Information Management

Introducing the World Register of Introduced Marine Species (WRiMS)

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Abstract

A major historical challenge for the management of anthropogenic introductions of species has been the absence of a globally standardised system for species nomenclature. For over a decade, the World Register of Marine Species (WoRMS) has provided a taxonomically authoritative classification and designation of the currently accepted names for all known marine species. However, WoRMS mainly focuses on taxonomy and does not specifically address species introductions. Here, we introduce the World Register of Introduced Marine Species (WRiMS), a database directly linked to WoRMS that includes all introduced marine species, distinguishing native and introduced geographic ranges. Both the WoRMS and WRiMS contents are continually updated by specialists who add citations of original species descriptions, key taxonomic literature, images and notes on native and introduced geographic distributions. WRiMS editors take responsibility for assessing the validity of species records by critically evaluating if a species has been introduced to a region, erroneously identified and/or potentially naturally present in a region but previously unnoticed. WRiMS currently contains 2,714 introduced species. The amount and quality of the information entered depend on the availability of experts to update its contents. Because WRiMS is global and it combines species taxonomic and geographic information with links to other resources and expertise, it is currently the most comprehensive standardised database of marine introduced species. In addition, WRiMS forms the basis for a future global early warning system of marine species introductions.

Key words: invasive, alien, naturalised, non-indigenous, ocean, biodiversity informatics

Introduction

Humans have intentionally and unintentionally moved species around the world since they started navigating the seas (Carlton 1985, 1989). These introduced species are variously called alien, exotic, non-native, non-indigenous and introduced alien species (Essl et al. 2018; Pyšek et al. 2020). Introduced species are a primary driver of global biodiversity change (Pecl et al. 2017), having both ecological and economic impacts across large geographic areas (Parker et al. 1999; David et al. 2017; Anton et al. 2019). Considering these impacts, there is an urgent need to document species introductions (Ojaveer et al. 2018). As a result, regional online lists detailing the presence and distribution of introduced species have been compiled (e.g., Katsanevakis et al. 2012; Robinson et al. 2016). A decade ago, there were over 250 lists (Sellers et al. 2010) and nowadays the Global Invasive Species Information Network lists 193 websites (Anon. 2019). These lists aim to support informed management decisions. For example, they are used to identify species that are not yet present in a region but for which vectors with the potential for transporting species exist (Roy et al. 2014) and the creation of "watch lists" of high-risk species (Faulkner et al. 2014). Should these species be likely to survive the environmental conditions in the new range, they can be added to a watch list of potential invaders (Swart and Robinson 2019). This helps focus monitoring and swift action should a new species introduction be recorded. However, there are several problems associated with the use of these regional lists, including the use of different taxonomic nomenclatures and bias due to available expertise. Thus, there have been calls for a single coordinated system that integrates all the knowledge within these lists into a single global database (Riccardi et al. 2000; Hulme and Weser 2011; McGeoch et al. 2012, 2016). Such a centralised system would allow standardising and achieving quality control at global level, aid risk assessment and be more cost-efficient for management of species introduction's nomenclature and knowledge.

The first step for listing introduced species is to give them the "correct" name. Using the scientifically most up to date name is critical because the allocation of the name links to the relevant information on its diagnostic characteristics, geographic distribution, ecology and possible environmental, economic and health impacts. However, this initial step may prove very challenging (Pyšek et al. 2013). There are almost 240,000 named marine species with 570,000 marine species names (Horton et al. 2020), and their classification changes in response to new scientific knowledge and hypotheses (Costello et al. 2010, 2013). This is complicated by the fact that some species have tens of scientific names for one biologically valid species (Appeltans et al. 2012; Horton et al. 2018). The great diversity of marine species means that it is beyond the skills of even a person familiar with the local fauna and flora to identify every single species found in the community.

As such, a species newly noted in an area may be allocated the wrong name because it was misidentified or misnamed, and thus the wrong species name may be added to the regional list of introduced species. In some areas where the native fauna is still being described, undescribed native species may be wrongly identified as an introduced species (Hutchings et al. 2002). This means that regional lists of introduced biota often have inaccuracies that can limit their value. Another challenge of regional lists is that the problem of species introductions is a global one, with the introduction of most species being associated with international trade and transport (Essl et al. 2015; Ojaveer et al. 2018) and aquaculture (Lavesque et al. 2020). Thus, local experts may not be able to decide if an unfamiliar species is introduced or native. For example, distinguishing native from introduced polychaetes (Kupriyanova et al. 2013) and unicellular plankton (Gómez 2008, 2019; Gómez et al. 2019) can be challenging. These challenges make comparisons among regions extremely difficult without a global perspective. Thus, there is an urgent need for an integrated database that details the global distribution of marine introduced species and accounts for the most up to date taxonomic nomenclature and classification.

While there are numerous online sources of data on introduced species (Table 1), these are not directly linked to the current taxonomic names and classification of species. To improve the efficiency of allocating the correct name to a newly noted species and mitigating the above challenges, researchers require an open access species database with expert validated nomenclature, species distributions, identification guides and contact details of experts. In the past decade, two global marine biodiversity databases have been established. The first one is the World Register of Marine Species (WoRMS, www.marinespecies.org) that provides a scientifically validated classified checklist of about 238,000 described marine species linked to source literature, synonyms, and contact details of taxonomic experts, amongst other information (Costello et al. 2013, 2018; Horton et al. 2017). This database is continually edited by about 300 experts. The second database is the Ocean Biodiversity (formerly Biogeographic) Information System (OBIS, www.iobis.org) that publishes standardised spatial and temporal records on reported locations of over 155,000 marine species (Wood et al. 2006; Costello et al. 2007, 2015). However, until recently, no open access, standardised, expert-edited list of marine introduced species has been available. This is despite the acknowledgement that such a database is key to tracking transboundary spatial patterns in biological invasions, especially considering contemporary climate change (Robinson et al. 2020).

Here we present the World Register of Introduced Marine Species (WRiMS), the first consolidated expert-edited world list of all introduced marine species (Rius et al. 2021). WRiMS is structurally linked to WoRMS, which means that the taxonomic information of the species found in WRiMS is automatically updated by the WoRMS experts.

Table 1. Examples of online databases related to marine introduced species and their scope. See Ricciardi et al. (2000) for a list of 27 regional and national databases concerning introduced species.

Database	Scope
Global Invasive Species Database GISD http://www.iucngisd.org/gisd/	Profiles on knowledge of selected invasive species.
Global Register of Introduced and Invasive Species (GRIIS) http://www.griis.org/	Checklists of species introduced to particular countries (Pagad et al. 2018).
European Alien Species Information Network - EASIN https://easin.jrc.ec.europa.eu/	Lists species introduced to Europe (Katsanevakis et al. 2012).
OBIS www.iobis.org	Primary data on the distribution of marine species in space and time.
GBIF www.gbif.org	Primary data on the distribution of species in space and time.
Aquamaps www.aquamaps.org	Maps of the geographic ranges of aquatic species predicted by their environmental range.
FishBase www.fishbase.org	Wide range of data on all fish species.
SeaLifeBase www.sealifebase.org	Like FishBase in design and structure, but for non-fish marine species.
AquaNIS http://www.corpi.ku.lt/databases/index.php/aquanis	A flexible multi-criteria search engine (by taxonomy, geography, pathways, biological traits, status in recipient habitat, etc) of marine introduced species.
Belgian Forum on Invasive Species (BFIS) https://ias.biodiversity.be/	Belgium
National Invasive Species Information Centre https://www.invasivespeciesinfo.gov/animals/main.shtml	USA
Centre for invasive species and ecosystem health https://www.invasive.org/	USA
National Estuarine and Marine Exotic Species Information System (NEMESIS) https://invasions.si.edu/nemesis/	USA
Invasive Species Compendium Centre for Agriculture and Bioscience International https://www.cabi.org/isc	Worldwide all-taxon scope.
NIMPIS database https://www.marinepests.gov.au/pests/nimpis	Profiles on knowledge of selected invasive species in Australia.

Materials and methods

Data sources and history

In 2008 and 2009 the IUCN Invasive Species Specialist Group (ISSG) worked on a project with the aim of developing resources for OBIS, which produced a first annotated dataset of marine introduced and invasive species for WoRMS. In 2013–2014, ISSG worked with the Flanders Marine Institute (VLIZ) on a data collection project developed within the framework of the Biology Project of the European Marine Observation and Data Network (EMODNet) to complete trait information related to "invasiveness" for marine species. WRiMS defines invasive species as introduced species that are "*spreading geographically, or where scientific evidence of negative impacts on native biodiversity has been recorded*" and provides a glossary of its terminology on its website.

Data were extracted from over 3,600 publications listed on the WRiMS website, including compilations at global (e.g., Molnar et al. 2008), regional (e.g., Streftaris et al. 2005), national (e.g. Galil 2007) and local (e.g. Marchini

et al. 2015a) scale inventories. Available information on species' abundance, evidence of impacts on biodiversity, and pathways of introduction and spread were documented. Mistaken or uncertain records, such as suspected misidentifications, species not introduced by human action but naturally spreading, and cryptogenic species, are all too often included in inventories and propagated through the literature (Marchini et al. 2015b). These questionable records are checked by the editors.

Data validation

WRiMS records are validated by the editors based on defined criteria on taxonomic identity and introduction status (following Marchini et al. 2015b), starting with a critical examination of primary (original introduction) records. For inclusion, at least one of the following criteria confirming the introduced status of a species is required: (a) comparison with scientific reference material (e.g., specimens, photographs, video); (b) examination of specimens by a taxonomic expert; and/or (c) molecular analysis.

The unequivocal designation of a species as "introduced" requires knowledge on its native range and likely vectors and pathways of introduction. Thus, based on this criterion, records requiring additional evidence before being classified as introduced in WRiMS include: (1) species of unknown native origin (cryptogenic species; *sensu* Carlton 1996); (2) widespread species with unknown biogeographic history; (3) species unlikely to have been introduced by human action (natural range expanding species); and (4) new records of species in the deep-sea (typically below 200 m depth) because such species may be rarely recorded but have very wide distributions.

Only species supported by reliable records, i.e., providing enough evidence that the species was present alive and has been collected in environments open to the sea, are included in WRiMS. Based on this criterion, records that require additional evidence before inclusion in WRiMS comprise: (1) freshwater species occasionally recorded in transitional environments that are unlikely to establish breeding populations and to spread further to other coastal environments; (2) species identified from shells (molluscs, serpulid worms, barnacles and other crustaceans, bryozoans, brachiopods) as they may have been transported as non-living material; (3) evidence of the species based only on dead or detached parts of the organisms, benthic species identified from unattached or floating specimens, or fragments unable to re-attach or generate viable propagules; and (4) species recorded exclusively from their associated vectors, e.g. moored vessels, ballast water or ballast tanks, gas or oil platforms.

Database structure and software

WRiMS is part of the Aphia platform, which is an infrastructure designed to capture taxonomic and related data and information in a structured way

(Vandepitte et al. 2015, 2018). The Aphia platform is a Microsoft Structured Query Language (MS SQL) database, containing more than 400 data-fields. Within Aphia, about 500 experts maintain several Global, Regional and Thematic Species Databases. WRiMS is one of the Thematic Species Databases of Aphia, as it groups existing taxa based on a specific theme (in this case "introduced"). As the relevant information for introduced species can be quite specific, a number of database fields and features have been made available specifically for WRiMS, to allow the editorial community of WRiMS to capture all relevant information. These extra database fields include: "Origin", "Invasiveness" and "Occurrence". The fields were added to the geographic distribution module of Aphia, so each separate distribution record can have these three properties assigned. Thus, a species distribution record can be considered introduced in a certain location rather than the species being introduced everywhere it occurs. The pathways and vectors per location were added as a note to the species record. The terminology used in WRiMS is intended to be self-explanatory and is listed and defined in Table 2.

Management

WRiMS is part of WoRMS, and as such it reports to the WoRMS Steering Committee and Editorial Board. The Steering Committee is elected by all taxonomic, regional and thematic editors of the underlying Aphia database. The Steering Committee decides on the general direction of WoRMS. In addition, WRiMS also relies on the taxonomic editors as they keep the taxonomy of WoRMS up to date on a voluntary basis (Costello et al. 2013; Vandepitte et al. 2015; Horton et al. 2017). WRiMS has its own steering committee (Rius et al. 2021), which is in charge of identifying data gaps and coordinating activities. Following the founding principles of WoRMS, its predecessor the European Register of Marine Species (ERMS) (Costello 2000), and the former Society for the Management of Electronic Biodiversity Data (SMEBD), the content is owned by the WoRMS Editorial Board which includes WRiMS editors and follows their terms of reference and conditions of participation (Box 1). Individual editors retain the full rights to use their own data and information, but have also given the Editorial Board the right and responsibility to publish, disseminate, expand and update the content. Thus, an editor cannot place restrictions on the dissemination of the data (it is published open-access), nor ask for their content to be removed, for example if they resign or retire or have a dispute with other editors, VLIZ, or the WoRMS or WRiMS committees. The WoRMS Steering Committee is responsible for coordinating all editors in the database, both those with taxonomic and thematic responsibilities. Where WRiMS requires special features or changes to Aphia that may affect other WoRMS editors, then the WoRMS Steering Committee may need to approve them.

Table 2. Terminology used in WRiMS. For a more detailed marine ecology glossary see Costello et al. (2020).

Invasiveness	Definition with respect to an introduced species
Invasive	Spreading geographically, or where scientific evidence of negative impacts on native biodiversity has been recorded.
Invasiveness not specified	"Invasiveness" has not been specified or evidence of impact documented.
Invasiveness uncertain	"Invasiveness" is uncertain and evidence of impact is not clear.
Management recorded	Species is being managed to prevent introduction and/or spread.
Not invasive	Which do not spread, or not shown to have impacts on native biodiversity.
Of concern	Species that have not displayed any invasiveness in the country or sea area where they have been introduced but are known to be invasive in their introduced range elsewhere; and whose life stage forms can be dispersed through ballast water and or hull fouling.

Self-explanatory terminology

Origin: Alien**;** Native; Native endemic; Native non-endemic; Origin uncertain; Origin unknown.

Location: Introduced country and/or sea area; Native country and/or native sea area; Source country and/or sea area.

Occurrence: Absent; Border Intercept; Detected in invasion pathway; Detected in the wild; Eradicated; Eradication unconfirmed; Established; Established and expanding; Established and stable; Extirpated; In captivity/cultivated; Introduction unverified; Occurrence Not specified; Present/controlled; Recorded in error; Reported; Sometimes present.

Impact: Adverse habitat modification; Alters bio-geochemical/hydrologic cycles; Alters trophic interactions; Aquatic transport; Consumes native species (predator or herbivore); Damage to marine structures or archaeology; Genetic impacts: hybridisation and introgression; Human health; Induces novel behavioural or eco-physiological responses; Loss or gain of aquaculture/commercial/recreational harvest; Loss of public/tourist amenity; Other impact – undefined or uncertain; Outcompetes native species for resources and/or space; Pathogen/parasite or carrier of a pathogen/parasite; Water abstraction or nuisance fouling.

Pathways and vectors: Aquaculture: accidental; Bio-control: accidental translocation with deliberate bio-control release; Bio-control: deliberate translocation as a bio-control agent; Canals: natural range expansion through man-made canals; Debris: transport of species on human generated debris; Fisheries: accidental as bait; Fisheries: accidental with deliberate translocations of fish or shellfish; Fisheries: accidental with fishery products, packing or substrate; Fisheries: deliberate translocations of fish or shellfish to establish or support fishery; Individual release: accidental release by individuals; Individual release: deliberate release by individuals; Natural dispersal; Pathway/vector: Other; Pathway/vector: Unknown; Plant introductions: accidental with deliberate plant translocations; Plant introductions: deliberate translocation of plant species; Recreational equipment: accidental with recreational equipment; Scientific research: accidental release with research activities; Scientific research: deliberate release with research activities; Seaplanes: accidental as attached or free-living fouling organisms; Ships: accidental as attached or free-living fouling organisms; Ships: accidental associated with cargo; Ships: accidental with ballast water, sea water systems, live wells or other deck basins; Ships: accidental with solid ballast; Ships: general.

The WRiMS editors are responsible for the quality and quantity of content in WRiMS. Editors can be thematic or taxonomic in focus and can edit the WRiMS content in their allocated field online. In addition, the editors can provide information directly to the "Data Management Team" for entry into WRiMS. The WRiMS steering committee appoints new editors and replaces those who retire. Editors may resign or be appointed at any time. This committee consists of at least five persons with terms of two years and no more than six years in total. Decisions are by consensus, and if consensus is not possible then a vote is taken with the Chair only voting if necessary. The citation of WRiMS includes all active editors in alphabetical order. Changes to these practices can be made following consultation with all WRiMS editors and the WoRMS Steering Committee.

Results

As of 18th December 2020, 2,714 marine species of 34 phyla were included in WRiMS (Table 3). Of these, 2,159 were confirmed introductions, of which 11% (213 Animalia, 17 Chromista and 23 Plantae) were classified as

Box 1.

Terms of Reference for the Steering Committee, editors and data management team of the World Register of Marine Species and associated databases, including the World Register of Introduced Marine Species (WRiMS).

This document establishes the basis on which data and/or intellectual property (IPR) is provided to the World Register of Marine Species database and associated databases (WoRMS) and how these data and IPR are managed. The associated databases may be defined geographically, taxonomically, or by other themes.

By voluntarily providing data or other documented expertise or assistance to WoRMS you as WoRMS editor accept the terms laid out below.

The governance structure of WoRMS comprises three components:
1. The **WoRMS editorial board (WoRMS editors)** includes all active editors and data providers.
2. The **WoRMS steering committee** (WoRMS SC) leads the editorial board. The WoRMS SC members appoint a chair and vice-chair by majority vote. The SC will have 12 elected members and 1 ex officio DMT member. Elections will be organized yearly, with a rotation time of 3 years for each member to ensure continuity and renewal. All taxonomic and theme editors and data provider head managers are eligible for candidacy and can nominate candidates.
3. The **WoRMS data management team** (WoRMS DMT) is appointed by VLIZ to run the database.
Together WoRMS DMT and WoRMS SC further consult to decide WoRMS policy, plan future developments, raise funding, and promote public use of the database.

Your rights as editor or data provider:
1. You keep the right to use and publish any data which you have provided without needing to inform the WoRMS SC.
2. You can provide your data to WoRMS either via the online interface or by direct communication with WoRMS DMT.
3. Your contributions will be acknowledged in all publications of the database and derivatives of it, either personally or by your membership to the editorial board.
4. You will receive reports on the actions taken by the WoRMS SC and DMT.
5. You will be invited to vote and nominate candidates (including self-nominations) for the WoRMS SC, at least one month prior to the elections.

You further agree that:
6. The data provided to the database can only be removed for scientific reasons, with larger datasets only to be removed after approval by the WoRMS SC.
7. You have taken reasonable measures to ensure that the data provided is scientifically correct, and free of copyright infringements, and to inform the DMT in case of doubts.
8. You will inform the DMT of errors in the database, copyright infringements or plagiarism by third parties.
9. When you use the online editing interface, you will follow the suggested procedures in the online manual, and if needed request support and clarification from the DMT at info@marinespecies.org and the chief editor for your taxon group.
10. You agree to respond to requests from DMT or users to add or correct data as soon as feasible.
11. You delegate to the WoRMS SC and the DMT the authority to take the necessary actions to **store**, **copy** and **disseminate** the database, to **modify** the provided data to protect the integrity and scientific correctness of the database, to further develop the database and promote its use.

A non-exhaustive list of WoRMS SC and DMT activities is laid out below.

Responsibilities and roles of the WoRMS SC:
1. Responsibility to **represent the editors** in all matters relating to the databases, including liaison with other international programs, projects and initiatives concerning the databases, in close collaboration with the Data Management Team (DMT).
2. Responsibility for the **scientific correctness** of the database, and for identifying data gaps.
3. Act to appoint or replace editors who contribute to or validate content of the database,
4. Responsibility to evaluate database download requests, to **license the use** of downloads through a standard agreement application form, and to negotiate exceptional uses of the databases outside the standard license.
5. Act to inform the editors and DMT of infringements in use of the databases and undertake necessary corrective actions.

Responsibilities and roles of the WoRMS DMT:
1. Responsibility for **online publishing** of the database including: taking all necessary actions to insure the database is online at all times; protecting the integrity of the database and the persistence of the unique identifiers; archiving the databases at regular intervals in a secure facility; acting as a first line of support to users; informing editors of remaining unresolved questions.
2. Act to **provide copies** of the databases to third parties upon prior approval by WoRMS SC.
3. Responsibility for informing the WoRMS SC Chair of infringements in use of the databases, and for undertaking necessary corrective actions.
4. Act to **supervise editing activities**, control access and editing rights of editors, support the editors in the use of the online editing environment, upload species registers or other information, maintain the taxonomy in close consultation with, or upon request of, the editors.
5. Act to organize workshops for WoRMS editors and to organize the yearly elections for the WoRMS SC.

Table 3. The number of marine taxon names (including above species level), species names (including synonyms), and accepted species names in WRiMS per kingdom and phylum. The percentage of WoRMS species in WRiMS is shown per taxon, with above average values (> 2.13%) in bold. Note that 265 species in WRiMS are not strictly marine but brackish water, and some 236 species are in WRiMS because they have been mistakenly classified as introduced. The number of accepted species that are both introduced and considered invasive in any place and time is also listed. A breakdown of introduced/invasive species for phyla with over 300 species is, [1] Arthropoda: Merostomata 1/0; Pycnogonida 8/1; Hexanauplia 82/11; Malacostraca 232/40; Ostracoda 1/0; Branchiopoda 4/1; Collembola 1/1; Insecta 3/1. [2] Chordata: Ascidiacea 73/21; Actinopterygii 225/30; Elasmobranchii 15/1; Aves 1/1; Mammalia 2/0; Reptilia 3/0. [3] Mollusca: Bivalvia 141/24; Cephalopoda 6/0, Gastropoda 207/18; Polyplacophora 5/0.

Taxon	Taxon names	Species names	Accepted species	% in WoRMS	Invasive species
All biota	7 974	3 410	2 714	1.46	*253*
Kingdom Animalia	5 881	2 477	2 020	1.25	213
Phylum Annelida	591	288	252	0.02	**24**
Phylum Arthropoda [1]	1 387	521	429	**2.18**	55
Phylum Brachiopoda	7	1	1	0.92	1
Phylum Bryozoa	340	161	136	0.24	13
Phylum Chaetognatha	9	3	2	**2.56**	**0**
Phylum Chordata [2]	1 235	573	521	**2.27**	**53**
Phylum Cnidaria	397	167	135	**2.50**	17
Phylum Ctenophora	19	4	4	1.41	**2**
Phylum Echinodermata	107	25	20	2.00	2
Phylum Entoprocta	10	4	4	0.02	**0**
Phylum Mollusca [3]	1 484	644	450	1.32	42
Phylum Nematoda	17	3	1	0.05	1
Phylum Nemertea	11	2	2	0.15	0
Phylum Platyhelminthes	95	27	25	0.23	0
Phylum Porifera	113	43	29	0.48	3
Phylum Rotifera	9	1	1	0.55	0
Phylum Sipuncula	33	10	8	**6.41**	**0**
Kingdom Bacteria	23	3	3	0.15	0
Phylum Cyanobacteria	7	1	1	0.13	0
Phylum Firmicutes	3	0	0	0.00	
Phylum Proteobacteria	9	2	2	0.25	0
Kingdom Chromista	1 101	465	322	**2.32**	**17**
Phylum Bigyra	6	1	1	1.39	**0**
Phylum Cercozoa	13	4	4	1.79	**0**
Phylum Ciliophora	30	5	4	0.19	0
Phylum Cryptophyta	5	1	1	0.96	0
Phylum Foraminifera	279	98	78	1.10	2
Phylum Haptophyta	21	5	5	1.58	**0**
Phylum Myzozoa	217	122	87	**7.63**	6
Phylum Ochrophyta	511	229	142	0.00	9
Phylum Oomycota	5	0	0	0.00	
Kingdom Plantae	927	457	361	**4.40**	**23**
Phylum (Division) Charophyta	17	6	5	**17.14**	
Phylum (Division) Chlorophyta	229	108	87	**4.26**	**7**
Phylum (Division) Rhodophyta	583	318	245	**4.24**	**10**
Phylum (Division) Tracheophyta	91	25	24	**9.43**	**6**
Kingdom Fungi	37	8	8	0.63	0
Phylum (Division) Ascomycota	28	7	7	0.75	0
Phylum (Division) Microsporidia	7	1	1	0.45	0

invasive. Species which may or may not have been introduced comprise 124 classified as being of unknown origin. Some 265 non-marine taxa are included, as well as brackish water taxa (e.g., charophyte plants) because they are sometimes included in marine literature. The most species-rich introduced phyla were Mollusca (450), Arthropoda (429, including 407 crustaceans), Chordata (521, of which 406 are fish and 107 are tunicates), Annelida worms (252, all polychaetes), and red algae (245) (Table 3). Overall,

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Box 2.

Example of a summary of knowledge on an introduced species in WRiMS.

Microcosmus squamiger is a solitary ascidian (Pyuridae, Ascidiacea, Chordata) characterised by a thick, brownish and sturdy tunic, covered by epibionts (www.marinespecies.org/introduced/aphia.php?p=taxdetails&id=236666#images).
It was first described in 1927 from samples collected in Australia (http://www.marinespecies.org/introduced/aphia.php?p=sourcedetails&id=130459).

In the last fifty years, *M. squamiger* has spread around the world (http://www.marinespecies.org/introduced/aphia.php?p=sourcedetails&id=192512). This species is now found along a large number of coastlines, including western Europe, South Africa, and California (www.marinespecies.org/introduced/aphia.php?p=taxdetails&id=236666#distributions).

Given that this species has managed to establish itself in many coastlines around the world, and that most introduced sites are around large commercial ports, the most likely vector of the introduction is via transoceanic shipping (http://www.marinespecies.org/introduced/aphia.php?p=taxdetails&id=236666#notes). Genetic studies have confirmed its Australian origin and showed that there is no significant genetic differentiation among the sites where this species has been introduced (http://www.marinespecies.org/introduced/aphia.php?p=sourcedetails&id=192512), indicating a high connectivity accross the introduced range.

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around 1% of species in WoRMS were listed in WRiMS. An example of the information available for an introduced species is shown in Box 2.

The Mediterranean Sea, especially its eastern part, has the most introduced species of any of the sea regions in the world (Table 4, Figure 1). Other European seas also featured high on the list of introductions. Of the geographic distribution records in WRiMS, 11% of the species were recorded as invasive in some place and time.

Discussion

WRiMS provides the first global open-access platform for expert-validated geographic distribution records of introduced marine species linked to the WoRMS standardised species taxonomic nomenclature and classification. WRiMS currently contains 2,159 introduced marine species, constituting *ca.* 1% of all known marine species. It is reasonable to expect that many more species have been introduced and have not yet been detected, either because they have not been searched for, not survived, or because they have not become abundant. The field of invasion science inherently suffers regional biases in sampling and taxonomic effort (Nuñez and Pauchard 2010; Mead et al. 2011), directly affecting WRiMS and other similar online databases. As a result, the patterns reported here (e.g., Figure 1) are influenced by all these biases. In addition, due to geographic and taxonomic gaps, and errors in the literature and online sources, users of WRiMS should realise that it may also contain mistakes of data entry and outdated information.

Table 4. Number of species reported to be Introduced and Invasive for each standardised sea area in WRiMS. B.C. = British Columbia. "Mediterranean Sea" overlaps with Mediterranean Eastern and Western; these areas in turn (partly) overlap with the ***Seas. Numbers for these (* & ***) regions cannot be added up, as they include overlapping species, which would provide erroneous numbers. The major Mediterranean sub-areas are represented separately. All areas are International Hydrographic Organization Sea Areas (Flanders Marine Institute (2020)).

Sea Area	Introduced	Invasive	%	Sea Area	Introduced	Invasive	%
Mediterranean Sea	1030	73	7	East China Sea	11	1	9
* Mediterranean Eastern	643	50	8	Rio de La Plata	11	0	0
* Mediterranean Western	115	16	14	Irish Sea	10	1	10
*** *Aegean Sea*	178	20	11	Bay of Fundy	6	4	67
*** *Adriatic Sea*	132	9	7	Lakshadweep Sea	6	0	0
*** *Ionian Sea*	58	5	9	Gulf of Siam	5	2	40
*** *Tyrrhenian Sea*	41	1	2	Yellow Sea	5	1	20
*** *Alboran Sea*	19	3	16	Arabian Sea	5	0	0
*** *Ligurian Sea*	16	2	13	Bay of Bengal	5	0	0
*** *Strait of Gibraltar*	2	0	0	Bristol Channel	5	0	0
North Sea	216	25	12	Gulf St Lawrence	5	0	0
North Atlantic Ocean	160	41	26	West Scotland	5	0	0
North Pacific Ocean	153	42	27	Finland Gulf	4	1	25
Black Sea	89	6	7	Riga Gulf	4	1	25
Baltic Sea	86	8	9	Banda Sea	4	0	0
English Channel	82	13	16	Gulf of Iran	4	0	0
Celtic Sea	64	16	25	Gulf of Suez	4	0	0
Kattegat	54	2	4	Red Sea	4	0	0
Marmara Sea	50	1	2	Bothnia Gulf	3	1	33
Skagerrak	50	1	2	Arafura Sea	3	0	0
Biscay Bay	49	3	6	Bering Sea	3	0	0
South-east Alaska & B.C.	48	2	4	Sea of Okhotsk	3	0	0
Caribbean Sea	44	5	11	Sea of Azov	2	2	100
Mexico Gulf	42	7	17	Barents Sea	2	0	0
Indian Ocean	35	19	54	Beaufort Sea	2	0	0
South Atlantic Ocean	25	10	40	Chukchi Sea	2	0	0
Tasman Sea	25	2	8	Gulf of Aden	2	0	0
Gulf of Guinea	19	1	5	Gulf of Oman	2	0	0
Sea of Cortez	18	0	0	Timor Sea	2	0	0
South Pacific Ocean	17	6	35	White Sea	2	0	0
Bass Strait	16	2	13	Inland Sea of Japan	1	1	100
Gulf of Alaska	15	1	7	Norwegian Sea	1	1	100
Japan Sea/East Sea	14	5	36	Burma Sea	1	0	0
Arctic Ocean	13	0	0	Labrador Sea	1	0	0
Coral Sea	12	1	8	Makasar Strait	1	0	0
Great Australian Bight	12	1	8	Malacca Strait	1	0	0
South China Sea	12	1	8	Singapore Strait	1	0	0
Philippine Sea	11	2	18	Solomon Sea	1	0	0
				TOTAL	1101	108	10

Data management

Groom et al. (2017) made seven recommendations for data management of introduced species, namely: (1) creation of data management plans; (2) increase interoperability of information sources; (3) documentation of data through metadata; (4) application of existing standards for data formatting; (5) adoption of controlled vocabularies; (6) increase data availability; (7) ensure long-term data preservation. Presently, WRiMS has fulfilled all these recommendations by establishing a social and technical infrastructure system for the management of introduced marine species which is interoperable with WoRMS, OBIS, and associated databases.
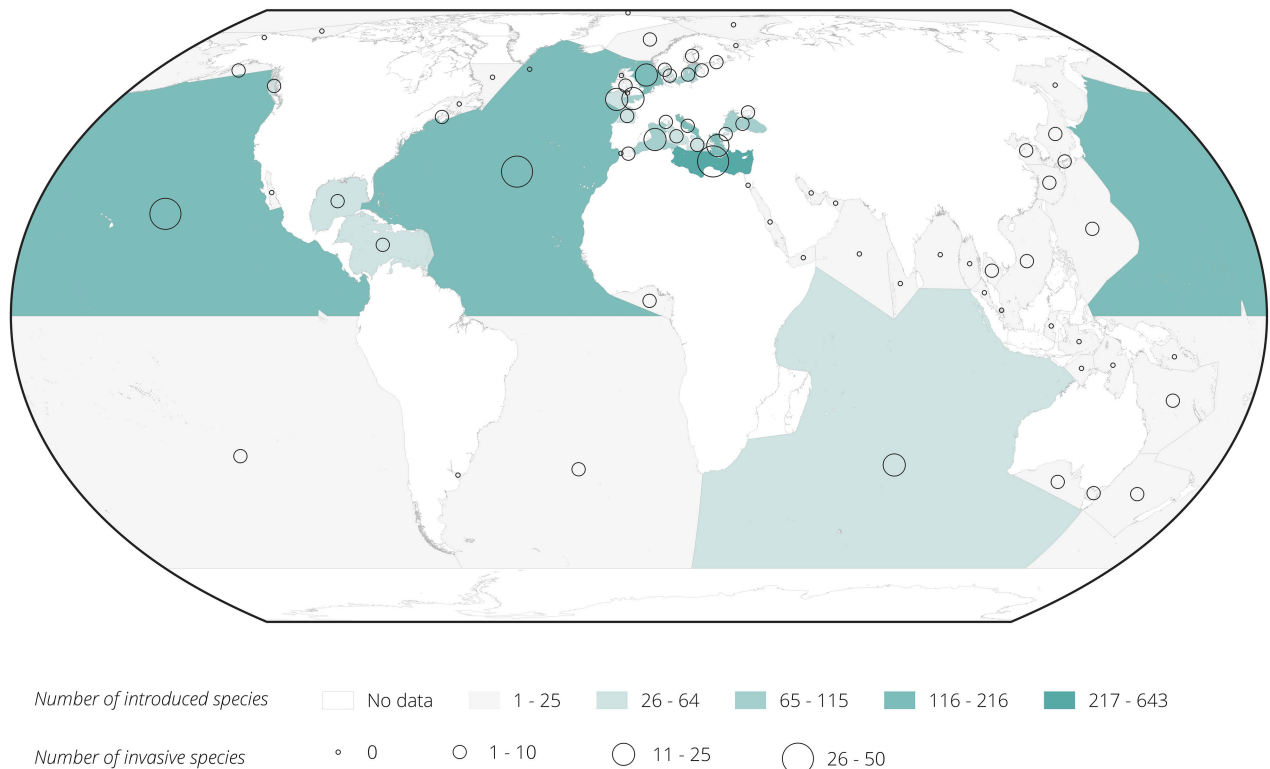
Figure 1. Map indicating the numbers of Introduced and Invasive species in seas as reported in the World Register of Introduced Marine Species.

The content is formatted in a relational database (Aphia) with controlled vocabularies based on commonly used classifications (Vandepitte et al. 2015). It is open-access and archived monthly with a Digital Object Identifier (DOI) to ensure long-term preservation of content (Ayhong et al. 2019).

A major challenge in developing WRiMS has been verifying the veracity of reports of species introductions. Too often, comments in the scientific literature suggest a species may be introduced without providing justification (Marchini et al. 2015b). The species may have been previously unreported from the area, misidentified and/or misnamed, or be a natural extension of its geographic range perhaps associated with climate change. Such speculation can lead to the perpetuation of incorrect information in both the literature and online databases. Another issue is the misuse of the term "invasive", which is often loosely applied to species that are not yet invasive or have naturally expanded their geographic range (perhaps due to climate change). WRiMS started with a list of some 2,200 species, which was reduced by 10%, and further taxonomic scrutiny may reduce the list further. Over-counting introductions may be a problem in taxonomically difficult taxa, such as microalgae and macro-invertebrates. For example, a critical synthesis of national inventories of introduced marine species of EU member states (Tsiamis et al. 2019) included 52 microalgae. However, Gómez (2019) questioned whether any of these species were really introduced to European seas. Another assessment found that only 52% of amphipod crustaceans alleged in the literature to be introduced could be

confirmed as species introductions (Marchini and Cardeccia 2017). Only attentive and meticulous validation by experienced taxonomists may help avoid costly risk assessment and the establishment of monitoring systems of "fake" NIS.

Future needs

Terminology related to invasive species has been debated and subject to many proposals over the past decades (e.g., Richardson et al. 2000; Colautti and MacIsaac 2004; Ricciardi and Cohen 2007; Blackburn et al. 2011, 2014; Jeschke et al. 2014; Ojaveer et al. 2015; Bacher et al. 2018; Essl et al. 2018). The currently used terminology in WRiMS may change should the scientific community develop more standardised terminology. Further, revisions of sub-categories more allied to the marine environment may be implemented, especially in describing introduction pathways, vectors and impacts.

In addition to an up to date terminology and context, users need open-access information and images to aid identification of the species of concern and their relatives (to avoid confusing them). WRiMS provides this feature through WoRMS and links to external online databases, although this is not designed as a guide to species identification. An online guide to marine species identification would be a welcome addition to available resources (Costello 2020).

Two decades ago, a single globally coordinated data system for all introduced species was proposed, part of which would include an early warning system to aid monitoring of species' spread (Ricciardi et al. 2000). WRiMS provides this centralised system for marine species and is an important first step in providing scientists and management authorities with access to quality information and expertise on all introduced marine species. The date of first reported occurrence (~ introduction) has been found to be the best predictor of whether a species becomes invasive (Byers et al. 2015) and is recorded in WRiMS when available. However, knowledge of repeated introductions is also important to report because "propagule pressure" increases the likelihood of an introduced species' survival and becoming invasive (Simberloff 2009; Viard et al. 2016; Liebold et al. 2017; Redding et al. 2019). What would build well on WRiMS is a system where users could report suspected records of introductions and re-introductions and get them validated by experts. This would be facilitated by WRiMS developing and maintaining a list of relevant experts by geographical area and they being notified automatically when such a record is reported. It could provide an early-warning system of the geographic spread of introduced species and support networking of experts and managers (Simpson et al. 2006). The technology for this system exists. For example, iNaturalist already provides a free online system for citizen scientists to upload photographs of any species and have their identification confirmed

by experts. Such a system could also report if species are no longer present at a location, whether due to intentional removal, or natural factors.

To be viable in the long-term, biodiversity databases that need sustained expert involvement, such as WRiMS, require both engagement from the community of experts, succession planning, and support from an institution to host a centralised database (Costello et al. 2014, 2018). WRiMS provides this continuity of expertise through an editorial board and technical support ensured by its host institution, VLIZ. Its editors are conversant in both taxonomy and invasion ecology, and are often specialised in identifying regional biota. The need for detailed taxonomic information, museum vouchers and genetic data (e.g. Rius and Teske 2013) must also be stressed. However, like any scientific endeavour, its success will depend on the availability of resources to facilitate and prioritise experts' engagement. Such resources may arise from involving major users of introduced species data in WRiMS development, including using WRiMS as a foundation for an effective global early warning system for marine species introductions.

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Authors' contribution

MJC led and all authors contributed to the writing of the paper and the creation of the underlying database and data reported in this paper.

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