NW Africa)
Species 8		✓	✓			✓		*Eriocheir sinensis* (Adriatic Sea), *Mytilops issallei* (successfully eradicated in Australia)
Species 9		✓	✓				✓	*Synchiropus sechellensis* (Aegean Sea), *Caesio varilineata* (Mediterranean Sea)
Species 10		✓		✓	✓			*Caulerpa taxifolia & C. cylindracea* (Western Mediterranean Sea), *Sargassum muticum* (Northeast Atlantic)
Species 11		✓		✓		✓		*Tubastraea coccinea & T. tagusensis* (Brazil, Gulf of Mexico, Caribbean), *Carcinus maenas* (North Pacific Ocean)
Species 12		✓		✓			✓	*Fistularia commersonii* (Mediterranean Sea), *Pterois miles* (Eastern Mediterranean & Caribbean Seas)

measures, 10: soft measure, 11: no intervention) was based on Thresher and Kuris (2004) and expert opinion. Action 10 was considered to be a 'soft' measure because it aims at changing people's perceptions and motivations to act against biological invasions rather than managing directly invasive populations. To our knowledge, management actions 5 to 9 have been applied so far for the control of invasive species only in the terrestrial and freshwater realms. Here, we explored the potential of such actions to be applied in the marine realm.

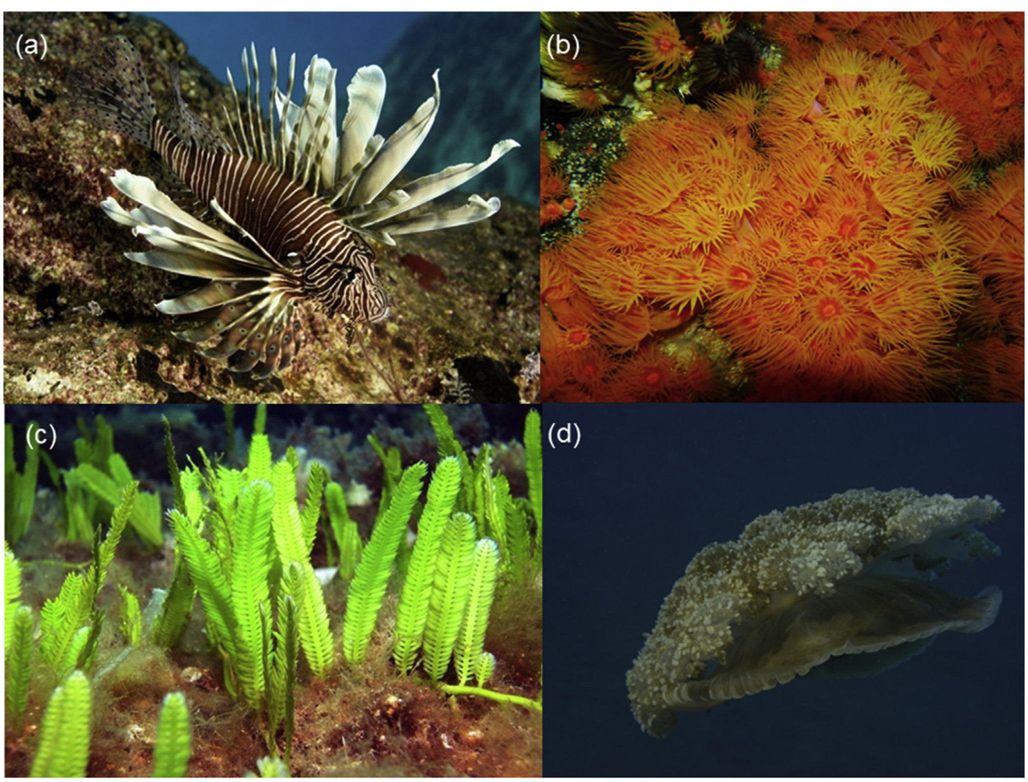

Fig. 1. Examples of invasive model species. (a) The lionfish (*Pterois miles*) has high dispersion capacity and is widely spread in the invaded Mediterranean and Caribbean Seas, and Western Atlantic Ocean (species 12). (b) The orange cup coral (*Tubastraea coccinea*) is a high dispersion invertebrate widely spread in the invaded regions of Brazil, the Gulf of Mexico, and the Caribbean Sea (species 11). (c) The killer alga (*Caulerpa taxifolia*), has high dispersion capacity but was successfully eradicated in California where its distribution was localized (species 7); conversely, its control has been challenging in the Mediterranean where it is widely spread (species 10) (d) The upside-down jellyfish *Cassiopea andromeda* is a low dispersion invertebrate with localized populations in the Mediterranean (species 2). Image credits: (a) and (d) ©M Draman; (b) ©JJ Hornung; (c) ©P Francour.

2.2. Expert knowledge elicitation

Currently, limited information is available on the key assessment parameters of actions for managing marine biological invasions. To address this gap, we followed an expert knowledge elicitation process. The 11 experts were participants of the collaborative project MarCons (Katsanevakis et al., 2017) and were selected based on their experience in marine biological invasions. Individual expert's experience ranged from 8 to 25 years, with an average of 15 years. A Nominal Group Technique (NGT) was applied (Van de Ven and Delbecq, 1974), which consisted of three stages: (1) estimate, (2) feedback, and (3) re-estimate.

First, experts were asked to fill in a questionnaire to elicit information independently. The questionnaire required assessment of the 11 management actions using the following criteria: a) the effectiveness of the action, b) its technical feasibility, c) its social acceptability, d) its negative impacts on native communities, and e) its direct cost (as defined in Table S1). The experts were asked to assess the 11 management actions for the 12 model species without being provided with specific species examples. Second, experts participated in a workshop where the results of their first assessment were shown to them as a visual anonymous summary and discussed. During the workshop, experts were not required to reach a consensus in the form of a single group score estimate but rather to achieve a common interpretation of the model species, management actions, and assessment criteria. Last, the original questionnaire was revised taking into consideration the workshop conclusions and experts were asked to make their final private estimates. These re-estimates were used for the prioritization of management actions for each model species.

2.3. Prioritization of actions

Experts assessed each criterion for each model species/management action combination, on a 1 to 5 scale (see Table S1). Furthermore, experts associated a confidence level (high, medium, low) to their estimates, which was converted into a weight (1, 0.75, 0.5 respectively). Weighted average scores across experts' responses for each species (i)/action (j) combination were estimated as:

$$\bar{x}_{ij} = \sum_{k=1}^{11} \frac{w_{ijk}}{\sum_{k=1}^{11} w_{ijk}} \cdot x_{ijk}$$

where x_{ijk} is the value given by each expert and w_{ijk} is the corresponding confidence value. The experts' estimates were weighted by the corresponding confidence value because better informed experts were expected to provide more accurate estimates (Cooke, 2015).

Subsequently, we took the geometric mean of the weighted averages of the five criteria to get a single overall score indicating how applicable a management action is for a model species. This combined measure was defined as 'applicability'. We assumed equal weighting of the five criteria because each of these could be a limiting factor for the application of an action. For example, a lack of social acceptance of invasive species management projects can have undesirable environmental and economic outcomes (Crowley et al., 2017). Bootstrapping (1000 resamples) was applied to estimate the 95% confidence intervals of the scores and thus quantify the variability originating from the different expert judgments.

3. Results

None of the management actions was considered ideal (fully applicable) for the control of any of the 12 model species (Fig. 2). Raising public awareness (action 10) was highly prioritized for the control of all model species. It had the highest applicability in all cases, except for localized populations of low dispersion capacity invertebrates and macrophytes (for which physical removal was perceived as the most applicable action). The overall high ranking ascribed to action 10 resulted from the high individual scores assigned to this action for all criteria except for effectiveness, which was assessed as 'fifty-fifty' (Figs. S1–S5).

Despite being perceived as having a low degree of effectiveness, 'doing nothing' (action 11) ranked high for all species because of its high perceived feasibility and acceptability, and its zero direct cost. Experts' scores assigned for the impacts of this action presented high variability (Fig. S4).

The most influential factors for prioritizing hard measures were the dispersion capacity and distribution of a species in the area to be managed. Conversely, the species' taxonomic group was deemed less important. The most applicable hard measure for all model species was the encouragement of targeted removal and commercial and/or recreational utilization (action 3) except for localized populations of low dispersion capacity species; physical removal (action 1) was the most applicable action for these species (Fig. 2). Action 3 ranked high mainly due to its perceived high acceptability and low cost, whereas the effectiveness, feasibility, and cost of action 1 were highly variable depending on the model species being assessed (Figs. S1, S2 and S5).

The use of alien parasites and/or diseases (action 7) was identified as the least applicable for controlling most model species (Fig. 2). Exceptions were the non-localized low dispersion capacity fish and the non-localized high dispersion capacity model species for which the use of biocides (action 4) was assessed as the least applicable action. Action 7 scored low mainly because of its low feasibility, low acceptability, and high impacts (Figs. S2-S4). Similar patterns were observed for the other actions involving some form of biological control (actions 6 and 8). The deployment of biocides (action 4) scored low mainly due to low acceptability and high ecological impacts to native communities (Figs. S3, S4).

4. Discussion

The approach presented herein allows decision-makers to prioritize management actions rapidly, without time-consuming species-specific evaluations but based on the species' dispersion capacity and its distribution in the area to be managed. Evidence shows that managing marine invasive species is more likely to succeed when the species are detected early and authorities' response is rapid (Ojaveer et al., 2015). Conversely, slow decision-making can hinder the efficient eradication and control of invasive species (see Coutts and Forrest, 2007) especially because species could have been introduced years to decades before the time of first detection (Crooks, 2005; Albano et al., 2018). Moreover, the proposed approach can assist decision-makers in selecting control strategies for species in subsequent invasion stages. It can guide the prioritization of management actions for more than one established invasive species that share common characteristics (and thus are represented by the same model species) within a management area. For example, the invasive algae *C. taxifolia* and *C. cylindracea* have both high dispersal capacity and are widely spread within marine protected areas (MPAs) in the Western Mediterranean Sea (e.g. in the Port-Cros MPA; Meinesz et al., 2010). These two species fit into model species 10 for which action 3 (encouragement of targeted removal and commercial and/or recreational utilization of specimens) was considered as the most applicable. The implementation of such an action could partially control these invasive algae and reduce their impacts on native benthic communities. Thus, commercial uses of these invasive algae should be envisaged. In fact, the extraction of bioactive compounds from *C. taxifolia* and *C. cylindracea* (such as caulerpin which has an anti-inflammatory activity) and their use in new biotechnological and pharmacological applications is currently under development (Mollo et al., 2014).

In general, the physical removal and encouragement of commercial utilization of marine invaders were highly prioritized. Lionfish population suppression through targeted removals has been widely applied in the Western Atlantic Ocean and the Caribbean Sea with beneficial

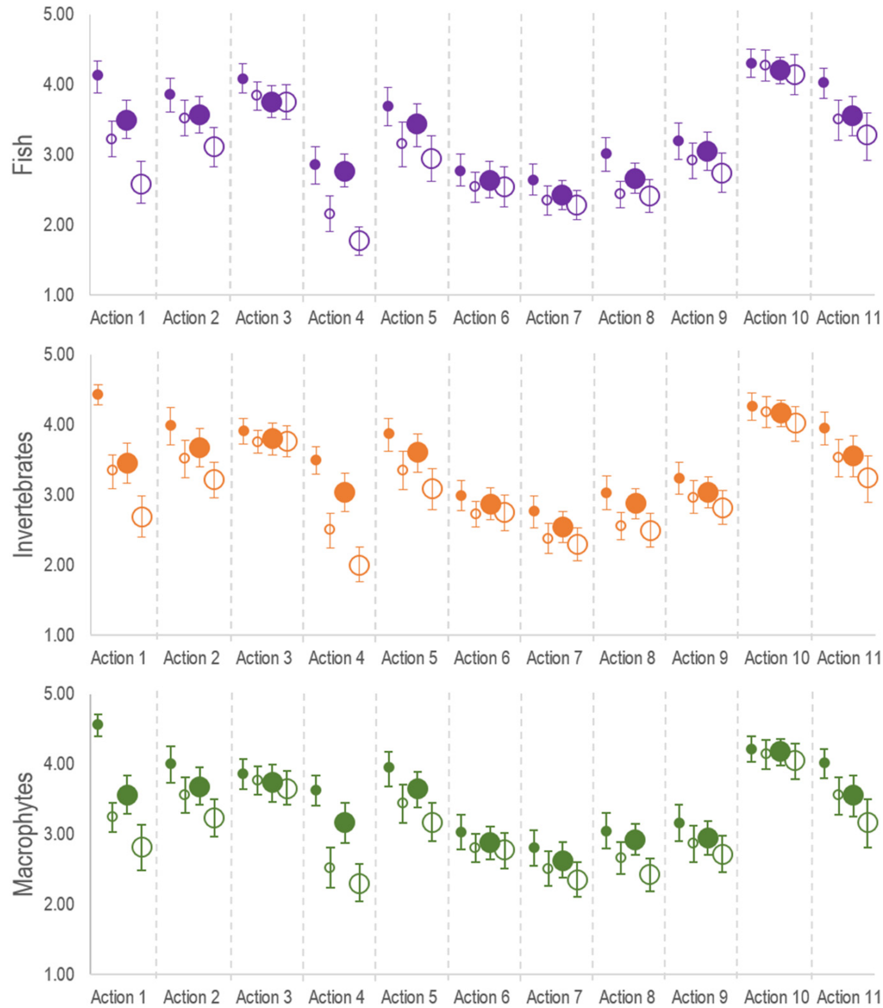

Fig. 2. Average (and 95% confidence intervals) applicability of actions for the 12 model species. The applicability values ranged between 1 and 5 (1 = not applicable, 5 = fully applicable). Small and large circles correspond to low and high dispersion capacity species respectively. Full and open circles correspond to localized and non-localized populations respectively. Each taxonomic group is presented separately (from bottom to the top): macrophytes (in green), invertebrates (orange), and fish (purple).

effects on native communities (Green et al., 2014; Usseglio et al., 2017). The adoption of a market-based approach through commercial fisheries has been suggested for the long-term management of lionfish (Chapman et al., 2016). This approach involves the establishment of a sustained supply and demand for lionfish supported with marketing campaigns. In the Black Sea, the invasive rapa whelk (*Rapana venosa*) has attained high market values and its abundance is controlled through commercial exploitation (Katsanevakis et al., 2014). However, projects aiming at controlling invasives through their economic exploitation should be carefully examined, as they may trigger the local community to protect their new source of income and contribute to the invasive species persistence and expansion (Nuñez et al., 2012).

Raising public awareness and developing education programs regarding the risks associated with invasive species and their exploitation are crucial for securing the public acceptance of management interventions (Hart and Larson, 2014) and reducing risks (e.g. Ben Souissi et al., 2014). The expert panel prioritized 'public awareness and education' over any other action acknowledging that substantial efforts should be invested in the engagement of stakeholders and the general public aiming at the prevention and control of invasive species. Citizens can substantially contribute to the early detection of new invasive species through citizen science projects (Azzurro et al., 2013; Bodilis et al., 2014; Maistrello et al., 2016). Such projects can reduce management response-time and increase public support for the implementation of other control measures (Scyphers et al., 2015). Moreover, stakeholders and citizens can assist in controlling the secondary spread of invasive species by avoiding certain practices, e.g. the re-use of SCUBA equipment without careful washing, or by active removal of the species (Miralles et al., 2016).

Biological control actions scored relatively low. The high risks associated with these actions are socially unacceptable because the actions' ecological impacts on native communities can be considerable while their effectiveness doubtful. We are unaware of cases where such actions have been implemented in the marine environment. However, experiences from biological control of invasive species in the freshwater and terrestrial realms justify the low scores assigned to relevant actions by the experts. An example from the freshwater realm is the introduction of the mosquitofish (*Gambusia holbrooki*) to many freshwater systems around the world in the 1930s and '40s to feed on mosquito larvae and hence combat malaria and other mosquito-borne diseases. However, this introduction provoked the decline or local extinction of many endemic fishes and amphibians through predation on their eggs and larvae or competition for food resources (Pyke, 2008). Moreover, this management action proved ineffective because mosquitofish also target insects that are natural predators of mosquitoes. Although enhancing native species populations that feed on invasive species ranked higher than other biological control options, when applying such actions, the impacts of consumers on native species either through predation or competition should also be considered.

The deployment of biocides was also not identified as a priority despite this action being recognized as effective by the experts. Poisoning programs have been extensively applied on land to control invasive species, e.g. the use of poison baits for feral cats and red foxes in East Australia (Moseby and Hill, 2011). Contrarily, in the marine environment the use of poisoning is far more challenging because the risk of poison diffusion is high, and the health of entire ecosystems could be jeopardized. Practice shows that biocide deployment in controlled environments has been effective for eradication in early invasion stages, as it was the case for *C. taxifolia* in Agua Hedionda Lagoon and Huntington Harbor in California (Anderson, 2005). However, the wide-spread use of biocides can impact non-targeted species and affect human health through the food chain (Terlizzi et al., 2001). Therefore, the deployment of biocides should be considered only when the area of application is restricted (i.e. the distribution of the species is localized) or when it is proven that the impacts of the biocide on native communities are minimal (Creed et al., 2019).

Environment rehabilitation through the protection and/or restoration of marine areas was considered a more applicable action for marine invasive species of low dispersion capacity with localized populations. Yet, even for this group of species, other management actions were given a higher priority. Although MPAs, especially no-take marine reserves, are important tools for marine conservation (Sala and Giakoumi, 2018), evidence shows that even well-enforced MPAs are not immune to biological invasions (e.g. Silva et al., 2011; Montefalcone et al., 2015; Caselle et al., 2018). In fact, some invasive species, such as the rabbitfishes *Siganus luridus* and *S. rivulatus*, may benefit from protection within MPAs and present higher density and biomass within their boundaries than in adjacent unprotected areas (e.g., Rilov et al., 2018; Giakoumi et al., 2019). Thus, additional actions, such as the targeted removal and commercial utilization of the dead specimens, should be adopted within their boundaries for the effective control of invasive species (Giakoumi et al., 2019). Evidence from the Western Mediterranean and the Caribbean Seas demonstrate that applying such additional actions within MPAs can be effective in controlling some invasive species even if these have high dispersal capacity and are widely spread (Barcelo et al., 2016; Usseglio et al., 2017).

Finally, the “do nothing” approach received relatively high scores by the expert panel, in agreement with a previous work focusing on the management of three invasive species in Australia (Thresher and Kuris, 2004). We recognize that in some cases, marine invaders have decreased spontaneously, after a growth phase, without any human intervention. For example, *C. taxifolia* populations have collapsed in several Mediterranean areas after a long period of expansion (Montefalcone et al., 2015). These ‘boom and bust’ dynamics, in which the introduced population grows to outbreak levels (or ‘boom’) followed by dramatic declines (the ‘bust’), represent a well-known phenomenon in invasion biology (Simberloff and Gibbons, 2004). Doing nothing and waiting for the invaders to diminish may be considered the easiest and less expensive solution for their management. Nevertheless, spontaneous population crashes are not guaranteed or may only occur after causing persistent ecological damage. Thus, the “do nothing” option should be considered with great caution.

5. Conclusions

Growing global trade and environmental change accentuate the spread and intensity of marine biological invasions, rendering their management a priority. Fast management responses require the prioritization of actions based on their effectiveness, technical feasibility, social acceptance, impacts, and cost. This work could guide the evaluation of management options for marine invaders at an early stage of invasion when reducing managers' response time is crucial. It could also guide decision-making in subsequent invasion stages, without requiring detailed species-specific information. Future research should investigate the potential synergism among multiple actions, as the optimal strategy for managing certain biological invasions could be the implementation of a set of actions rather than a single action.

Authors' contribution

SG conceived and designed the study, performed the analyses and wrote the first draft of the manuscript. SK designed the study, performed the analyses and contributed to the writing of the first draft. All authors contributed to data collection and to the writing of the final manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.06.282.

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