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Prioritizing marine invasive alien species in the EU through Horizon Scanning

Konstantinos Tsiamis[1*], Ernesto Azzurro[2], Michel Bariche[3], Melih E. Çinar[4], Fabio Crocetta[5], Olivier De Clerck[6], Bella Galil[7], Fernando Gómez[8], Razy Hoffman[7], Kathe Jensen[9], Lyudmila Kamburska[10], Joachim Langeneck[11], Martin R. Langer[12], Ya'arit Levitt-Barmats[7,13], Marco Lezzi[14], Agnese Marchini[15], Anna Occhipinti-Ambrogi[15], Henn Ojaveer[16,17], Stefano Piraino[18], Noa Shenkar[7,13], Maria Yankova[19], Argyro Zenetos[20], Ante Žuljević[21] & Ana Cristina Cardoso[1]

[1] European Commission, Joint Research Centre (JRC), Ispra, Italy

[2] ISPRA, Livorno, Italy

[3] American University of Beirut, Department of Biology, Beirut 1107 2020, Lebanon

[4] Ege University, Faculty of Fisheries, Department of Hydrobiology, 35100, Bornova, Izmir, Turkey

[5] Department of Integrative Marine Ecology, Stazione Zoologica Anton Dohrn, Villa Comunale, I-80121 Napoli, Italy

[6] Phycology Research Group and Centre for Molecular Phylogenetics and Evolution, Ghent University, Ghent, Belgium

[7] The Steinhardt Museum of Natural History, Israel National Center for Biodiversity Studies, Tel-Aviv University, Tel Aviv 69978, Israel

[8] Carmen Campos 3, E-1500 Puerto Santa Maria, Spain

[9] Zoological Museum (Natural History Museum of Denmark), Universitetsparken 15, DK-2100 Copenhagen Ø, Denmark

[10] Water Research Institute- IRSA-CNR, VialeTonolli 50 -28922, *Verbania*-Pallanza, Italy

[11] Department of Biology, University of Pisa, via Derna 1, 56126 Pisa, Italy

[12] Institut für Geowissenschaften, Abteilung Paläontologie, Universität Bonn, Nussallee 8, 53115 Bonn, Germany

[13] School of Zoology, George S. Wise Faculty of Life Science, Tel-Aviv University, Tel Aviv 69978, Israel

[14] ARPAT, Regional Agency for Environmental Protection of Tuscany, Via V. Veneto, Pisa, Italy

[15] Department of Earth and Environmental Sciences, University of Pavia, Via S.Epifanio,14, 27100 Pavia, Italy

[16] Pärnu College, University of Tartu, Ringi 35, 80012, Pärnu, Estonia

[17] National Institute of Aquatic Resources, Technical University of Denmark, Kemitorvet Building 201, 2800 Kgs. Lyngby, Denmark

[18] Department of Biological and Environmental Sciences and Technologies, Università del Salento, 73100 Lecce, Italy

[19] Institute of Oceanology, Department of Marine biology and ecology, Varna, Bulgaria

[20] Hellenic Centre for Marine Research, Institute of Marine Biological Resources and Inland Waters, GR-19013 Anavyssos, Greece

[21] Institute of Oceanography and Fisheries, I. Meštrovića 63, 21000 Split, Croatia

* corresponding author

ABSTRACT

1. The unproportionally low presence of marine species in the list of Invasive Alien Species (IAS) of Union Concern of the European Union (EU) Regulation 1143/2014 does not fully acknowledge the threat they pose to the EU marine environment.
2. In this study the first EU-scale Horizon Scanning (HS) focusing on marine alien species was performed, aiming to deliver a ranked list of species that should be of high priority for risk assessment (Article 5 of the EU IAS Regulation).
3. Species absent from or with a limited distribution in EU marine waters were targeted. In total, 363 alien species were initially screened for HS by a panel of experts, including a broad range of taxonomic groups. Species were scored for their likelihood of arrival, establishment, spread, and impact in EU waters.
4. A consensus workshop ranked 267 species, including a subset of 26 prioritized species. These species are considered to be mainly introduced by shipping (fouling and ballast water), the Suez Canal, and aquaculture activities. The 26 priority species were also scrutinized in terms of feasibility of their management; 18 of them were suggested for performing risk assessments on the basis of the EU IAS Regulation.
5. Since biological invasions are dynamic and connected with accelerated globalization and diversified human activities, we recommend HS to be repeated periodically to review the species already listed and assess new ones.

KEYWORDS: biodiversity, coastal, IAS Regulation, introduced species, legislation, ocean

1. INTRODUCTION

Introduction of alien species [as defined in the European Union's Regulation 1143/2014; EU, 2014 (= non-indigenous species included in the EU Marine Strategy Framework Directive 2008/56/EC; EC, 2008)] constitute a major threat to the marine environment. Several of them can be invasive in their new environment, causing biodiversity loss and alterations to ecosystem structure and functions, and may result in socio-economic impacts (Katsanevakis, Wallentinus, et al., 2014; Molnar, Gamboa, Revenga, & Spalding, 2008; Ojaveer et al., 2015; Wallentinus & Nyberg, 2007). Alien species introductions have increased during the past decades, due to globalization and increases in various activities, such as shipping, fisheries, aquaculture, aquarium trade, etc. (Katsanevakis, Zenetos, Belchior, & Cardoso, 2013; Ojaveer et al., 2018). European seas may host the highest number of alien species worldwide, with 1,411 alien, cryptogenic and questionable taxa reported (Tsiamis, Zenetos, Deriu, Gervasini, & Cardoso, 2018). Among Europe's seas, the Mediterranean Sea is the most affected in terms of number of introductions, mainly due to the Suez Canal and its heavy shipping traffic, which is widely documented in a long history of marine monitoring (Galil et al., 2014; Zenetos et al., 2017).

There is wide international consensus that holistic, preventive, multivector pathways-based management is an absolute priority in effectively combating marine alien species (Ojaveer et al., 2018). The Descriptor 2 of the European Union (EU) Marine Strategy Framework Directive (MSFD) (EC, 2008) and the Biodiversity Strategy (EC, 2014) highlight the importance of managing the introduction pathways, emphasizing the target of decreasing the number of new introductions into EU countries. Additional management concepts, such as a species-based approach, should aim to mitigate the impacts of targeted established invasive species as well as to limit their secondary spread.

The recently published EU Regulation on Invasive Alien Species (IAS) no.1143/2014 (EU, 2014; hereafter referred to as the IAS Regulation) provides a list of IAS of Union concern. This list focuses on priority species, whose inclusion would effectively prevent, minimize, or mitigate their adverse impact in a cost-efficient manner (EU, 2014). EU Member States should undertake appropriate actions to prevent the introduction and further spread of the listed species, enforce effective early detection tools and rapid eradication protocols for new introductions, and adopt management measures for those that are already widely spread (Darling & Frederick, 2017; Darling et al., 2017). However, with the exception of *Plotosus lineatus*, which was recently introduced into the list (EC, 2019), no other marine species is included among the IAS of Union concern. Still, the list has a dynamic character, and additional species can be added based on specific criteria and formal risk assessments meeting the requirements of the IAS Regulation.

Horizon Scanning (HS) is an essential tool to prioritize the most threatening new and emerging IAS with the highest potential impact on a target area (Shine et al., 2010; Sutherland et al., 2015). The species examined are usually absent or not yet widely spread within the area investigated. Thus, in the case of the EU marine waters, the HS tool can deliver a ranked list of IAS which are likely to arrive, establish, spread, and have an impact on native biodiversity and associated ecosystem services over the next decade (Roy et al., 2014).

Roy et al. (2015, 2019) performed a large-scale HS proposing high-priority alien species that are not present or with a limited distribution within the EU for risk assessment in relation to the IAS Regulation. Five thematic groups (namely terrestrial and freshwater plants, terrestrial and freshwater vertebrates, terrestrial invertebrates, freshwater invertebrates and fishes, and marine species) were examined. The result was a ranked list of species considered at very high or high risk of introduction, establishment, spread, and impact. However, the need to review the ranking of the identified priority species every three years was highlighted. In addition, several phyla were scarcely represented within the marine species group and it was recommended that expertise in these groups should be increased for future assessments.

After three years from the said first EU-scale HS, a revised assessment following the recommendations of the first assessment of Roy et al. (2015) was performed. The focus of the current HS was exclusively on marine IAS, taking into account their limited coverage in the previous exercise and the fact that only one marine species is currently listed in the Union concern list of the IAS Regulation. The final aim was to deliver a ranked list of marine IAS that should be of high priority for performing a risk assessment (Article 5 of the IAS Regulation), which possibly can lead to future inclusion of the species in the list of IAS of Union concern of the IAS Regulation.

2. METHODS

In general, the methodology followed the procedure of Roy et al. (2015). In order to scan a large proportion of marine IAS, seven thematic taxonomic groups of marine organisms were considered, taking into account the known number of alien marine species per group occurring in

Europe's seas (Tsiamis et al., 2018): 1) microalgae and foraminiferans, 2) macrophytes, 3) polychaetes, 4) molluscs, 5) arthropods and ascidians, 6) fishes, and 7) bryozoans, cnidarians and remaining taxonomic groups. In total, 24 experts were involved, with at least three experts assigned to each group (Appendix 1). The HS exercise operated in two phases:

2.1. Phase 1: Identify and score the species

A provisional list of species for HS assessment was created independently by each expert, involving species that fell under his/her thematic group (see Appendix 1), based on published literature, IAS worldwide databases (such as NEMESIS: Fofonoff, Ruiz, Steves, Simkanin, & Carlton, 2018) and expert opinion. Marine species examined in the HS exercise by Roy et al. (2015) were included. The species included in the HS satisfied the following criteria:

1) Geographic range: alien species that are absent from EU Member States marine areas (i.e. the marine waters surrounding EU Member States, including UK; the Macaronesia region was not considered) but could be introduced in the future and become invasive, or alien species that currently present a limited distribution across EU countries but expected to further spread and become invasive (if not already). The definition of "limited distribution" was based on expert judgement, but in most cases it corresponded to presence in up to five EU countries. In any case, species already widespread across EU marine waters were not considered for HS.
2) Temporal range: species likely to arrive or further spread across EU marine waters within the next 10 years.
3) Species status: species that are already or would be alien across the whole EU marine waters. Cryptogenic, questionable taxa and species that are alien in only some regions of EU, but native in others, were excluded. Species that may arrive to Europe by means of natural spread/dispersal without human intervention in response to changing ecological conditions and climate change were also excluded.
4) Impact: species with a potential impact on the native species and habitats of EU marine waters.

In addition, the following species were excluded from the HS exercise: a) species listed in Annex IV to Regulation (EC) No 708/2007 when used in aquaculture; b) genetically-modified organisms; c) species already included in the list of IAS of Union concern of the IAS Regulation (*Plotosus lineatus*; EC, 2019) or recently risk assessed and submitted to the IAS Regulation (*Homarus americanus;* SwAM, 2016).

Basic information was assembled for each species included in the HS assessment (Appendix 2): general taxonomic group, functional group (based on Roy et al., 2015), native range (based on Spalding et al., 2007, as modified by Tsiamis et al., 2018), current presence in European seas and in EU countries, and most likely primary introduction pathway (based on CBD, 2014). Species nomenclature followed WoRMS Editorial Board (2018). Species distribution across the European seas (i.e. the main seas surrounding European countries: Black Sea, Mediterranean Sea, NE Atlantic Ocean, Baltic Sea) when applicable, was based on EASIN (2018), AquaNIS (2018), and published literature. To have full coverage of the four seas, the whole Mediterranean Sea was considered, including North African and Near East Mediterranean countries.

Based on each expert's independent list of species for HS assessment under his/her thematic group, an aggregated and combined list of species was created for each thematic group. Afterwards, each expert received the combined list corresponding to his/her group and scored each species on the four following parameters:

i) the likelihood of arrival in EU;

ii) the likelihood of establishment in EU;

iii) the likelihood of spread post invasion across EU;

iv) the potential of environmental impact in EU marine waters.

Scores on a *1 - 4* scale for each of the parameters (Table 1), coupled with information on the level of confidence (high, medium, low; Table 2) of the relevant scores, were applied independently by each expert to each species. Scoring was performed taking into consideration and indicating the European sea(s) where the worst-case scenario (highest score) is more applicable on the basis of biological features and likely introduction pathway(s) of the scored species. For each species, experts indicated to which European sea(s) their scoring corresponded to, which could be one, more or all. All scores were summarized in a final list for each thematic group. When the given scores differed among the experts, the median value was used. When the scores were equal but the confidence level differed, the median value was also used. These differences in scoring were discussed and addressed among the experts during the consensus workshop (Phase 2).

2.2. Phase 2: Review and validate the HS results through a consensus workshop

A dedicated workshop was held on 4-5 October 2018 in the Joint Research Centre (European Commission, Italy). In a first session, a consultation among the experts within each thematic group was performed. Experts had the opportunity to revise their scores and exclude species (Appendix 3) that did not fit the HS criteria. Each thematic group arrived at a consolidated and commonly agreed list of species, their scores and their associated confidence levels for each of the four parameters.

The resulting thematic group lists were combined together into a single overall list. The score of each parameter of each species was weighted based on the confidence level, following the principle that higher confidence gives a higher weighted score (Table 3). Then, the sum of the weighted scores of each of the four parameters per species was calculated, based on which the final ranking of the species was made (see Appendix 2).

A common discussion on the overall list was carried out, involving all workshop participants, in order to better harmonize the assessments presented by each group and reduce as much as possible the bias of single groups. Experts were invited to challenge the rankings in the overall list and the responsible team was asked to defend the ranking of "their species". Rankings of individual species were adjusted following the outcome of the discussions. Consensus was reached amongst the workshop participants on a final ranked list of HS species.

Species that obtained the highest sum of the parameters weighted scores (at least a score of 45 points) were classified as "**top-priority HS species**". They were ranked top in the final HS list. In addition, species that have not been introduced yet in any European sea but exhibited high scores (at least a score of 38 points) were also considered as top-priority HS species. All the top-priority HS species were analysed in terms of their potential impact on the marine ecosystem services, following the scheme by Liquete et al. (2013) and Katsanevakis, Wallentinus, et al. (2014).

Finally, a supplementary exercise was performed for the top-priority HS species specifically. In more detail, the feasibility of their management options (i.e. prevention, early eradication, mitigation) was addressed, taking into consideration the following criteria: a) external morphology/appearance, the ease of species identification in the field; b) mobility and mode of natural dispersal; c) management potential of the primary introduction pathway(s) into Europe (for species that are not present yet in any European sea); d) management potential of the secondary pathway(s) of dispersal to or across EU countries (from already established European populations); e) cost-efficiency of eradication or mitigation of the population, bearing in mind the species distribution status and natural dispersal capabilities.

During the final session of the workshop the feasibility of management (*Yes* or *No*) for each top-priority HS species was marked. In order to better suit the practical purposes of the exercise, several species were tagged as "*partially*" manageable when it was acknowledged that their pathway could be managed, but that their population cannot be controlled once established (e.g. a foraminifera species introduced by ballast-water), or conversely, when their population in the wild can be mitigated to some extent, but their introduction pathway is impossible to control (e.g. the Suez Canal). Other cases of HS species being labelled as "partially manageable" included: species whose related management can be possible only at a local extent (e.g. a marine protected area), or species for which there was a debate among the workshop participants regarding their management feasibility.

Since listing a species as IAS of Union concern under the protocols of the IAS Regulation evaluates, among other features, the management options of an IAS, top-priority HS species considered as most suitable for performing risk assessments were those with feasibility of management tagged as "Yes". In addition, since there was a debate for several species regarding their management feasibility, and following the worst-case scenario concept, it was decided to include also the "partially" manageable species in the list of most suitable species for performing risk assessments.

3. RESULTS

A first set of 363 marine alien species to EU marine waters was initially considered for the HS assessment (Appendix 1). Ninety-six of them were later excluded from the HS assessment, either during the assessment phase or based on the discussions during the workshop (Appendices 1, 3). At the end, 267 taxa were assessed, which included 15 foraminiferans, 21 macrophytes, 68 polychaetes, 21 molluscs, 71 arthropods and ascidians, 36 fishes, and 35 bryozoans, cnidarians and other taxa (Appendices 1, 2). Most taxa were filter feeders (86 taxa) and predators (64 taxa), while the least represented were the primary producers (32 taxa) and the herbivores (13 taxa) (Appendix 2).

Among the 267 HS taxa, 44 of them have not been reported from any European sea yet, 67 have been found in a European sea but not yet in EU marine waters (e.g. taxa found along the southern and eastern coasts of the Mediterranean Sea), while the remaining 156 taxa have been already reported from EU countries (Appendix 2).

Experts considered that the Mediterranean Sea appeared to be the most threatened European sea, as it is likely to be affected by the arrival or further spread of the highest number of HS marine species considered (232 taxa) and their (potential) impact. These 232 taxa included mostly polychaetes, arthropods, and fishes (Figure 1), representing 56% of the total number of species of all groups. The NE Atlantic is expected to be affected by 86 HS taxa, most of them corresponding to polychaetes, molluscs, and arthropods, representing 72% of the total number of HS species of all groups in the NE Atlantic. On the other hand, very few taxa are expected to affect the Baltic Sea (17 taxa) and the Black Sea (13 taxa) (Figure 1). Most of the HS taxa have their native distribution range in the Western and Central Indo-Pacific, Temperate Northern Pacific, and Tropical Atlantic (Figure 2).

As far as pathways are concerned, it is useful to distinguish between HS species currently absent from Europe and HS species already present in Europe. New arrivals of HS species into Europe are expected to be introduced mainly through i) transport-stowaway: ship/boat hull fouling (hereafter referred to as shipping-fouling) ii) transport-stowaway: ship/boat ballast (hereafter referred to as shipping-ballast), iii) transport-contaminant: contaminant on animals (except parasites, species transported by host/vector) (hereafter referred to as aquaculture), and iv) corridor: interconnected waterways/basins/seas (hereafter referred to as the Suez Canal) (Figure 3).

Primary introductions of HS species already introduced in Europe have been associated mainly with i) the Suez Canal; ii) shipping-fouling; iii) shipping-ballast; and iv) aquaculture (Figure 3). These species are expected to further spread within Europe through secondary pathways of introduction. These pathways may include natural expansion through the mobility of the species or through sea water currents transporting propagules, or else dissemination assisted by human activities, such as recreational boating.

The top-priority HS species included 26 species (Tables 4, 5). These are having or are expected to have negative impacts mainly on i) food provision, ii) habitats' lifecycle maintenance, iii) recreation and tourism, and iv) ocean nourishment in the EU marine waters (Table 4). Their native distribution range encompasses mainly the Western and Central Indo-Pacific and Temperate Northern Pacific. They are primarily introduced into Europe (or expected to be introduced) mainly through the Suez Canal, shipping-fouling and shipping-ballast (Table 5).

Finally, based on the feasibility of management, the 26 top-priority marine HS species were categorized as follows (see also Table 5):

a) three species not yet introduced in European seas, with feasible pathway management (*Caulerpa serrulata*, *Kappaphycus alvarezii*, *Zostera japonica*);

b) fifteen species with partially feasible management, three yet unknown from any European sea (i.e. *Didemnum perlucidum*, *Hydroides sanctaecrucis*, *Perna viridis*), others already present (i.e. *Pterois miles*, *Lagocephalus sceleratus*, *Siganus luridus*, *Siganus rivulatus*, *Chama pacifica*, *Xenostrobus securis*, *Matuta victor*, *Hemigrapsus sanguineus*, *Portunus segnis*, *Spirobranchus kraussii*, *Microcosmus exasperatus*, *Herdmania momus*);

c) eight species with no feasible management (*Codium parvulum*, *Halimeda incrassata*, *Erugosquilla massavensis*, *Penaeus pulchricaudatus*, *Charybdis* (*Goniohellenus*) *longicollis*, *Pseudodiaptomus marinus*, *Amphistegina lobifera*, *Rhopilema nomadica*), all of which have been already introduced in at least one European sea.

Among the 26 top-priority marine HS species, those with feasibility of management tagged as "Yes" and "partially manageable" were considered as most suitable for performing risk assessments, i.e. 18 species in total (Table 5).

4. DISCUSSION

Horizon Scanning approaches to alien species, including marine ones, have been already adopted at a country-level scale in some European countries, such as in Ireland (Minchin, 2014) and the United Kingdom (Roy et al., 2014). Roy et al. (2015, 2019) performed the first EU-scale HS, considering species from all environmental realms, including 24 marine species. In the current study, the first EU-scale HS assessment exclusively addressing marine alien species was provided. As a result, the number of species addressed for HS analysis reached 267, a much higher number if compared to the work of Roy et al. (2019). This is attributed to the higher number of marine experts engaged and the broader coverage of taxonomic groups, ranging from foraminiferans to fishes. Moreover, 96 additional taxa were initially considered in the current HS assessment but were subsequently excluded during the HS exercise or the workshop. In particular, all diatoms, dinoflagellates, and other microalgae were excluded due to the high uncertainty concerning their status as alien in European seas (Gómez, 2008, 2019).

Most marine HS species considered in the current study are native to the Western and Central Indo-Pacific, the Temperate Northern Pacific, and the Tropical Atlantic, following the overall pattern of marine aliens in Europe (Tsiamis et al., 2018). When it comes to their primary introduction pathways of species expected to arrive into Europe, these mainly include shipping-fouling, shipping-ballast, aquaculture and the Suez Canal, which correspond to the most common primary pathways for the totality of alien species in Europe's seas (Katsanevakis, Coll, et al., 2014; Nunes, Katsanevakis, Zenetos, & Cardoso, 2014). To this end, the recent adoption by the International Maritime Organization of the "International Convention for the Control and Management of Ships' Ballast Water and Sediments" is encouraging. Shipping-fouling has an important role for introductions, which also applies to secondary spread of already introduced alien populations (Davidson et al., 2016; Foster, Giesler, Wilson, Nall, & Cook, 2016; Gewing & Shenkar, 2017; Simard et al., 2017; Ulman et al., 2017, 2019). The related guidance developed in the context of the Marine Environmental Protection Committee (MEPC, 2011) is a step forward, but we would stress the need for more enforceable control of this pathway. Finally, the recent enlargement of the Suez Canal is worrying for a potential increase for Lessepsian introductions into the Mediterranean Sea (Galil et al., 2015; Galil, Marchini, Occhipinti-Ambrogi, & Ojaveer, 2017).

Based on the current study, the Mediterranean Sea is by far the most threatened European regional sea as very likely to be affected by the arrival, establishment, spread, and impact of the highest number of HS species. This is in agreement both with Roy et al. (2015, 2019), and with several studies revealing that the Mediterranean Sea is the one of the most heavily impacted marine areas worldwide in terms of bioinvasions based on current knowledge, attributed to the

Suez Canal and the intense human activities within it (Boudouresque et al., 2017; Galil, 2008; Langer, 2008; Katsanevakis, Coll, et al. 2014; Tsiamis et al., 2018; Zenetos et al., 2010). In contrast, lower number of HS species are expected to primarily arrive into the Baltic and Black Seas. However, these marine areas are vulnerable to secondary introductions of IAS from infested neighboring areas (e.g. many species introduced in the North Sea spread secondarily into the Baltic Sea, either by natural or human intervention – Ojaveer et al., 2017).

The majority of the HS species considered in the current study have been already introduced, even if generally not widespread, in at least one European sea. Consequently, these species were over-represented in the final ranking list, especially at higher ranking since they were given the score of "*4*" for the parameters of the likelihood of arrival and establishment. In order to overcome this bias, we chose to highlight also the top scoring species that are not present yet in Europe, such as *Didemnum perlucidum* and *Zostera japonica*, despite their lower ranking position (lower overall score) compared to other IAS that already exist in Europe. The assessment ultimately resulted in a top-priority list of HS species, including species both present and absent from Europe.

Roy et al. (2019) identified eight marine HS species of very high or high risk of arrival, establishment, spread and potential impact; our investigation, on the other hand, resulted in identification of 26 top-priority marine HS species. Only two species – *Codium parvulum* and *Perna viridis* – are in common for these two lists. Although Roy et al. (2019) considered *Crepidula onyx*, *Mytilopsis sallei*, *Acanthophora spicifera*, *Potamocorbula amurensis*, and *Symplegma reptans* as very high or high risk HS species, these species scored lower in our ranking and were not included in the top-priority HS group. *Plotosus lineatus*, ranked as a very high risk species by Roy et al. (2019), was excluded from our analysis since it is already included in the list of IAS of Union concern of the IAS Regulation (EC, 2019). Finally, several species included in our top-priority HS list either scored low (*Didemnum perlucidum*, *Zostera japonica*) or were not considered at all (e.g. *Kappaphycus alvarezii*, *Hemigrapsus sanguineus*, *Lagocephalus sceleratus*, *Spirobranchus kraussii*, *Microcosmus exasperatus*, *Matuta victor*, *Siganus luridus*, *Siganus rivulatus*) by Roy et al. (2019). The above discrepancies on the lists of species between the two studies could be attributed to methodological differences, such as the consideration of the confidence level in weighting the scores given by the experts in our study, which was absent in Roy et al. (2019) study. In addition, the latter authors excluded from their analysis species with distribution wider than three European countries, instead of five countries as was followed by our work. This can explain the exclusion/not consideration in Roy et al. (2019) assessment of species such as *Siganus* spp. and *Lagocephalus sceleratus*, which have distribution wider than three European countries. Finally, the wider geographic coverage of the expertise involved in the current exercise and the engagement of a much higher number of marine experts specialized in specific taxonomic groups in our study - allowing for a more accurate scoring of species - could also explain the differences on the outcomes between the two lists of species.

Carboneras et al. (2018) performed a pan-European prioritization exercise for alien species to be risk assessed and possibly listed in the list of IAS of Union concern of the IAS Regulation. This work investigated 1,323 alien species from diverse environments (terrestrial, fresh water, marine) focusing on their spread and impact, including species both absent and already widespread across Europe. In their top priority list (urgent need for a risk assessment by 2018) marine species were poorly represented, with only eight marine species listed from a total of 59. Among them, *Crepidula fornicata*, *Didemnum vexillum*, *Gammarus tigrinus*, *Lophocladia lallemandi*, *Mnemiopsis leidyi* are species already widespread across Europe, which was the reason for their exclusion from our HS list. The remaining three species by Carboneras et al. (2018) were *Homarus americanus*, *Pterois miles*, and *Rapana venosa*. *Homarus americanus* was excluded from our study since it has been already risk assessed and submitted to the IAS Regulation, while the other two species have been included in our HS list.

Based on Article 4 of the IAS Regulation, one of the criteria set for inclusion of species in the list of IAS of Union concern is that "*it is likely that the inclusion on the Union list will effectively prevent, minimize or mitigate their adverse impact*" (EU, 2014). Therefore, an HS species can be more suitable for performing a risk assessment for the IAS Regulation if its associated management can offer effective prevention and/or mitigation of its population. Widespread species place an unrealistic challenge to management (Lehtiniemi et al., 2015; Ojaveer et al., 2018). Managing species that are as yet absent or have a limited distribution across the EU marine waters should be more realistic. Under that concept, the HS species taken into consideration in the current study are all in principle suitable for performing a risk assessment and possibly to be listed in the Union list.

The ranking and prioritization of the HS species examined in our study resulted in 26 top-priority marine HS species. Considering those, a further screening based on the feasibility of their management resulted in a list of 18 species. The management of these 18 species seems at least partially feasible, and we believe that they are the most suitable species for performing risk assessments for the IAS Regulation. Among the 18 species, 6 of them are not present yet in any European sea: the macrophytes *Caulerpa serrulata*, *Kappaphycus alvarezii*, *Zostera japonica*, the mollusc *Perna viridis*, the polychaete *Hydroides sanctaecrucis,* and the ascidian *Didemnum perlucidum*, which can all have serious impacts on the marine native communities (Baker, Fajans, & Bergquist, 2003; Chandrasekaran, Arun Nagendran, Pandiaraja, Krishnankutty, & Kamalakannan, 2008; Posey, 1988; Simpson, Wernberg, & McDonald, 2016; Vranken et al., 2018). Thus, an effective control of their possible primary introduction pathways into Europe (ship fouling, ballast, aquaculture, aquarium trade) should be applied.

Among the 18 species proposed as suitable for performing risk assessments, 12 of them are already introduced into Europe. The fishes *Pterois miles*, *Lagocephalus sceleratus*, *Siganus luridus*, and *Siganus rivulatus*, already quite widespread in Cyprus and Greece and reaching the Italian coasts, pose a severe threat to native marine ecosystems (Azzurro, Fanelli, Mostarda, Catra, & Andaloro, 2007; Bariche, Letourneur, & Harmelin-Vivien, 2004; Kalogirou, 2011; Morris, 2012; Sala, Kizilkaya, Yildirim, & Ballesteros, 2011; Salomidi et al., 2016; Vergés et al., 2014), highlighting the need for management action. Their conspicuous size and easily identifiable morphology could facilitate efficient removal, helping actions for controlling established populations through targeted fisheries or by the involvement of motivated citizens (such a recreational divers and spear-fishers). The arthropods *Matuta victo*r, *Hemigrapsus sanguineus*, and *Portunus segnis* can have negative effects on native benthic invertebrates through predation (Galil & Mendelson, 2013; Gerard, Cerrator, & Larson, 1999; Rabaoui, Arculeo, Mansour, & Tlig-Zouari, 2015); their dispersal to other EU countries could be prevented through vessel-ballast management and early-warning eradication at local level. The molluscs *Xenostrobus securis* and *Chama pacifica* can smother native fauna (Mienis, 2003; Russo, 2001), while the former can be a key host favouring the spread of parasites (*Marteilia refringens*) to native bivalve populations (Pascual et al., 2010). Mitigation of established populations of *Xenostrobus securis* could be achieved through targeted population control, while prevention of secondary dispersal of *Chama pacifica* to other EU countries could be prevented through hull management and early-warning alert and local eradication. Finally, biofouling species such as the polychaete *Spirobranchus kraussii* and the ascidians *Microcosmus exasperatus* and *Herdmania momus* may outcompete native species and overgrow on cultured bivalves, as well as on man-made structures, such as ropes, floating pontoons, pipes, buoys, mooring blocks, fish cages, etc., hence compromising their functioning (Eno, Clark, & Sanderson, 1997; Lambert, 2007; Mineur et al., 2012). Their dispersal to other EU countries could be prevented through vessel-fouling management (MEPC, 2011) and early-warning alert and local eradication.

It has to be noted, however, that most of above species (see also Table 5) entered the Mediterranean Sea through the Suez Canal (a pathway of introduction unmanaged, and unlikely to be managed in the foreseeable future). The large populations established in the Levantine Sea by species such as *Lagocephalus sceleratus*, *Siganus luridus*, *S. rivulatus*, *Matuta victor*, *Portunus segnis*, *Chama pacifica*, *Spirobranchus kraussii*, *Microcosmus exasperatus* and *Herdmania momus*, and the presence of their planktonic larval stages, argue to the difficulty of control/mitigation attempts – as propagules pressure will continue, perhaps increase with the continued warming of the water. In addition, localized mitigation efforts have proven impractical for the lionfish (*Pterois volitans*) in the West Atlantic Ocean (Johnston & Purkis, 2015; Dahl, Patterson, & Snyder, 2016). These concerns should be addressed in depth in the upcoming listing process of IAS of Union concern.

Horizon Scanning assessments usually include high levels of uncertainty (Roy et al., 2015), and this definitely applies when assessing marine invasions in EU waters. The relevant details of life-history characteristics, invasion history and associated pathways of marine IAS, useful for assessing the likelihood of arrival, establishment and spread, are not always available (Minchin, Gollasch, Cohen, Hewitt, & Olenin, 2009; Ojaveer et al., 2018). Similarly, the worldwide information on the impacts of marine invasive species is often very limited (Ojaveer & Kotta, 2015; Ojaveer et al., 2015). Therefore, expert judgement was applied in many cases, which resulted often in variation among the experts scoring of the species parameters. This problem was addressed by the use of the confidence level on the scoring and the consensus among the experts of the same thematic group. However, bias was also observed among the different thematic groups of evaluators. The overall consensus workshop mitigated this bias, although we do acknowledge that the complete elimination of the experts' bias is rather difficult.

Experts' bias was even more evident in the evaluation of the management feasibility of the top-priority marine HS species, due to the limited number of applied management efforts against marine IAS worldwide (Bax et al., 2001; Thresher & Kuris, 2004). Therefore, the attributed feasibility of management for the current top-priority HS species must be considered with caution and should be further investigated under the listing process of IAS of Union concern. For the same reason, we would encourage, ideally, the performance of risk assessments for all the 26 top-priority HS species of our study. The HS participants concur that region-wide, multivector pathways-based management is most effective in preventing the introduction of marine IAS.

5. CONCLUSIONS

Almost 4 years after the publication of the IAS Regulation, the list of IAS of Union concern includes only one fully marine species. This under-representation of marine species from the Union list does not acknowledge the magnitude of their threat to the EU marine environment. The current HS exercise provides 26 top-priority marine HS species, 18 of which are considered as most suitable to perform risk assessments in the frame of the IAS Regulation: *Caulerpa serrulata*, *Chama pacifica*, *Didemnum perlucidum*, *Hemigrapsus sanguineus*, *Herdmania momus*, *Hydroides sanctaecrucis*, *Kappaphycus alvarezii*, *Lagocephalus sceleratus*, *Matuta victor*, *Microcosmus exasperates*, *Perna viridis*, *Portunus segnis*, *Pterois miles*, *Siganus luridus*, *S. rivulatus*, *Spirobranchus kraussii*, *Xenostrobus securis, and Zostera japonica.*

In depth-assessment should consider the feasibility of management of the species, since the subjectivity of the issue on certain species is quite evident. Indeed, although the panel of experts of the current HS exercise had a consensus in the final list of the top-priority HS species, there was a strong debate among them on the feasibility of management of certain species already established in Europe. However, all experts agreed that preventive measures aiming at holistic management of the introduction pathways of the species are to be privileged.

Biological invasions are dynamic, and the HS should be performed periodically, in order to review listed species and assess new ones. To this end, knowledge on marine biological invasions as well as on the taxonomy and biogeography across the wide range of marine phyla are crucial for successfully assessing HS assessments on marine species, and this kind of expertise should be encouraged.

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TABLES

TABLE 1. Overall basis for scoring the likelihood of arrival, establishment, spread, and potential impact of each marine Horizon Scanning species in EU marine waters.

Likelihood of arrival, based on a consideration of previous invasion history of the species in other marine regions worldwide (Spalding et al. 2007, Tsiamis et al. 2018) and its known introduction pathway(s).	
Score 4	➢ species already introduced in EU marine waters or ➢ species introduced in European seas, but still outside EU marine waters (e.g. North Africa Mediterranean coasts) which are expected to reach EU marine waters within the next 10 years;
Score 3	➢ species absent from European seas but with an invasive history in two or more marine realms worldwide or ➢ species native in the Red Sea which are expected to reach EU marine waters within the next 10 years through the Suez Canal (or through shipping via the Suez Canal);
Score 2	➢ species absent from European seas, with an invasive history in one marine realm worldwide only, known to be associated with introduction pathways which commonly apply for primary introductions in the European seas (shipping, aquaculture, aquarium trade);
Score 1	➢ species absent from European seas, with no invasive history or an invasion history in one marine realm worldwide only, associated with uncommon or unknown pathways of introduction.
Likelihood of establishment, based on the life-history characteristics of the species, its reproductive cycle, and its tolerance to a broad range of environmental conditions. It was also considered whether the bioclimatic conditions and habitat types of the native distribution range of the species are comparable to those of the EU marine waters.	
Score 4	➢ species with broad ecological tolerance and high ability of adaptation to new habitats and environmental conditions, being native in marine realms with similar bioclimatic conditions and habitat types compared to the EU marine waters;

	➢ species already established in EU marine waters;
Score 3	➢ species with broad ecological tolerance and high ability of adaptation to new habitats and environmental conditions, being native in marine realms with different bioclimatic conditions and habitat types compared to the EU marine waters;
Score 2	➢ species with narrow ecological tolerance and low ability of adaptation to new habitats and environmental conditions, being native in marine realms with similar bioclimatic conditions and habitat types compared to the EU marine waters;
Score 1	➢ species with narrow ecological tolerance and low ability of adaptation to new habitats and environmental conditions, being native in marine realms with different bioclimatic conditions and habitat types compared to the EU marine waters.
Likelihood of spread, primarily determined by the dispersal capacity of the species, associated with the reproductive capacity and the ability to achieve a population size / density that would prompt dispersal, and its history and speed of spread in other regions. Dispersal through secondary anthropogenic pathways (e.g. fouling, fishing nets) was also considered.	
Score 4	➢ species with high dispersal capacity, commonly associated with secondary pathways of introduction;
Score 3	➢ species with high dispersal capacity, but not known to be associated with secondary pathways of introduction;
Score 2	➢ species with low dispersal capacity, commonly associated with secondary pathways of introduction;
Score 1	➢ species with low dispersal capacity, but not known to be associated with secondary pathways of introduction.
Potential impact, based on the known history of environmental impact in European seas or in other marine regions of the world.	
Score 4	➢ species that would cause large or massive losses on the population of at least one native species (75–100% of the population is lost) and/or ➢ species that would cause large or massive alterations or losses of at least one native habitat type (75–100% of the habitat is altered or lost);
Score 3	➢ species that would cause considerable losses on the population of at least one native species (50–75% of the population is lost) and/or ➢ species that would cause considerable alterations or losses of at least one native habitat type (50–75% of the habitat is altered or lost);
Score 2	➢ species that would cause some losses on the population of at least one native species (25–50% of the population is lost) and/or ➢ species that would cause some alterations or losses of at least one native habitat type (25–50% of the habitat is altered or lost);
Score 1	➢ species that would cause inconsequential losses on the population of at least one native species (< 25% of the population is lost) and/or ➢ species that would cause inconsequential alterations or losses of at least 1 native habitat type (< 25% of the habitat is altered or lost).

TABLE 2. Basis for providing the appropriate confidence level for each scoring of the 4 parameters of each marine Horizon Scanning species.	
High	➢ there is direct relevant evidence to support the statement, the available evidence is not controversial;
Medium	➢ there is direct relevant evidence to support the statement but it is controversial and/or ➢ there is indirect relevant evidence to support the statement (from other species of the same genus or higher taxonomic group) and/or ➢ there is no evidence but statement is supported by expert judgment of good confidence level (degree of confidence in being correct: 50–100%);
Low	➢ there is no direct or indirect relevant evidence to support the statement and/or ➢ statement is supported by expert judgment of poor confidence level (degree of confidence in being correct: 0–50%).

TABLE 3. Scheme applied for weighting the parameters' scores of each marine Horizon Scanning species by the confidence level.		
Parameters' score	Confidence level	Weighted final score
Score 4	High	12
	Medium	11
	Low	10
Score 3	High	9
	Medium	8
	Low	7
Score 2	High	6
	Medium	5
	Low	4
Score 1	High	3
	Medium	2
	Low	1

TABLE 4. Top-priority marine invasive alien species listed through the current Horizon Scanning for EU marine waters, their final ranking score, and their negative impacts on ecosystem services.

		Provisional services			Regulating and maintenance services								Cultural services		
	Ranking score points	Food provision	Water storage and provision	Biotic materials and biofuels	Water purification	Air quality regulation	Coastal protection	Climate regulation	Weather regulation	Ocean nourishment	Lifecycle maintenance	Biological regulation	Symbolic and aesthetic values	Recreation and tourism	Cognitive effects
A. HS species with the highest ranking:															
Codium parvulum	48	×								×	×			×	
Halimeda incrassata	48									×	×				
Erugosquilla massavensis	48										×				
Hemigrapsus sanguineus	48	×					×								
Penaeus pulchricaudatus	48	×													
Portunus segnis	48	×													
Pterois miles	48	×									×		×	×	

Amphistegina lobifera	48						×								
Xenostrobus securis	48	×											×		
Rhopilema nomadica	47	×	×											×	
Lagocephalus sceleratus	47	×													
Chama pacifica	47	×								×					
Spirobranchus kraussii	47	×			×									×	
Microcosmus exasperatus	45													×	
Charybdis longicollis	45	×													
Herdmania momus	45													×	
Matuta victor	45	×													
Pseudodiaptomus marinus	45	×										×			
Siganus luridus	45	×		×	×			×			×		×	×	×
Siganus rivulatus	45	×		×	×			×			×		×	×	×
B. HS species absent from European seas that gathered the highest scoring:															
Didemnum perlucidum	44	×												×	
Hydroides sanctaecrucis	42	×			×									×	
Zostera japonica	42									×	×				
Caulerpa serrulata	41									×	×				
Perna viridis	39	×													
Kappaphycus alvarezii	38									×					

TABLE 5. Top-priority marine invasive alien species listed through the current Horizon Scanning for EU marine waters. For each species, information is given on their distribution in EU, the taxonomic group, the native distribution range, the most likely primary and secondary introduction pathway(s) into and within Europe respectively, and the feasibility of their management. Hull=shipping-fouling; Ballast=shipping-ballast; Aquarium=Pet/aquarium/terrarium species (including live food for such species).

Species	present in EU	Taxonomic group	Native distribution range	Primary pathway(s) into Europe	Secondary pathway(s) within Europe	Feasibility of management
A. HS species already present in Europe that attained the highest scoring:						
Codium parvulum	-	macrophyte	Western Indo-Pacific	Suez Canal	Natural	**No:** established in Israel, Lebanon, Syria and Turkey, difficult taxonomy, prevention of dispersal to EU impossible
Halimeda incrassata	ES	macrophyte	Tropical Atlantic	Hull, aquarium	Natural, hull	**No:** effective prevention of secondary dispersal to other EU countries and mitigation of established populations are impossible
Erugosquilla massavensis	EL, IT, CY	arthropod	Western Indo-Pacific	Suez Canal	Natural	**No:** effective prevention of secondary dispersal to other EU countries and mitigation of established populations are impossible
Hemigrapsus sanguineus	FR, NL, BE, DE, SE, HR	arthropod	Temperate Northern Pacific	Ballast	Natural, ballast	**partially:** effective mitigation of established populations difficult but secondary dispersal to other EU countries could be prevented through ballast management and early-warning eradication; risk assessed by IUCN (Galanidi & Zenetos, 2017)
Penaeus pulchricaudatus	CY, EL	arthropod	Western Indo-Pacific	Suez Canal	Natural	**No:** effective prevention of secondary dispersal to other EU countries and mitigation of established populations are impossible
Portunus segnis	CY, EL, IT, MT	arthropod	Western Indo-Pacific	Suez Canal	Natural, ballast	**partially:** secondary dispersal to other EU countries (mostly to non-Mediterranean EU marine waters) could be prevented through ballast management; population control and mitigation of ecological impacts could be attempted through targeted fisheries, and by promoting its consumption

Pterois miles	CY, EL, IT	fish	Western Indo-Pacific, Temperate Southern Africa	Suez Canal, aquarium	Natural	**partially:** effective prevention of secondary dispersal to other EU countries is impossible; population control and mitigation of ecological impacts could be attempted through targeted fisheries, engaging recreational divers in removal actions, and by promoting its consumption
Amphistegina lobifera	CY, EL, IT, MT	foraminifera	Western-Central Indo-Pacific	Ballast, Suez Canal, parasites on animals	Natural, ballast	**No:** microscopic, effective prevention of secondary dispersal to other EU countries and mitigation of established populations are impossible
Xenostrobus securis	IT, ES, FR	mollusc	Central Indo-Pacific	Hull, aquaculture	Natural	**partially:** prevention of secondary dispersal to other EU countries is rather impossible; mitigation of established populations could be attempted through targeted collections
Rhopilema nomadica	CY, EL, IT, MT	cnidarian	Western Indo-Pacific	Suez Canal	Natural	**No:** effective prevention of secondary dispersal to other EU countries and control of established populations are impossible; however, potential mitigation of local impacts could be investigated through targeted fisheries and Blue Growth exploitation of jellyfish biomass for nutritional, cosmeceutical and pharmaceutical applications
Lagocephalus sceleratus	CY, EL, HR, IT, MT, ES	fish	Western Indo-Pacific	Suez Canal	Natural	**partially:** effective prevention of secondary dispersal to other EU countries is impossible; population control and mitigation of ecological impacts could be attempted through targeted fisheries; risk of tetradotoxin poisoning can be reduced through public awareness initiatives
Chama pacifica	CY, EL	mollusc	Western-Central-Eastern Indo-Pacific, Temperate Northern Pacific	Suez Canal	Natural, hull	**partially:** effective mitigation of established populations impossible but secondary dispersal to other EU countries (mostly to non-Mediterranean EU marine waters) could be prevented through hull management and early-warning eradication
Spirobranchus kraussii	-	polychaete	Western Indo-Pacific, Temperate Southern Africa	Suez Canal, hull	Natural, hull	**partially:** established in the Levantine Sea, secondary dispersal to the EU might be prevented through hull management and early-warning eradication

Microcosmus exasperatus	CY	ascidian	Western-Central Indo-Pacific	Suez Canal, hull	Natural, hull	**partially:** effective mitigation of established populations impossible but secondary dispersal to other EU countries (mostly to non-Mediterranean EU marine waters) could be prevented through hull management and early-warning eradication
Charybdis longicollis	CY, EL	arthropod	Western Indo-Pacific	Suez Canal	Natural	**No:** effective prevention of secondary dispersal to other EU countries and mitigation of established populations are impossible
Herdmania momus	CY, EL, MT	ascidian	Western-Central Indo-Pacific	Suez Canal, hull	Natural, hull	**partially:** effective mitigation of established populations impossible but secondary dispersal to other EU countries (mostly to non-Mediterranean EU marine waters) could be prevented through hull management and early-warning eradication
Matuta victor	EL	arthropod	Western-Central Indo-Pacific	Suez Canal	Natural, ballast	**partially:** established in the Levantine Sea, secondary dispersal to the EU (mostly to non-Mediterranean EU marine waters) could be prevented through ballast management and early-warning eradication
Pseudodiaptomus marinus	BE, DE, FR, IT, ES, SI, HR	arthropod	Temperate Northern Pacific	Ballast	Natural	**No:** microscopic, difficult identification, effective prevention of secondary dispersal to other EU countries and mitigation of established populations are impossible
Siganus luridus	CY, EL, HR, IT, FR, MT	fish	Western Indo-Pacific	Suez Canal	Natural	**partially:** effective prevention of secondary dispersal to other EU is impossible; population control and mitigation of ecological impacts could be attempted through targeted fisheries and promoting consumption
Siganus rivulatus	CY, EL, HR, IT	fish	Western Indo-Pacific	Suez Canal	Natural	**partially:** effective prevention of secondary dispersal to other EU is impossible; population control and mitigation of ecological impacts could be attempted through targeted fisheries and promoting consumption
B. HS species absent from European seas that attained the highest scoring:						

Didemnum perlucidum	-	ascidian	Unknown	Hull, ballast	not applicable	**partially:** difficult identification, effective prevention could be achieved by managing shipping and applying early-warning eradication
Hydroides sanctaecrucis	-	polychaete	Tropical Atlantic	Hull	not applicable	**partially:** effective prevention could be achieved by managing shipping and applying early-warning eradication
Zostera japonica	-	macrophyte	Temperate Northern Pacific, Central Indo-Pacific	Aquaculture	not applicable	**Yes:** effective prevention can be achieved by managing oyster imports into Europe
Caulerpa serrulata	-	macrophyte	Western-Central Indo-Pacific, Tropical Atlantic	Aquarium	not applicable	**Yes:** effective prevention can be achieved by managing aquarium trade
Perna viridis	-	mollusc	Western-Central Indo-Pacific	Hull, ballast	not applicable	**partially:** effective prevention could be achieved by managing shipping and applying early-warning eradication
Kappaphycus alvarezii	-	macrophyte	Temperate Northern Pacific, Central Indo-Pacific	Other intentional release	not applicable	**Yes:** effective prevention can be achieved by managing seaweed species imported for aquaculture cultivation in Europe

FIGURE LEGENDS

FIGURE 1. Threatened European seas likely to be affected by the arrival, establishment, spread and impact of the marine alien species, listed through the current Horizon Scanning, within the next 10 years. The size of each pie chart represents the total number of the Horizon Scanning species expected to affect a specific European sea. Each species can affect one or more European seas. The proportion of the species groups is given for each sea.

FIGURE 2. Native distribution range of marine alien species listed through the current Horizon Scanning expected to (further) affect EU marine waters. Each species can have a native distribution range extending to one or more marine realms.

FIGURE 3. Number of marine alien species listed through the current Horizon Scanning which are already introduced or expected to arrive in Europe's seas through primary introduction pathways. Several species are linked to more than one pathway.

APPENDICES

APPENDIX 1. Thematic taxonomic groups of marine alien species examined in the Horizon Scanning (HS) exercise and workshop and the corresponding experts involved in each of them. The initial number of species considered for each group, the number of species excluded during the exercise and workshop, and the final number of HS species agreed for each group after the consensus workshop are also given.

APPENDIX 2. Ranked list of species addressed for Horizon Scanning and their associated scores (after the consensus workshop) per each parameter: i) the likelihood of each species arrival in EU, ii) the likelihood of establishment in EU, iii) the likelihood of spread post invasion across EU, iv) the potential environmental impact in EU waters. Corresponding confidence levels (after consensus), weighted final score (based on Table 3 of the manuscript) per each parameters' score as well as the corresponding European Sea(s) per each species are given. Basic information is provided for each species: already presence in European seas and European Union countries (Yes/No), taxonomic group, functional group (based on Roy et al., 2015), native distribution range (based on Spalding et al., 2007, and Tsiamis et al., 2018), and most likely primary introduction pathway(s) into Europe (following CBD, 2014 scheme). MED=Mediterranean Sea.

APPENDIX 3. List of species initially considered for Horizon Scanning but eventually excluded during the exercise and consensus workshop. The reason of exclusion and the taxonomic group for each species are also given.