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Ten recommendations for advancing the assessment and management of non-indigenous species in marine ecosystems

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ABSTRACT

The main objective of recent international legislative measures and policies concerning marine ecosystems is to ensure sustainable environmental management to maintain a good status for marine waters, habitats and resources, with the ultimate target of achieving an integrated ecosystem-based approach to management. Because bioinvasions pose significant threats to marine ecosystems and the goods and services these provide, non-indigenous species (NIS) are included in the more recent legislative documents. A major challenge for the scientific community is to translate the principles of the legislative directives into a realistic, integrated ecosystem-based approach and at the same time provide stakeholders with best practices for managing NIS. The aim of this paper, prepared by members of the Working Group on Introductions and Transfers of Marine Organisms (WGITMO) of the International Council for the Exploration of the Sea (ICES), is to provide guidance for the application of NIS related management in the European Union Marine Strategy Framework Directive (MSFD). Ten recommendations, including NIS identification, standardization of sampling and data, indicators, propagule pressure and management issues are considered in this paper. While most of these suggestions were developed to improve the implementation of the MSFD, several may be more widely applicable.

1. Introduction

Because of increasing and diversifying human pressures and the associated degradation of marine ecosystems, several policies

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and framework legislations were adopted during the early 1990s. The goal of these legislations was to restore good environmental quality, with the ultimate aim to be part of an integrated environmental management. Such measures include the Clean Water Act and National Oceans Policy Executive Order in USA, the Water Act Canada, the Environmental protection and Biodiversity Conservation Act in Australia, the Water Framework and the Marine Strategy Framework Directives in the European Union and the National Water Act in South Africa. The main objectives of these legislative measures and policies are to achieve or maintain a good status for marine and fresh waters, habitats and resources by providing integrated ecosystem-based approach to management [1]. The latest legislation, the European Union Marine Strategy Framework Directive [2] lists 11 descriptors that constitute the basis for the evaluation of "Good Environmental Status" (GES) of marine ecosystems: (1) biodiversity; (2) non-indigenous species; (3) exploited fishes and shellfishes; (4) food webs; (5) human-induced eutrophication; (6) sea-floor integrity; (7) hydrographical conditions; (8) contaminants in water and sediment; (9) contaminants in fish and shellfish; (10) marine litter; and (11) introduction of energy/noise.

Non-indigenous species (NIS) are considered one of the major threats to global marine ecosystems for impacting their structure and function [3], with socio-economic consequences that may lead to social conflicts, economic and production losses [4]. These NIS are mainly introduced unintentionally by discharges of ballast water (BW) and accumulated sediments, as vessel hull hitchhickers [5–7], by the aquaculture industry [8] and through canals [9,10]. NIS have negative impacts on biodiversity and ecosystem function, whereas some form an important basis for commercial fisheries by providing an increased production over similar native species, or otherwise provide economically important cultured products [11,12].

To manage the main introduction pathways and vectors of potential NIS arrivals and secondary spread, several dedicated policy/legislative frameworks/tools are already in place. These include the Code of Practice on the Introductions and Transfers of Marine Organisms of the International Council for the Exploration of the Sea [13], the IUCN Considerations for Responsible Use of NIS in Culture [14], the International Maritime Organization's the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWMC) [7,15], the European Community Regulation Concerning Use of Alien and Locally Absent Species in Aquaculture, with detailed rules for their implementation [16–18], the European Code of Conduct on Zoological Gardens and Aquaria and Invasive Alien Species [19] and an EU biodiversity strategy to 2020 [20]. Further measures are under development: such as the international ship hull fouling guidelines [21], and the Invasive Species Strategy of the EU [22].

In the present paper, members of the ICES Working Group on Introductions and Transfers of Marine Organisms (WGITMO) identify and discuss issues relating to the assessment and management of NIS. These range from taxonomic expertise and identification of NIS, data collection/monitoring, limitations of data usage, assessment of pressures and impacts and industry-involved multivector management. Whilst these points were developed towards the implementation of the MSFD GES Descriptor 2 [2,23], several are of general nature and may be applied more widely.

2. Definitions and EU MSFD D2 criteria and indicators

The following definitions were adopted [24]:

Non-indigenous species (NIS; synonyms: alien, exotic, non-native, allochthonous) are species, subspecies or lower taxa introduced outside of their natural range (past or present) and outside of their natural dispersal potential. This includes any part, gamete or propagule of such species that might survive and subsequently reproduce. Their presence in the given region is due to intentional or unintentional introduction resulting from human activities. Natural shifts in distribution ranges (e.g. due to climate change or dispersal by ocean currents) do not qualify a species as a NIS. However, secondary introductions of NIS from the area(s) of their first arrival could occur with or without human involvement due to spread by natural means. Species of unknown origin that cannot be ascribed as being native or alien are termed cryptogenic species. Invasive alien species (IAS) are a subset of established NIS that have spread, are spreading or have demonstrated their potential to spread elsewhere, and have or might have an adverse effect on biological diversity, ecosystem function, socio-economic values and/or human health in invaded regions.

The European Commission Decision [23] contains two criteria and three indicators for assessing progress towards good environmental status relevant to the MSFD Descriptor 2 "Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystem":

Criterion 2.1: Abundance and state characterization of non-indigenous species (NIS), in particular invasive species.
Indicator 2.1.1: Trends in abundance, temporal occurrence and spatial distribution in the wild of non-indigenous species, particularly invasive non-indigenous species, notably in risk areas, in relation to the main vectors and pathways of spreading of such species.
Criterion 2.2: Environmental impact of invasive non-indigenous species.
Indicator 2.2.1: Ratio between invasive non-indigenous species and native species in some well studied taxonomic groups (e.g. fish, macroalgae, molluscs) that may provide a measure of change in species composition (e.g. further to the displacement of native species).
Indicator 2.2.2: Impacts of non-indigenous invasive species at the level of species, habitats and ecosystem, where feasible.

3. Ten key requirements for NIS assessment and management

The following were identified as crucial issues for dealing with the European MSFD Descriptor 2, as well as global management of marine NIS.

3.1. Availability of taxonomic expertise

"Taxonomy provides a basic understanding of the components of biodiversity which is necessary for effective decision making about conservation and sustainable use" [25].

Marine environmental issues associated with the current rapid biodiversity change require multidisciplinary approaches. Yet, taxonomy and systematics—the foundational disciplines that distinguish, classify, and document biodiversity—are at their nadir. Despite Europe's proud history of contributions to marine taxonomic research, its present state is a cause for concern [26–28]. Loss of taxonomic expertise in highly diverse and poorly understood marine taxa results in reduced capacity to evaluate the response of marine biodiversity to global change, its value for mitigation and adaptation, to assess decline in native species, and risks the mis-identification of NIS and inaccurate information about their spread and potential for harm. This knowledge gap means that Europe lacks sufficient capacity to manage, conserve,

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and utilize ecosystem services provided by marine biodiversity, and risks making policy decisions related to the management of marine biodiversity resources on the basis of inadequate, obsolete data. These may result in enormous potential impacts for biodiversity loss and the erosion of associated ecological services that provide benefits for the economy and the well-being of its citizens.

3.2. Application of molecular tools

Whilst classical taxonomy has historically been the most important contributor to marine biodiversity knowledge, recent advances in field and laboratory technologies provide an additional means for species descriptions/identifications as well as valuable insight into species distributions and trophic interactions [29].

Marine invasion narratives are remarkably complex. Unraveling the routes of invasion and colonization histories are tortuous. The new molecular tools and methodologies are invaluable in addressing gaps of knowledge concerning marine bioinvasions. These may aid the tracking of the origin and source of an NIS following a recent arrival, the identification/discrimination of species, recognition of either direct or stepping stone progression and the introduction pathways and vectors that may be involved, the assessment of effective propagule pressure during an establishment of a recently arriving population [30,31]. Employment of techniques such as DNA barcoding [32], Inter Simple Sequence Repeats, ISSR [33], Next Generation Sequencing Technologies, NGST [34] and microsatellite approaches provide powerful tools for identifying the inter-dependence of human-mediated transfer and dispersal of NIS.

3.3. Common guidelines for surveillance and monitoring of NIS

The recorded numbers of brackish and marine NIS underestimate the extent of invasions. There are several reasons for this. Field studies are limited in time and space, focussing on selected taxa or size groups. The number of practising morphological taxonomists that specialize in the smaller-sized marine invertebrate taxa is insufficient for the task at hand (see Section 3.1) and molecular taxonomy has yet to develop its full potential. Some entire communities have not been fully studied, e.g. interstitial fauna, which may have been moved large distances over many centuries in ship's and ballast in, for example, sand ballast and more recently within BW sediments [35]. The problem of incomplete inventories is further compounded by the presence of cryptogenic species (see Section 2, for definition) yet to be classified as 'native' or non-indigenous species [36], but there are also problems arising out of misclassification of species and changes in nomenclature over time.

Surveillance and monitoring of NIS may do well focus on well-studied taxa for which long-term records are both available and reliable. Macroalgae, molluscs, decapod crustaceans and teleost fishes, which are mostly large and distinctive, generally make up most of the complete and current records. To these can be added those taxa of region-specific concerns such as bloom-forming microalgae and gelationous zooplankton (scyphozoans and ctenophorans). Surveillance and monitoring methodologies should be standardized to take account of target species [37–39].

In addition, other emerging technologies such as apps for online identification of species via image analysis and for the development of cost-effective detection networks may provide new and effective opportunities in the future to aid monitoring.

3.4. Early detection and monitoring

Shipping and mariculture-mediated introduction and transfer of NIS are implicated in the majority of new introductions in Europe [40], therefore mariculture facilities, ports and marinas and/or vicinity areas ought to be naturally prioritized as hubs for NIS surveillance. However, as the subsequent dispersal of NIS, either by human or natural means, is often inevitable, surveillance at 'points of entry' should be accompanied by a broader-scale surveillance and monitoring of the coastal regions. Ports and mariculture facilities are circumscribed and enclosed environments, but they are often prone to extreme levels of human disturbance (including pollution and eutrophication). These specific conditions may facilitate NIS establishment [41] and, as they are characterized by numerous transport vectors bringing invasion propagules, these areas are actually colonised by a high number of NIS compared to other regions [42].

In accordance with the several EU directives mentioned earlier, as well as with national and regional agreements (like HELCOM and OSPAR), several EU Member States conduct routine marine monitoring programmes that also include a substantial component of biological sampling. These programmes, such as young fish surveys, may provide, with some modification, an increased level of detection of NIS occurrence, spread and abundance. As a first priority, samples collected by long-term monitoring programmes, should be screened for NIS by taxonomic experts (see Section 3.1). A region-wide standardized surveillence and monitoring program that includes observations on NIS would allow for the inclusion of NIS into integrated ecosystem assessments in future managment [1].

3.5. Standardization of data and information systems

Recent evaluations of online NIS databases (including marine NIS) in Europe, which are entirely dependent on the quality of the underlying data [9,43,44], highlighted failures in comparability due to a lack of standard criteria in the definition of species status, terminology, taxonomic classification, time frame and comprehensiveness. Hulme and Weser [43] advised that "considerable caution should be applied when collating data from different databases because often their underlying structure and content may differ markedly". Standardization will result in more accurate datasets, which then may be compared across regions. The terminology and recording methods applied should be standardized to facilitate the comparison between datasets from different regions and to enable holistic assessments.

Ensuring the accuracy, veracity and quality of national and European NIS databases and information systems is essential, as they play a pivotal role in informing regional policy and management decisions as well as in identifying resource priorities. Therefore, with so much at stake for regulators, scientists, and stakeholders, as well as for the marine environment, it is important that existing NIS datasets, as well as the data produced by current and future surveillance and monitoring programmes, used for the implementation of MSFD policy decisions are standardized and scientifically verified.

3.6. Investigation and assessment of propagule pressure

'Propagule pressure'—a composite measure of the number of viable NIS individuals, genotypes and taxa, the number of discrete introduction events, their frequency and duration—is recognized as the primary determinant of invasion success. Pathways and vectors deliver propagules: *pathways* are the routes a NIS takes to invade into a recipient ecosystem and *vectors* are the actual physical transfer mechanisms responsible for an arrival (Table 1). As a result, one pathway can involve a number of vectors [13,45]. Introduction events may involve a number of vectors within a pathway for its overall dispersal or involve different pathways for continued spread.

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Table 1
A classification of pathways and their vectors, based on [24]. The first three pathways are deemed to be the most frequent modes of primary spread.

Pathway	Vectors
Vessels: ships, vessels, platforms	Ballast water and sediments, sea-chests, hull fouling
Canals	A specific canal (e.g. Suez Canal)
Aquaculture activities	Aquaculture equipment, packaging, stock movement
Aquarium trade/public aquaria	Transported water, waste discharge, direct release, packaging
Leisure activities	Angling baits, stocking, discharges, sport equipment
Live food trade	Intentional release, waste discharge, transported water
Management	Habitat management, biological control
Research and education	With equipment, intentional release, waste discharges
Wild fisheries	Fishing gear, discharges, stock movements

The primary introduction vectors of NIS, or their secondary spread by human or natural mechanisms, remain poorly studied, though for the aquarium trade, evidence is increasing of human releases of unwanted pets [46,47]. Local range expansions are often difficult to relate to a specific pathway or vector; this requires standardization according to different levels of certainty [48].

3.7. Careful choice of indicators

The Commission Decision [23] contains two criteria and three indicators for assessing progress towards good environmental status (GES, see Section 2 above); these are habitat and region specific and predicated on detailed recent inventories. Accurate taxonomic identification, exposure of an area to propagule pressure, diversity of habitats and taxa included in the indicator calculations are some of the issues to be considered.

Comparisons among regions/countries would be invalid should these deal with different sets of habitats of varying spatial and temporal scales or should they be exposed to different oceanographic conditions. Accuracy of data necessarily reflects on the similarity of species included in an analysis, the level of effort in identifying species within each area being compared and the scale and diversity of all habitats surveyed. This is particularly relevant when using the ratio NIS/native species as an indicator since it depends on the native biodiversity or habitat invasibility, which cannot necessarily be managed through NIS control. Therefore, standardized monitoring/survey protocols (see Section 3.3) and reliable information systems (see Section 3.5) not only form the inevitable background, but also define limits for indicator development and their application for assessment purposes.

3.8. Multi-vector management

Eradication of some terrestrial and some freshwater NIS has proven effective [49]. However, most marine eradication attempts have failed: Rapana whelk *Rapana venosa* along the Brittany coast, France [50], brown seaweed *Undaria pinnatifida* in Italy, United Kingdom, Netherlands, New Zealand, Australia and California, United States [51], sea squirt *Didemnum vexillum* in New Zealand [52] and in the United Kingdom [53]. The few successful eradications of marine NIS in-qj;clude *Mytilopsis sallei* in Australia [54], sabellid polychaete *Terebrasabella heterouncinata* in California [55] and the green algae *Caulerpa taxifolia* in California [56] and Australia [57]; these eradications owe their success to a discovery soon after an arrival and their occurrence within confined habitats.

While species-oriented management may be useful in special cases, e.g. the red king crab *Paralithodes camtschaticus* in Norway and Russia [58], there is an obvious need to generate vector-focused approaches, which should form the chief constituent of invasions management [59]. Further more, there is a need for clear recognition of the multiplicity of vectors involved in the invasion process (see Section 3.7) and, where applicable, focus on tackling vectors simultaneously. The relative importance of vectors differs regionally as well as temporally [40]. For instance, the focus on ballast management over past decades resulted in an international convention [15], but this 'one matter at a time' approach has left us with the continuing problem of having to manage several other invasion vectors, such as the biofouling of commercial and recreational vessels. It is suggested here that implementation of multi-vector management should be seen as a means of reducing risk from further NIS invasions.

3.9. Cooperation with stakeholders

Human interactions with the marine environment have both intensified and diversified over time. Therefore, the involvement of stakeholder groups (including industry) should be consulted in relation to marine monitoring and research. Their active participation in a dialogue may not only be informative, but could aid in selecting agreed management options. Such interactions are practical and are becoming increasingly important.

As examples, the sampling of ballast tank contents, the testing of ballast water treatment methodologies or developing safer mariculture methodologies or technologies may require close co-operation with those involved in these industries. To comply with existing legislation and/or voluntary guidelines, such as the ICES Code of Practice on the Introductions and Transfers of Marine Organisms [13] and the European Code of Conduct on Zoological Gardens and Aquaria and Invasive Alien Species [19], may also require the agreement of national and local authorities. Such interaction is likely to improve the operability of future legislation and thereby enable more effective implementation. Furthermore, as invasion vectors may act concurrently, significant progress in NIS management can only be achieved through cooperation and coordination of several different stakeholders, including for example shipping, mariculture, recreation and capture fisheries. Bearing in mind current practices, both at national and regional levels, this is certainly a major, but inevitable challenge.

3.10. Adoption of the 'single authority' approach

The most effective management of marine NIS is through the prevention of new introductions. This cannot be achieved within a management system characterised by fragmented responsibilities. Port authorities, fishery/agriculture ministries, custom authorities and environmental ministries/agencies are all important players that are often impeded by a lack of effective communication and on occasion, an unwillingness to communicate. This impedes management of NIS introductions and may result in increased rate of arrivals or prevent a possible eradication. We suggest that management of marine NIS should be brought to a single authority at national level. An example of a national coordinating body is the Non-native Species Secretariat of the Great Britain [60].

Instruments supporting regional management should be harmonized and there should be an avoidance of duplication but using recognized local experts for surveillance and provided information. Several international directives, policies and regulations deal with alien species in Europe (for details, see Section 1). However, management targets and the required responses do not often coincide, creating difficulties when addressing relevant legislative documentation. Thus, there is a need for effective cooperation and coordination of activities between countries sharing a marine region, to reduce risk of NIS arrivals and their spread.

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4. Conclusions

Compared to several other MSFD descriptors, there is limited knowledge of NIS and their impacts on ecosystems. Most importantly, our knowledge of the pathways, vectors and propagule influx for both primary and secondary introductions is fragmentary. To advance the knowledge of NIS, taxonomic expertise is a key requirement. Recent advances in molecular methods provide tools with which to identify NIS, their origin and source may enable a historical reconstruction of some introductions. Cooperation between morphological and molecular taxonomists is needed in order to supply more complete data, which are required to comply with the MSFD. For reliable and consistent assessments, evaluations of the numbers of NIS, their dispersal and impacts needs to be standardised. Surveillance and monitoring of NIS can begin with the better studied taxonomic groups, but this should be accompanied by a pathway and vector analysis. To improve and enhance the accumulation of systematic standardized information, dedicated NIS monitoring programmes should be established with strict guidelines. Quantitative assessments of changes in habitats, communities and ecosystem function over time due to NIS invasions should facilitate the implementation of an ecosystem approach to marine management. An important pre-condition for success is the involvement of stakeholders, in particular industry, in the research and management of NIS, and this management should be coordinated by a single authority.

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