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MarINvaders: A web toolkit of marine species for use in environmental assessments

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Abstract

Invasive species are the second most important reason for species extinction since 1500 AD. In addition, these invasive species can cause vast economic loss. In marine ecoregions, alien species introductions are increasing, and those that become invasive have caused profound changes in many marine ecoregions. We compiled a database consisting of information about where species are alien, where they are not, and which species are listed as threatened by invasive species. In addition, we developed an interactive Webapp for visualizing and analyzing the results. We used the Ocean Biogeographic Information System (OBIS) for identifying the presence of a species in a marine ecoregion. Information from the World Register of Marine Species (WoRMS), the Global Invasive Species Database (GISD), and the Nature Conservancy database on marine invasive species (NatCon) was used to identify the names and locations of marine alien species. Information from the International Union for Conservation of Nature (IUCN) Red List revealed which species are considered to be threatened by invasive species. Our database lists 112,399 marine species, of which 966 are alien species and 1655 are listed as threatened by invasive species by the IUCN. These are distributed throughout 225 marine ecoregions (97% of marine ecoregions). Our results confirm previous studies about the prevalence of alien and invasive species and provide an up-to-date status about known and recorded species and their distribution. This information can be used as a fundament for developing impact assessment models and identifying management strategies to combat marine invasive species.

KEYWORDS

alien species, database, environmental decision-making, invasive species, life cycle impact assessment, marine ecosystem

INTRODUCTION

Invasive species are a threat to biodiversity and are the cause of large, and rising, economic costs (Diagne et al., 2021). After habitat destruction, they are considered to have been the second most important threat for species (plants, amphibians, reptiles, birds, and mammals) that have gone extinct since 1500 AD (Bellard et al., 2016). In addition, invasive species have been implied as drivers for 25% of plant and 33% of animal extinctions since 1500 AD (Blackburn et al., 2019).

To understand the drivers of invasive species impacts, it is important to have an insight into the invasion process. An invasion process can be divided into several stages that are separated by barriers that a species must overcome. Depending on the stage of the alien species, its status can be either introduced, established, or invasive (Blackburn et al., 2011). Such an invasion process starts with the translocation of a species from a donor to a recipient community. These translocations can be distinguished between introductions and shifts (Sorte et al., 2010).

While shifts occur between adjacent regions and along corridors, enabled for instance by changing environmental parameters, introductions are human-assisted (deliberate and accidental) translocations of species over distances that the species are unlikely to reach on their own (Sorte et al., 2010). Examples of the latter translocation mode include, among others, introductions via shipping, for example, by means of ballast water or hull fouling, aquaculture escapes, and increasingly ocean rafting (Carlton et al., 2017; Wittenberg & Cock, 2001). Physical and chemical conditions, as well as the biotic environment of source and receiving regions, are more similar for the slower shifts compared with the quicker introductions (Sorte et al., 2010). Climatic fluctuations may also inhibit or facilitate the spread of alien species via changes in the abiotic environment (Richardson et al., 2000).

Following the translocation and according to the "tens rule" proposed by Williamson and Fitter (1996), 10% of all introduced species become established of which another 10% become invasive. Generally, established alien richness is higher in regions characterized by high GDP per capita and international trade activity (Dawson et al., 2017; McGeoch et al., 2010). However, a higher research effort in these regions is a potential source of bias (Pyšek et al., 2008). Even though the success rate of new species establishing themselves in new marine systems is generally small (Mack et al., 2000), potentially smaller than the one proposed by Williamson and Fitter (1996), the ones which do establish themselves have contributed to profound transformations in almost all marine environments around the world, for instance via competition, predation, or parasitism (Blackburn et al., 2014). Moreover, initial impacts may result in secondary effects in an ecosystem, for example, via trophic cascades, or amplify via synergistic effects such as invasional meltdowns (Heath et al., 2014; Pace et al., 1999; Rinaldi & Scheffer, 2000; Simberloff & Von Holle, 1999; Thomsen et al., 2014). The widely acknowledged Millennium Ecosystem Assessment and the Living Blue Planet report concluded unanimously that invasive species have serious consequences on regional and global marine biodiversity (Millennium Ecosystem Assessment, 2005; WWF, 2015). In addition, the rate of new species being introduced into new habitats around the world is accelerating, especially because of shipping, canal constructions, aquaculture, and aquarium trade (Hulme, 2009; Katsanevakis et al., 2013). The main reason for this rate increase is the growth of international trade and travel (Westphal et al., 2008).

Due to the rising number and increasingly recognized importance of invasive species, including marine species, research into the introduction processes and impacts of such species is growing (Blackburn et al., 2011). It is, however, not easy to navigate within this research field due to differences in definitions and concepts (Blackburn et al., 2011). For our purposes, it is important to distinguish between alien and invasive species. We follow the suggested terminology from Robinson et al. (2016), who define alien species as "species whose presence in a region is attributable to human actions that enabled them to overcome fundamental biogeographical barriers" (synonymous with introduced, exotic, or nonnative species) and invasive species as "Alien species that have self-replacing populations over several generations and that have spread from their point of introduction." In addition, invasive species are alien species that pose a threat to other species and the ecosystem.

An important pillar for policy responses and management interventions to marine alien and invasive species is species monitoring and impact assessments. Over recent years, several information platforms have been initiated including the European Alien Species Information Network (EASIN; European Commission – Joint Research Centre, 2018), the Global Register of Introduced and Invasive Species (GRIIS; Pagad et al., 2018), the Global Invasive Species Database (GISD; Invasive Species Specialist Group [ISSG], 2015), and the World Register of Introduced Marine Species (WriMS; Rius et al., 2023). And although the impacts of marine invasive species are difficult to measure due to the diversity of impact mechanisms, several assessment methods have been developed to measure the effects of marine invasive species on their non-native ecosystems, including both mathematical/statistical approaches (Catford et al., 2012; Gallardo et al., 2016; Heath et al., 2014;

McGeoch et al., 2010; Thomsen et al., 2014) and qualitative scoring methods (Blackburn et al., 2014; Çinar & Bakir, 2014; Katsanevakis et al., 2016; Molnar et al., 2008; Olenin et al., 2007).

However, comprehensive, large-scale, and cross-taxa impact assessments on marine invasive species are only scarcely available. The major prerequisite for such assessments is harmonized global data on marine invasive species' alien and native ranges, introduction pathways, and their impacts. Although various databases like the abovementioned exist that contain accounts of marine invasive species on regional or global scales, the level of detail and breadth of content are often not sufficient. Moreover, no database distinguishes alien and native regions according to one and the same classification, nor provides an easy way of producing downloadable maps of these ranges. Also, live interaction with data is limited to simple taxonomic query options in most existing databases. Information on which species are affected by invasive species in which regions is also not available in a consistent manner.

For these reasons, we successfully developed a database and web toolkit called "MarINvaders" that expands the scope of previous databases on marine alien species toward the development of large-scale impact assessments of marine invasive species. MarINvaders not only contains information on marine alien species, including taxonomic details, but also enables the user to create maps for each species, distinguishing its alien and non-alien ranges, as well as delineating maps for species affected by invasive species, albeit without identifying the species that are impacting a specific species. In addition, MarINvaders allows for the interactive querying of alien species and affected species and the creation of new database collections based on such queries. In the following, we outline data resources, the database construction, current limitations, as well as the database's functionalities and usage, the latter of which we exemplify with a case study on a set of marine species. Showing introduction pathways and species-specific impacts is, however, beyond the scope of this study.

MATERIALS AND METHODS

Data and software resources

The MarINvaders web app builds upon a previously developed open-source Python 3 module for gathering and harmonizing marine species distribution data (Lonka et al., 2021). This module provides a programmatic way to find the alien and non-alien distribution of a given species or to get an overview of all species found in one marine ecoregion.

The spatial units used for the geographical representation of the database are the 232 marine ecoregions of the world (Spalding et al., 2007). Ecoregions are defined by Spalding et al. (2007) to "reflect unique ecological patterns that extend beyond the broad drivers of evolutionary processes" and they are "marking approximate locations of relatively rapid change in dominant habitats or community composition". The framework of ecoregions thus avoids the use of arbitrary "qualitative" geographical distributions like countries or sea areas.

The species databases for the toolkit, and in turn for the MarINvaders web app, are five databases, namely, the World Register of Marine Species (WoRMS) (Horton et al., 2018), the GISD (Invasive Species Specialist Group [ISSG], 2013), the Nature Conservancy database on marine invasive species (NatCon) (Molnar et al., 2008), the Ocean Biogeographic Information System (OBIS, 2021), and the International Union for Conservation of Nature (IUCN) Red List (IUCN, 2021). All these databases have global coverage, but they vary in their number of species accounts. OBIS was used to inform about the presence in a marine ecoregion of any given species listed in WoRMS. WoRMS, GISD, and NatCon were then used to assess the alien and invasive species status within an ecoregion. We included all of them since their level of detail regarding species and impact descriptions varies (Table 1). It is also important to note that WoRMS flags *alien* species (of which many are invasive), while NatCon directly lists *invasive* species.

WoRMS was chosen as the basic building block, as it is the most comprehensive database on marine species available. It is sourced from several other databases including various registers and world lists of specific taxa such as AlgaeBase or the World Amphipoda Database. Entries in WoRMS flagged as an alien marine species are the same as in the separate database WRiMS (Rius et al., 2023) which is sourced from WoRMS. WRiMS contains records on species that are now found outside their native range because of (deliberate or accidental) human interventions, but excludes the range expansion of species (e.g., due to climate change). For its comprehensiveness, however, WoRMS was chosen as it facilitates the data retrieval of entries for both marine invasive species and total marine species. Information from WoRMS was collected for the totality of marine species covered in the database. Following WoRMS, we use AphiaIDs as the identification code of a species (as documented on WoRMS' Aphia platform; https://marinespecies.org/about.php). Additionally, geographic data on species distributions were retrieved from OBIS (2021). Although the Global Biodiversity Information Facility (GBIF) (GBIF.org, 2017) contains more species observations, OBIS was

TABLE 1 Source database characteristics (information valid for respective access dates); the quality of descriptions is evaluated by the authors.

Database	Relevant entries	Taxonomy	Geographical distribution	Distinction between native and alien range	Habitat description	Impact description	Impact quantification	Invasion pathway description
WoRMS (May 2021)	238,252 accepted species of which 898 are marine alien species included here	Detailed, including synonyms and common names	Qualitative	Distinction into various regional classifications	Inconsistent	Inconsistent	No	Inconsistent
GISD (May 2021)	55 invasive species in marine and brackish habitats (filtered search)	Detailed, including synonyms (inconsistent) and common names	Qualitative	Distinction into country and subregion	Yes	Yes, location specific (if available)	No	No
NatCon (static, see Molnar et al., 2008)	375 marine invasive species	Only species name and higher species taxa; including common names	Qualitative	Non-native ranges are outlined according to the marine ecoregion classification; native ranges are coarse	Yes	Yes	Impacts are quantified via four different scores, that is, ecological impact, invasive potential, geographic extent, and management difficulty	Detailed
OBIS (19 February 2021)	Over 66 million presence records of more than 154,000 accepted marine species	Detailed without synonyms and common names; taken from WoRMS	Latitude/longitude point records	No	No	No	No	No
IUCN Red List (10 February 2021)	14,924 marine species included on the red list, of which 1655 are affected by invasive species	Detailed without synonyms and common names	Qualitative (not included in the .csv download)	Native ranges are indicated (not included in the .csv download)	Yes (not included in the .csv download)	No	No	No

Note: "Qualitative" regarding geographical distribution means verbal descriptions like names of countries or sea areas. Note that all 63 species of GISD are also contained in WoRMS and/or NatCon but do not add new information.

Abbreviations: GISD, Global Invasive Species Database; IUCN, International Union for Conservation of Nature; NatCon, Nature Conservancy database on marine invasive species; OBIS, Ocean Biogeographic Information System; WoRMS, World Register of Marine Species.

used as the source for such distribution records, since both OBIS and WoRMS follow the LifeWatch taxonomic backbone. This enhances search and matching options via the respective taxonomies and the unique AphiaIDs. NatCon includes information on 71 invasive species that are not present in OBIS and that were added additionally to our database.

Data from the IUCN Red List (IUCN, 2021) were included to indicate which species are affected by invasive species. The threat status of the included red-listed species spans over the whole IUCN Red List assessment range, that is, from least concern to extinct. We excluded extinct species from the analysis. We downloaded these data from the IUCN Red List in June 2021. All the search parameters can be found in the MarINavders Toolbox (Lonka et al., 2021).

More details on the data handling and harmonization, as well as the matching of distribution data to the ecoregions, can be found in the article describing the MarINvaders Python module (Lonka et al., 2021), as well as in the online documentation, in particular in the data background/handling section (https://marinvaders.gitlab.io/marinvaders/data_background/). The Python module is also our recommendation for programmatically reproducing/accessing the data presented in the MarINvaders web app as several of the used databases do not allow redistribution in their entirety (e.g., for the IUCN data, https://marinvaders.gitlab.io/marinvaders/iucn_data/). As the toolkit is Open Source, we very much welcome collaboration on the further improvement of the package, which would then also be integrated in the MarINvaders web toolkit (Lonka et al., 2021).

Database construction and web app development

The previously developed MarINvaders Python module was used to loop through all ecoregions and collect these data in a sqlite database which provides information on the non-alien/alien status of each species recorded in any of the marine ecoregions. The looping through all ecoregions was implemented with delayed API calls in order to not hit any bandwidth limits from the different data providers. As a consequence, the data gathering process takes several days and is only run quarterly.

The resulting database includes all species data from OBIS and NatCon for the queried ecoregions; the alien status based on WoRMS, GISD, and NatCon; as well as the data on species threatened by invasive species based on the ICUN Red List. This database forms the backbone of the MarINvaders web app.

The web app itself was developed with Python 3 with a Flask backend coupled with the sqlite db constructed as explained above. The front end was developed with Flask, Openlayers, and html coupled with javascript. The web app is free of use and available at https://marinvaders.atlantis-erc.eu/.

It allows the selection of an ecoregion or a species and then provides summary statistics on alien/non-alien status as well as a map-based visualization of these data (see Figure 1A). It also shows the data source for the information about whether a species is listed as alien.

The formal correctness of the approach is assured by unit tests covering the majority of the code. Besides the basic testing of the API calls and remote data retrieval, the tests rely on some examples of known distributions which are checked against the data we constructed with the toolkit. These tests are implemented in the underlying MarINvaders Python toolkit (Lonka et al., 2021) and run automatically upon each submitted code change (see folder tests at https://gitlab.com/marinvaders/marinvaders).

Demonstration of use

The usage of the MarINvaders web-app is shown through the example of one randomly chosen ecoregion, the "Western Mediterranean" (Figure 2). Ecoregions and individual species can be queried for in MarINvaders through simple searches for their names or, in the case of species, their scientific names.

RESULTS AND DISCUSSION

Database content and coverage

Molnar et al. (2008) had put tremendous work into compiling a database (here called NatCon) that was covering 329 marine invasive species in 194 ecoregions. Building on this database and adding all the other information has increased the spatial coverage of alien species to 225 (97%) out of 232 marine ecoregions. The number of invasive species has increased from 329 to 966 species in our database (Table 1). In total, we have 112,399 marine species in the database, of which 1655 species are flagged as being threatened by invasive species specifically (Table 1). OBIS, the backbone for our species collection, lists more than 154,000 species. Still, our database only covers 112,399 of them as it only includes species that are assigned to one of the 232 marine ecoregions. Thus, species that are only found outside the marine ecoregions or that have not been assigned to an ecoregion are neglected.

In NatCon, the taxonomic groups with most invasive species were crustaceans (59 species), mollusks

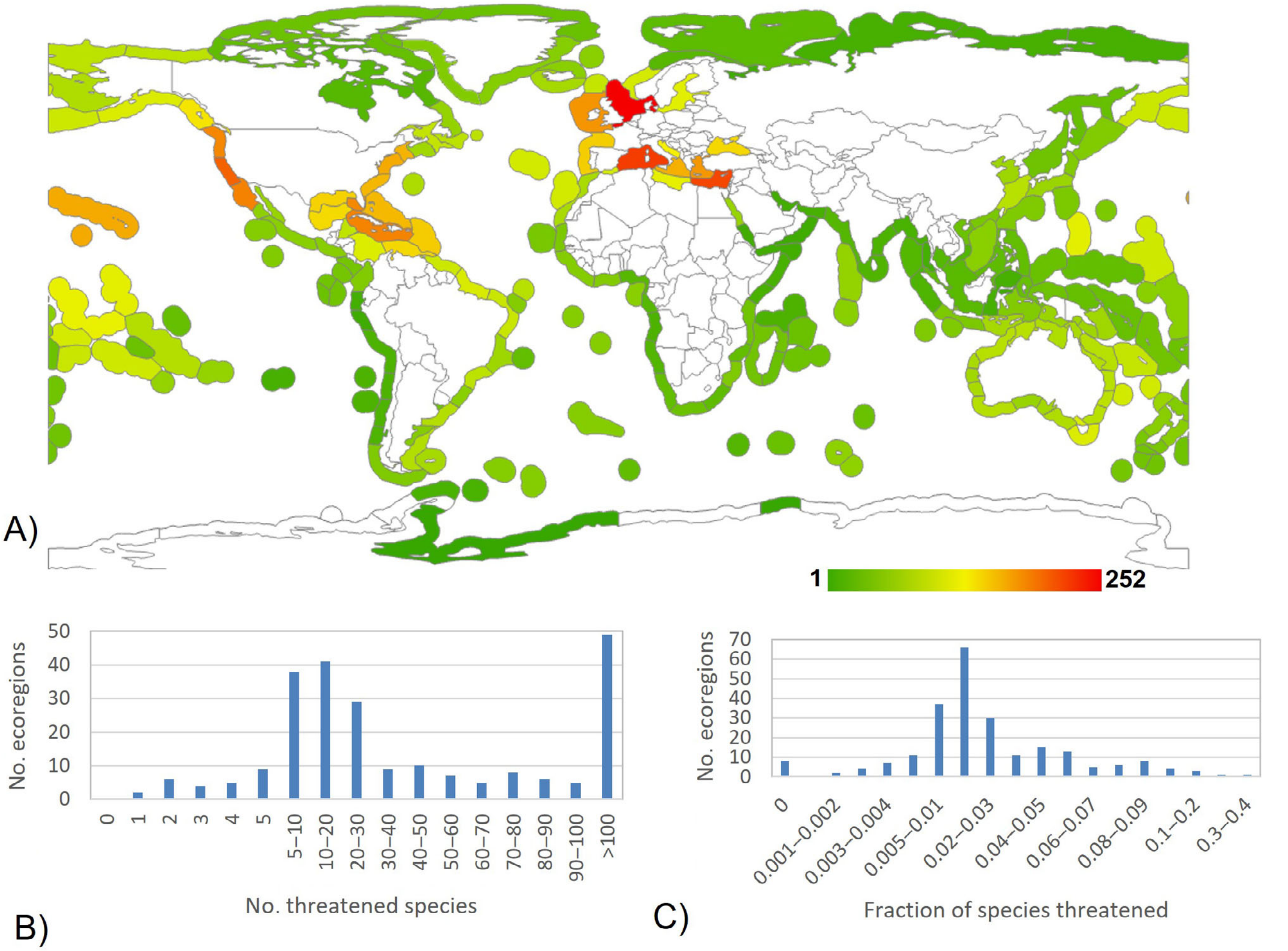

FIGURE 1 (A) Map of the distribution of alien species included in the database. Hollow ecoregions do not contain any records of alien species. Underlying country map is taken from Sandvik (2009); ecoregions as per Spalding et al. (2007). (B) Number of threatened species per ecoregion. (C) Fraction of threatened species per ecoregion.

(54 species), and algae (46 species). In our database, alien species records are dominated by fish (*Actinopterygii*, 157 species), crustaceans (143 species, 138 of which belong to the class Malacostraca), red algae (*Florideophyceae*, 81 species), and bristle worms (Polychaeta, 80 species) (see data deposition on Zenodo for a full list of classes: https://doi.org/10.5281/zenodo.6916352).

The results from the web app show the total number of species that are recorded in OBIS, the number of species that are listed as alien, and the number of species listed as being threatened by invasive species for each ecoregion. There are two categories of alien species in the web app: (1) reported sightings of alien species from OBIS and NatCon, which are associated with location coordinates (OBIS) or specific ecoregions (NatCon) and are considered a more certain data source than (2) reports and range estimates given in the form of qualitatively described geographical areas from all other databases. For example, *Alexandrium minutum* is alien in 164 ecoregions of which 25 are identified from specific species observations, while the species is identified as present in a further 139 ecoregions based on qualitative geographic distribution descriptions (e.g., from GISD) such as "present in the United States," which includes several ecoregions. The web app results allow for statistics, such as which regions have the highest fraction of alien species or number of species threatened by invasive species (Figure 1). The number of alien species (Figure 1A) varies between 0 and 252, and according to the IUCN, there are between 0 and 354 species per ecoregion listed as being threatened by invasive species. More alien species are found in the areas around Europe, North America, and Australia (Figure 1A), which confirms the findings from Dawson et al. (2017) that alien species are very often found in waters surrounding developed regions. The fraction of species that are affected by invasive species varies greatly but reaches up to a third of

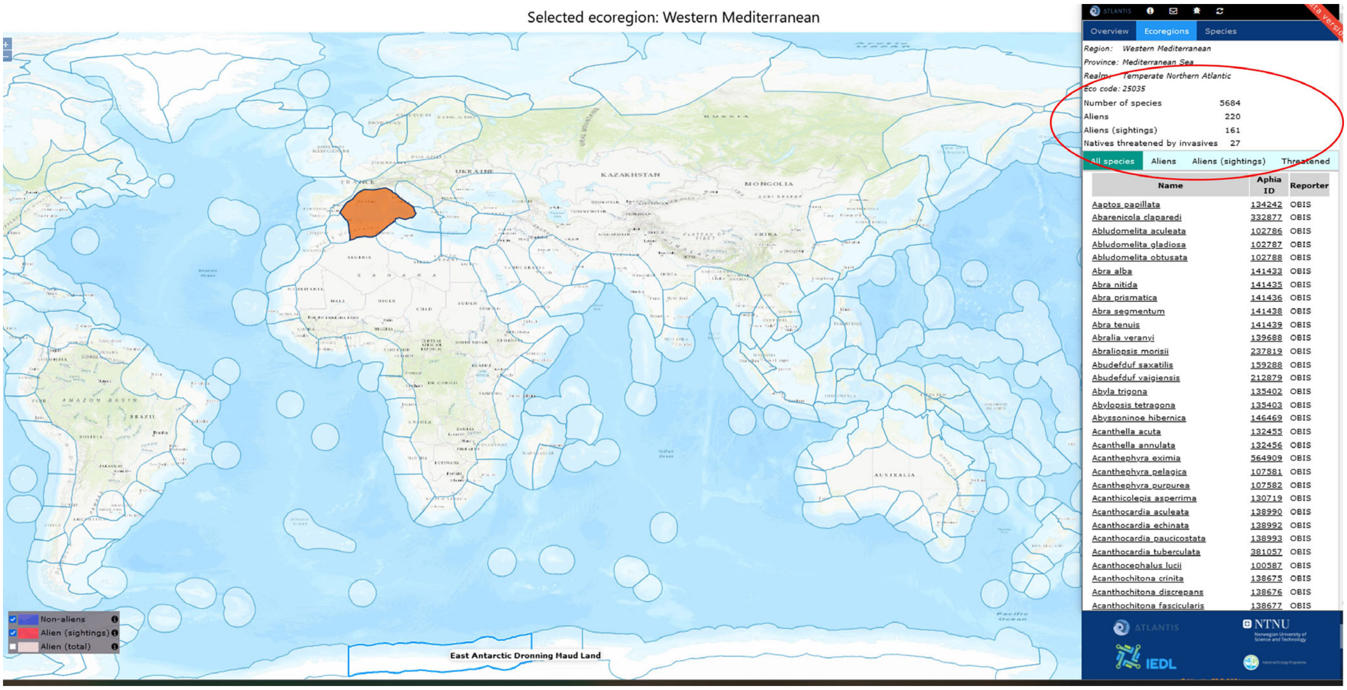

FIGURE 2 Screenshot of the MarInvaders webApp with "Western Mediterranean" selected as marine ecoregion. In the map, the chosen ecoregion is shown in orange. On the right side (red circle), a summary of the species numbers available for all species, aliens, and threatened species is shown. The species list with corresponding AphiaID and reporter is given below. Underlying country map is taken from Sandvik (2009); ecoregions as per Spalding et al. (2007).

species (ecoregion "Northern Monsoon Current Coast," see data deposition on Zenodo: https://doi.org/10.5281/zenodo.6916352). However, we have to acknowledge a certain bias regarding the reporting of alien species, as some ecoregions are studied in more detail than others and thus may report more alien species.

Illustrative examples of the MarINvaders web toolkit

The randomly chosen ecoregion "Western Mediterranean" is located between Spain, France, Italy, Algeria, and Tunisia. By clicking the "Western Mediterranean" ecoregion in the world map on https://marinvaders.atlantis-erc.eu/, the overall results for this ecoregion are shown. In MarINvaders, we have listed 5684 species based on OBIS records in that ecoregion, of which 220 are listed as alien according to all databases and 161 are listed as alien sightings by NatCon and OBIS. The "Aliens" tab's "Reporter" column reveals that 45 species are listed as alien by both WoRMS and NatCon, 6 species by WoRMS and GISD, 13 by all three, and the remaining species are reported only by one of these databases. Twenty-seven non-alien species are listed as being threatened by alien species that have become invasive, according to IUCN records (tab "Threatened").

By clicking on any one species in any of the three tabs or entering a species name in the search tab under "Species," the ecoregions where this species is non-alien, and alien (if available), distinguishing between those ecoregions with presence based on location coordinates (OBIS) or specific ecoregions (NatCon), and those with more qualitative data sources, are shown.

We exemplify this with three species: *Undaria pinnatifida*, *Mytilus galloprovincialis*, and *Carcinus maenas* (Figures 3–5).

The Japanese kelp (*U. pinnatifida*) is observed as non-alien in three ecoregions around Japan (blue in Figure 3). It is considered alien in 138 ecoregions across the world, although there have only been alien sightings within 28 of these ecoregions (see Figure 3). GISD indicates for example "the United States" as being a region where *U. pinnatifida* is alien, without detailing the ecoregions further; thus, our database indicates the entire coast as potential distribution area. Similarly, WoRMS indicates "Australia" as an alien ecoregion without more details. NatCon, being on an ecoregion level, indicates more detail, and these observations are thus indicated as "sightings" in red. The blue mussel (*M. galloprovincialis*) is listed in totally 136 ecoregions around the world, in 130 of those as alien, and sighted directly in 29 ecoregions (Figure 4), and the European green crab (*C. maenas*) is listed in 171 ecoregions, as alien in 162, and sighted in 47 ecoregions (Figure 5).

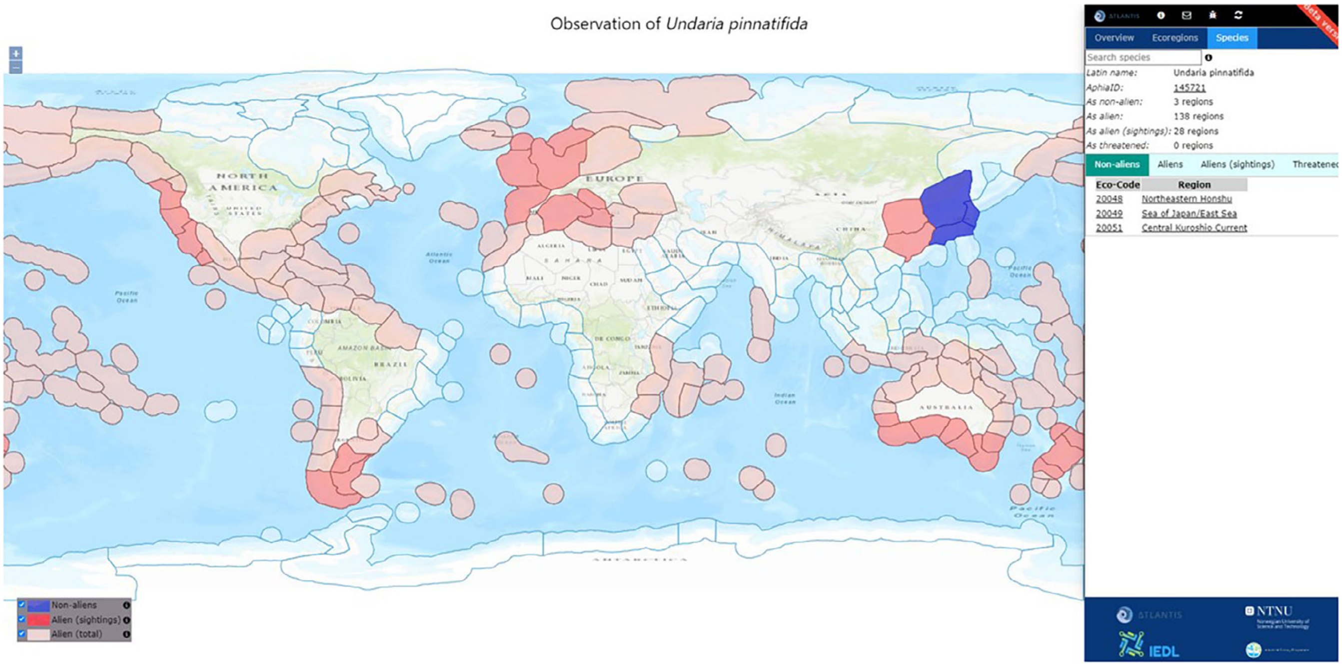

FIGURE 3 Distribution of the Japanese kelp (*Undaria pinnatifida*). Blue: the species is present as non-alien species. Rose: the species is sighted as alien species in Nature Conservancy database on marine invasive species. Red: the species is classified as alien based on all databases. Unshaded: the species is not present. Underlying country map is taken from Sandvik (2009); ecoregions as per Spalding et al. (2007).

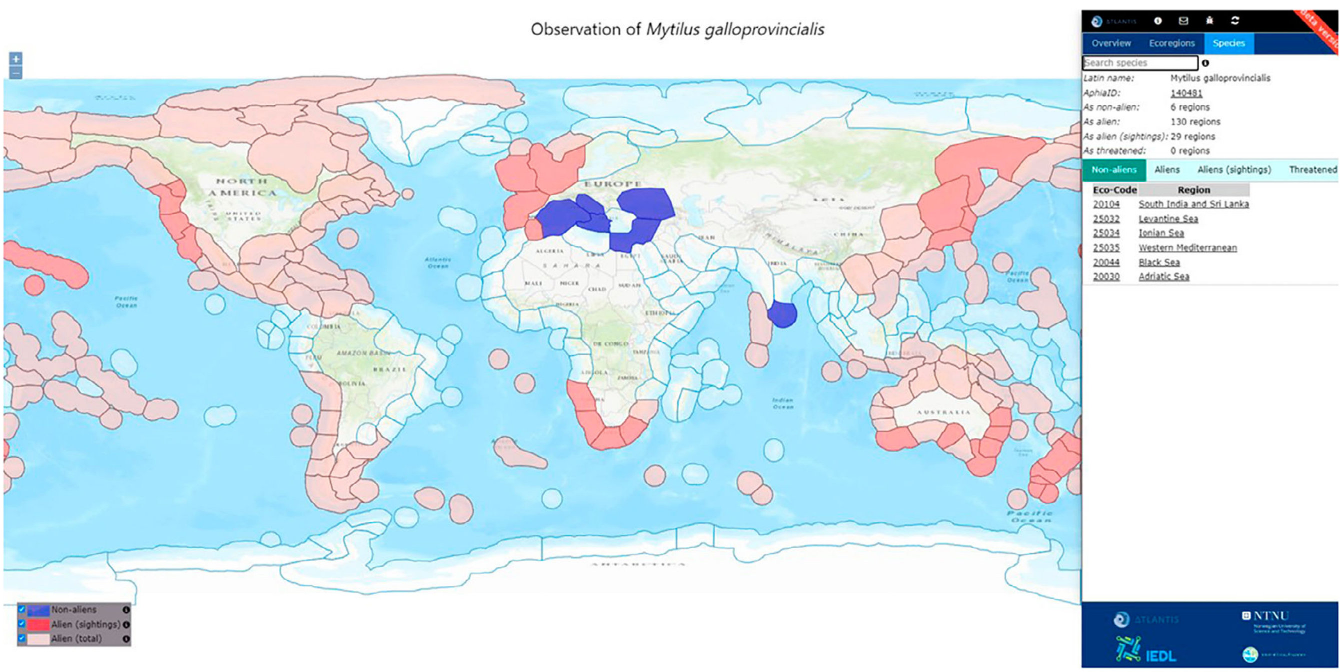

FIGURE 4 Distribution of the blue mussel (*Mytilus galloprovincialis*). Blue: the species is present as non-alien species. Rose: the species is sighted as alien species in Nature Conservancy database on marine invasive species. Red: the species is classified as alien based on all databases. Unshaded: the species is not present. Underlying country map is taken from Sandvik (2009); ecoregions as per Spalding et al. (2007).

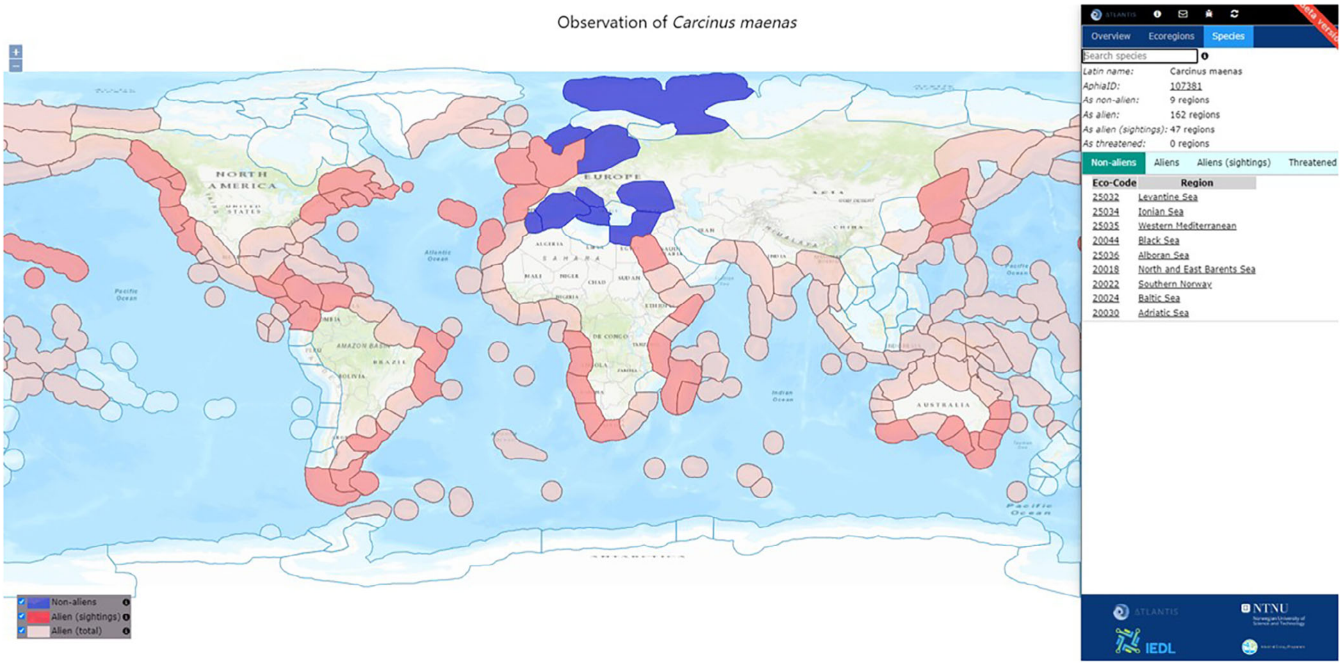

FIGURE 5 Distribution of the European green crab (*Carcinus maenas*). Blue: the species is present as non-alien species. Rose: the species is sighted as alien species in Nature Conservancy database on marine invasive species. Red: the species is classified as alien based on all databases. Unshaded: the species is not present. Underlying country map is taken from Sandvik (2009); ecoregions as per Spalding et al. (2007).

Further use cases for the MarINvaders database

We believe that the MarINvaders database can be useful for different purposes, such as (1) visual investigation of the distribution of alien species as a starting measure to manage invasive species, (2) statistical analyses, and (3) further development of models for environmental decision-making.

A visual investigation of an alien species allows to showcase in which marine ecoregions the species is native and in which ecoregions the species is alien. Since an alien species can be spread globally in very different regions and countries, this can help as a basis for finding other regions where species are alien or even invasive and may be managed already. The Japanese kelp (*U. pinnatifida*) for example is distributed as an alien species in marine ecoregions bordering many different countries, namely, Australia, New Zealand, China, Spain, France, UK, Belgium, Netherlands, Denmark, Norway, Sweden, Italy, Greece, Algeria, Tunisia, Southern Chile, Mexico, the United States, and southern Argentina. However, of all these countries, Epstein and Smale (2017) only found dedicated management initiatives for controlling the spread and abundance of *U. pinnatifida* in two countries (New Zealand and France). Other regions that experience an invasion with *U. pinnatifida* could check what countries in other regions are doing to try and combat the spread of that invasive species.

In addition, there is an increasing interest to integrate the impacts from invasive species into environmental decision-making tools, such as life cycle assessment. So far, only one approach exists for the transport of freshwater invasive species within the framework of life cycle assessment (Hanafiah et al., 2013). Future work within the ATLANTIS project (www.atlantis-erc.eu) aims to develop a model for quantifying the impact of marine invasive species. This database forms the basis for the development of these models to highlight the transport and introduction pathways and environmental impacts of marine invasive species. As an example, GISD and NatCon, both based on extensive literature reviews and expert information, can be used to append the invasive species information obtained from WoRMS with more details on impacts, distribution, and introduction pathways. While this was not done in the example presented herein, it is very useful for future studies as also mentioned in Lonka et al. (2021).

Further discussion

Even though the database is integrating a lot of information from other databases, we know that the picture it provides is incomplete. We are aware of the fact that none of the databases we use are complete in terms of species and geographic coverage. The reason is that not all species are identified (as aliens) yet and thus not listed in the databases, records may contain errors like misspelled names and wrong coordinates and may not include all known geographic extent, and not all parts of a species' geographic range may yet be known.

An apparent mistake is when a species is mistakenly flagged as non-alien. When species are presented as alien, it is because WoRMS, GISD, or NatCon has an occurrence point or mentioning of the species, flagged as alien, within an ecoregion. MarINvaders prioritizes alien flags, so if both alien and non-alien flags are present, the species is considered alien. Based on the assumption that a species can naturally disperse within an ecoregion, a species truly being alien and native within one ecoregion is rare. It is also more likely that a species is truly alien than non-alien when it is actively flagged as alien by the reporter, because for species simply "present" the reporter may not have known of its native range and thus alien status—hence our priority. Nonetheless, in citizen science, this mistake can happen for new occurrences especially.

The IUCN Red List is a global database, that is, if a species is considered to be threatened on a global scale by a certain impact mechanism, it still does not automatically follow that this species is affected in every single ecoregion it is inhabiting; that is, there can be differences between global and regional intensity and presence of threats (Strongin et al., 2020). In addition, we have mentioned above that there are differences between more qualitative descriptions of species distribution (e.g., "the United States" and "Northwest Pacific") and more detailed descriptions at the ecoregion level. We show this difference in the web app by having two categories of showing alien species, whether as sightings only or including all the mentions we have in all databases. The latter clearly shows a more uncertain picture for some species but allowed increasing the number of alien species that we could cover. All of the issues mentioned above introduce uncertainty into the database that is inherent in all databases of such a type. However, data availability will likely increase over the coming years. The IUCN, for example, update their database around two times per year. By repeatedly updating the database, we are confident that some of the discussed uncertainties will decrease over time, in line with the growth in information on other databases. MarINvaders will therefore be regularly updated to reflect data improvements in the underlying data providers. Currently, we have secured funding for quarterly update runs for at minimum the next 5 years.

For now, we have chosen the marine ecoregions as the geographic unit for reporting. This is the native resolution of our modeled species distributions following the assumption of presence throughout an ecoregion given the presence of an occurrence point within that ecoregion. In addition, as ecoregions are areas with relatively distinct ecological characteristics (Spalding et al., 2007), marine ecoregions also give an appropriate resolution for considering potential impacts of invasive species. Nevertheless, decision-making often occurs at spatial scales defined politically, for example, areas of national jurisdiction or subnational or international marine management areas. In such applications, the toolkit can be interrogated using a selection of spatially coincident marine ecoregions to generate an inventory of alien species that are potentially relevant for further consideration.

The database and tool are, as described above, relevant for the further development of a method for life cycle impact assessment. Once this model is developed, we can complement the MarINvaders database with the model outcomes, the so-called fate, effect, and characterization factors, per ecoregion. This will make the web app interesting for the lifer cycle assessment community to use the results for identifying impacts of marine invasive species.

AUTHOR CONTRIBUTIONS

Francesca Verones had the original idea, designed the data flow, contributed to data collection, analyzed results, and wrote the manuscript. Philip Gjedde contributed to writing, coding, and data collection and curation. Maximilian Koslowski contributed to data collection, coding, and writing. John S. Woods contributed to the original idea and writing. Radek Lonka coded the MarINvaders application, database and web app, and collected data. Konstantin Stadler contributed to data collection, coding, analyzing the results, and writing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (number of species per ecoregion and classes of alien species; Verones et al., 2022) are available from Zenodo: https://doi.org/10.5281/zenodo.6916352. The code for querying and harmonizing the databases was published as a separate package (see Lonka et al., 2021) and is available from GitLab: https://gitlab.com/marinvaders/marinvaders. This module was used to query the species for all ecoregions and the data were combined with IUCN data (GISD and Red List). Although the IUCN data are openly available, IUCN prohibits the redistribution of the data. Individual requests to the database for sqlite data can be made through the web app as described in the article at https://marinvaders.atlantis-erc.eu/.

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