Assessing the global threat of invasive species to marine biodiversity

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Although invasive species are widely recognized as a major threat to marine biodiversity, there has been no quantitative global assessment of their impacts and routes of introduction. Here, we report initial results from the first such global assessment. Drawing from over 350 databases and other sources, we synthesized information on 329 marine invasive species, including their distribution, impacts on biodiversity, and introduction pathways. Initial analyses show that only 16% of marine ecoregions have no reported marine invasions, and even that figure may be inflated due to under-reporting. International shipping, followed by aquaculture, represent the major means of introduction. Our geographically referenced and publicly available database provides a framework that can be used to highlight the invasive taxa that are most threatening, as well as to prioritize the invasion pathways that pose the greatest threat.

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Invasive species have transformed marine habitats around the world. The most harmful of these invaders displace native species, change community structure and food webs, and alter fundamental processes, such as nutrient cycling and sedimentation. Alien invasives have damaged economies by diminishing fisheries, fouling ships' hulls, and clogging intake pipes. Some can even directly impact human health by causing disease (Ruiz *et al.* 1997). Although only a small fraction of the many marine species introduced outside of their native range are able to thrive and invade new habitats (Mack *et al.* 2000), their impact can be dramatic.

The impacts of invasions may be seen locally, but the drivers of biological invasion are, to an increasing degree, global. Unfortunately, there is a paucity of information on invasive species at the global scale. The Convention on Biological Diversity (CBD) has identified the need for "compilation and dissemination of information on alien species that threaten ecosystems, habitats, or species, to be used in the context of any prevention, introduction and mitigation activities" (CBD 2000). Most data have been compiled at local, national, or regional scales (Ricciardi *et al.* 2000). Data that do exist often do not have consistent formats or definitions, and are therefore not easily comparable (Crall *et al.* 2006). Many datasets also lack information regarding ecological and economic impacts, and are therefore unable to inform risk assessments or to catalyze effective policies across national borders.

In a nutshell:

- Marine invasive species are a major threat to biodiversity, and have had profound ecological and economic impacts
- Developing effective prevention strategies requires global information, but most datasets are local or regional
- A new database, containing a simple, quantified threat-scoring index and introduction pathways classification, provides a critical tool for objectively comparing marine invasions worldwide
- Initial results confirm earlier assessments of the primary importance of shipping and aquaculture as introduction pathways and of the high levels of invasion in the temperate regions of Europe, North America, and Australia

Once alien species become established in marine habitats, it can be nearly impossible to eliminate them (Thresher and Kuris 2004). Interception or removal of pathways are probably the only effective strategies for reducing future impacts (Carlton and Ruiz 2005). With limited funds, establishing priorities is key, so that money allocated for prevention of invasions is well spent. Prioritizing actions requires knowing which species are likely to be most harmful to native ecosystems (Byers *et al.* 2002), current distributions of these species, and how they are likely to be transported to new regions.

This paper describes a new effort to quantify the geographic distribution of the threat of invasive species to marine biodiversity worldwide. We present an analytical framework that allows users to capitalize on existing information by: (1) integrating data from diverse sources in a uniform manner; (2) systematically scoring the threat of each alien species to native biodiversity; (3) collecting information by geographic units (marine ecoregions), so that data can be summarized and analyzed with other datasets at this scale; and (4) documenting introduction pathways for each species. Using the information compiled to date, we also present some initial findings from this dataset. This is not an exhaustive analysis, but illustrates the utility of the database, and provides some

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new insight into patterns and processes of global marine invasions.

Scope of the assessment

This assessment is focused on the global distribution patterns and impacts of alien species on native species and habitats in the coastal marine environment. Species that primarily occur in and modify human-managed waters (eg aquaculture) have been included, but only their impacts on native biodiversity are documented.

There are multiple ways to define "invasive species" (Lodge *et al.* 2006). Recognizing the limitations and practical needs of a global study, we use a broad definition that includes any species reported to have become established outside of its native range (Richardson *et al.* 2000; Rejmánek *et al.* 2002). This differs from the narrower definition used for public policy purposes, which requires that the species cause negative economic, environmental, or public health impacts (eg US Federal Executive Order 13112 1999; McNeely *et al.* 2001), but it allows incorporation of information from a broader array of data sources. We devised a threat scoring system to indicate the magnitude of species' ecological impact and invasive potential within the global framework.

We report non-native occurrences by ecoregion, using a biogeographic classification recently developed for marine coastal environments (www.nature.org/MEOW; Spalding *et al.* 2007). Ecoregions are widely used for conservation planning and strategic analysis by major conservation NGOs (Olson *et al.* 2001). Marine ecoregions have been defined as "areas of relatively homogeneous species composition, quite clearly distinct from adjacent systems" (Spalding *et al.* 2007). They are contained within marine realms, which are defined as large areas of ocean in which biota share a similar evolutionary history due to isolation or other factors (Spalding *et al.* 2007). We selected these units of analysis because they are global in scale and commensurate with the resolution of the data in a way that is useful for ecologically guided, regional risk assessment. Additional research was often necessary to convert data reported by political units (eg countries, states) into biogeographic terms.

We developed our data collection methods to allow consistent documentation of information across taxa and habitats. Related ongoing assessments of terrestrial and freshwater invasive species will be reported elsewhere.

Database development

We collected information on marine invasive species from a variety of sources and compiled the information in a geographically referenced database. In addition to non-native distributions by marine ecoregion, we documented habitat types, native distributions, and introduction pathways for each species. We also collected detailed information about the threat that each species posed to native biodiversity, using the scoring system described below. A description of our data collection methods is provided in WebPanel 1.

Input data were restricted to published sources or otherwise highly credible, publicly available datasets, with a robust scientific framework; all sources are referenced in the database. We initially targeted datasets that covered broad spatial scales and taxonomic groups. Regional, national, and some sub-national datasets, along with literature and internet resources, were used to supplement data gaps and provide information at a finer scale. Data collection is ongoing. The database is available online (www.nature.org/marineinvasions) and will be updated periodically.

Threat scoring system

The number of alien species in a habitat does not indicate the level of threat posed to native biota or the damage already done. Many species establish in a new habitat with few disruptions, whereas others alter entire ecosystems or put native species at risk of extinction. We developed a threat-scoring system, based on several existing threat classification systems (Cal-IPC 2003; Salafsky *et al.* 2003; NatureServe 2004), to capture information on the threat posed by alien species.

Each invasive species was assigned a score (where data allowed) for the following categories: ecological impact, geographic extent, invasive potential, and management difficulty (Panel 1).

The "ecological impact" score measures the severity of the impact of a species on the viability and integrity of native species and natural biodiversity. For example, the green alga, *Caulerpa taxifolia*, was assigned the highest ecological impact score (4), based on its ability to outcompete native species and reduce overall biodiversity (Jousson *et al.* 2000). The sea slug, *Godiva quadricolor*, was conservatively assigned a lower score (2), because its only known impact is feeding on one taxon – other sea slugs – with no wider effects documented (Hewitt *et al.* 2002).

The ecological impact score was assigned globally for each species, not for specific occurrences. For consistency, this score reflects the most damaging documented impacts, although geographic variation and diversity of impacts were also noted where available. Where impact information was ambiguous, we were conservative and assigned a lower score. Because we are assessing the ecological impacts of invasive species, we have, to date, only included species for which we found documentation of ecological impacts, or lack thereof. We did not track how many species were excluded due to this criterion. We believe that the most harmful species are also the best documented, so that even at this stage, our work has a representative coverage of these most harmful species.

Species not captured in our database probably have relatively low ecological or economic impact and may include microorganisms whose introductions are largely unrecorded and whose impacts remain poorly understood (Drake *et al.* 2007). "Geographic extent" captured the scale of each species' invasive range. It was defined relative to ecoregion size, instead of by absolute units (eg area, length of coastline), to allow use across marine, freshwater, and terrestrial environments. "Invasive potential" is an estimate of the magnitude of the current or recent rate of spread and the potential for future spread after introduction to new habitats. The "management difficulty" score indicates the effort required to reverse the threat, remove the species, and/or manage its presence.

Threat scores were necessarily semi-quantitative, but they correspond to categories that differ substantially in threat level, with clearly defined parameters for assigning individual scores (WebPanel 1). This enabled us to include a broad range of information and to use the same categorical scoring across marine, freshwater, and terrestrial habitats.

Pathways

To consistently document introduction information in our database, we needed a classification of marine, terrestrial, and freshwater species pathways that would allow for the capture and summary of data with various levels of detail. We based our framework on the outline developed by the US National Invasive Species Council's Pathways Team (Campbell and Kriesch 2003; revised by Lodge *et al.* 2006). This team developed "a system for evaluating the significance of invasive species pathways" into and within the US, broadly defining pathways as "any means that allows entry or spread of an invasive species" (Campbell and Kriesch 2003). Although this system includes routes of introduction that others may consider to be vectors (Carlton and Ruiz 2005) and categories are not always mutually exclusive, it allows the practical categorization of commonly reported information on pathways and vectors. We modified this system slightly, to better fit a global assessment and made category adjustments to allow effective gathering of data by species (Panel 2).

Using this framework, we documented all known and likely pathways for each species in our database. We only included pathways to new habitats, not methods for local dispersal. We were not geographically specific (eg we recorded that a particular species could be carried in ballast water, but not the specific ports between which it traveled). We documented additional introduction information, including whether the introduction of a species via a pathway was intentional or accidental.

Panel 1. Threat scoring system

Each species in our assessment was assigned a score for each of the following categories (where data allowed), to indicate the magnitude of the threat it poses to native biodiversity. The scoring system was devised so that it could be applied consistently to different types of species and to those living in marine, freshwater, and terrestrial habitats.

Ecological impact

4 – Disrupts entire ecosystem processes with wider abiotic influences
3 – Disrupts multiple species, some wider ecosystem function, and/or keystone species or species of high conservation value (eg threatened species)
2 – Disrupts single species with little or no wider ecosystem impact
1 – Little or no disruption
U – Unknown or not enough information to determine score

Geographic extent

4 – Multi-ecoregion
3 – Ecoregion
2 – Local ecosystem/sub-ecoregion
1 – Single site
U – Unknown or not enough information to determine score

Invasive potential

4 – Currently/recently spreading rapidly (doubling in < 10 years) and/or high potential for future rapid spread
3 – Currently/recently spreading less rapidly and/or potential for future less rapid spread
2 – Established/present, but not currently spreading and high potential for future spread
1 – Established/present, but not currently spreading and/or low potential for future spread
U – Unknown or not enough information to determine score

Management difficulty

4 – Irreversible and/or cannot be contained or controlled
3 – Reversible with difficulty and/or can be controlled with significant ongoing management
2 – Reversible with some difficulty and/or can be controlled with periodic management
1 – Easily reversible, with no ongoing management necessary (eradication)
U – Unknown or not enough information to determine score

Assessing the extent and impact of invasive species

We have compiled information from over 350 data sources. The database now includes 329 marine invasive species, with at least one species documented in 194 ecoregions (84% of the world's 232 marine ecoregions; Figure 1). The dominant groups of species in our database are crustaceans (59 species), mollusks (54), algae (46), fish (38), annelids (31), plants (19), and cnidarians (17).

We scored all 329 species for ecological impact and geographic extent. The mean ecological impact score was 2.55 (SD = 1.04) – halfway between "disrupts single species with little or no wider ecosystem impact" and "dis-

Panel 2. Pathways framework

We used this framework to document known and likely pathways for each marine species in our assessment. It was adapted from the National Invasive Species Council Invasive Species Pathway Team, with "pathways" defined broadly as "any means that allows entry or spread of an invasive species" (Campbell and Kriesch 2003). This outline has been summarized to highlight sub-pathways for marine species; see WebPanel 2 for full outline with all sub-pathways.

Transportation-related pathways
- Modes of transportation
  - Air transportation
  - Freshwater/marine transportation
    - Ballast and/or fouling
      - Ballast water and sediments
      - Hull/surface fouling
    - Stowaways in holds
    - Superstructures/structures above the water line
    - Dredge spoil material
    - Canals that connect waterways
  - Land/terrestrial transportation
- Items used in shipping process
  - Containers – both exterior and interior
  - Packing materials
- Tourism/travel/relocation
- Mail/internet/overnight shipping companies

Commerce in living organisms pathways
- Live seafood trade
- Livestock
- Aquaculture and mariculture activities
  - Enclosed facilities
  - Stocking in open water
- Pet, aquarium, and water garden trade
- Bait industry
- Biocontrol
- Nurseries/garden/landscaping
- Agricultural and forestry species trade
- Plants and plant parts as food
- Other animal trade
- Other plant trade

Other human-assisted pathways
- Ecosystem disturbance
- Climate change

Natural spread

rupts multiple species, some wider ecosystem function". Most species have been found in multiple ecoregions (mean geographic extent score of 3.98, SD = 0.19). We scored 324 species for invasive potential, with a mean score of 2.05 (SD = 1.03; "established/present…high potential for future spread"). The 268 species scored for management difficulty had a mean of 3.56 (SD = 0.71), indicating that most are difficult if not impossible to remove or control.

A primary driver for the development of this assessment was to provide a means of distinguishing relatively low-impact invasive species from those with potentially severe detrimental effects. We defined "harmful" invasive species as those having ecological impact scores of 3 or 4 (disrupting multiple species or wider ecosystems). Using this definition, 57% of species in our database are harmful, ranging from 47% of cnidarians to 84% of plants (Figure 2). The database also allows a geographic perspective; Figure 1 shows the number of harmful invasive species by ecoregion.

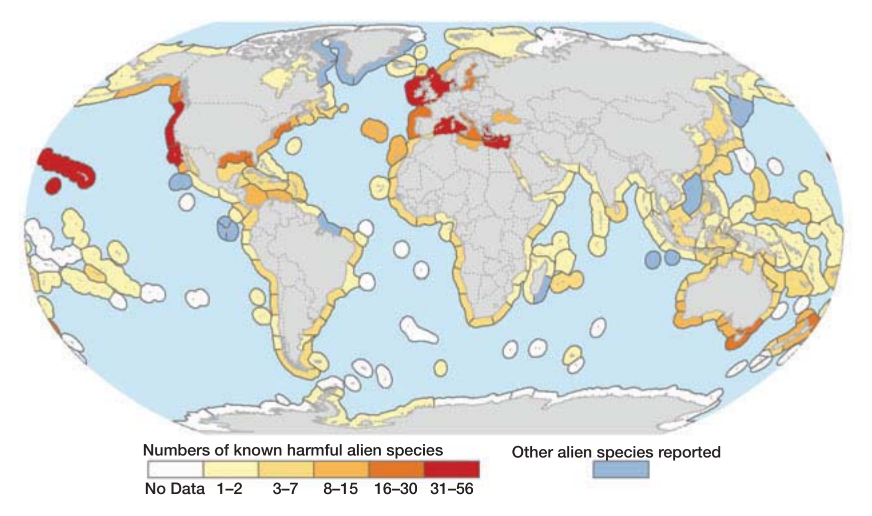

Figure 1. *Map of the number of harmful alien species by coastal ecoregion, with darker red shades indicating a greater number of species with high ecological impact scores (3 or 4). Ecoregions in which only less harmful species have been documented are shown in dark blue.*

Our data reveal high levels of invasion in the following ecoregions: Northern California, including San Francisco Bay (n = 85 species, 66% of which are harmful), the Hawaiian Islands (73, 42%), the North Sea (73, 64%), and the Levantine Sea in the eastern Mediterranean (72, 50%). Realms that feature the highest degree of invasion are the Temperate Northern Atlantic (240, 57%), Temperate Northern Pacific (123, 63%), and Eastern Indo-Pacific (76, 45%). The least invaded realms are the Southern and Arctic Oceans (1, 100%, and 9, 56%, respectively).

We documented known or likely pathways for all 329 marine invasive species, with a mean of 2.0 pathways per species (SD = 1.1). More than 80% of species were introduced unintentionally. The most common pathway for marine species in the database was shipping (ballast and/or fouling; 228 species, 57% of which are harmful). Of the 205 species with more detailed shipping pathway information, 39% are known to have been, or are likely to have been transported only by ship fouling, 31% are transported only by ballast, and 31% are transported by either ship fouling or ballast. The aquaculture industry is the next most common pathway (134 species, 64% of which are harmful; Figure 3).

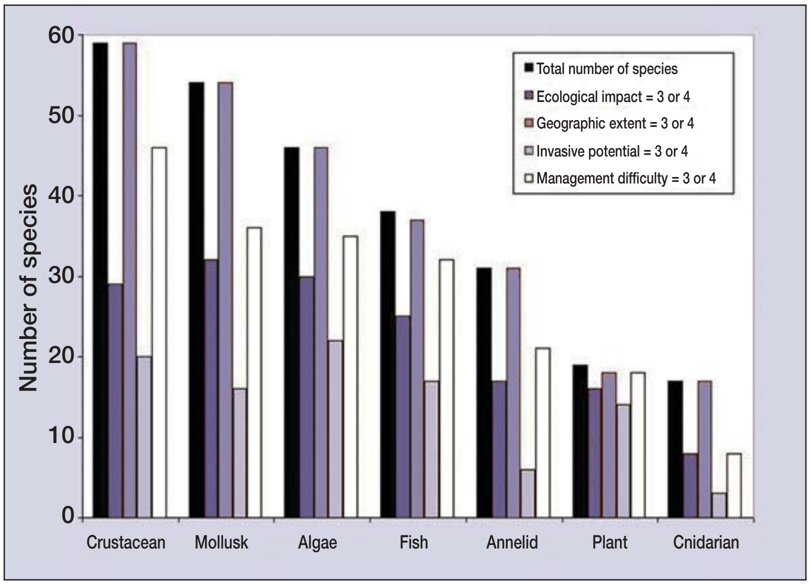

Figure 2. *Number of species in the dominant groups that fall into the highest two categories (3 or 4) of each threat score.*

To demonstrate regional variation, key pathways into the most heavily invaded ecoregions were determined by aggregating the known and likely pathways of species recorded in those ecoregions (Table 1). While shipping pathways are generally dominant, aquaculture is an important conduit for invasions on the west coast of the US, while the Suez Canal is a key pathway into the eastern Mediterranean.

Among the 359 data sources compiled to date, 47% are from peer-reviewed literature, 33% are from other published reports, 11% are from existing databases and atlases, and 3% are from unpublished reports (a list of database sources is provided in WebPanel 3). Most species were initially entered into our database using other databases and atlases, which, in almost every case, were compiled from the peer-reviewed literature and/or by regional experts. Additional information was obtained from the literature and reports. The accuracy of the patterns we found is dependent, in part, on the reliability of the data sources we used. Of course, even with reliable sources it is probable that, over time, corrections will be required. Necessary amendments may include incorporation of new studies or correction of errors from original field assessments, but environmental, evolutionary, or stochastic changes may also necessitate revision of the information in our database. For example, a heretofore benign, non-native species could invade a new niche and become a greater threat, or a native species could adapt to consume or out-compete an invader.

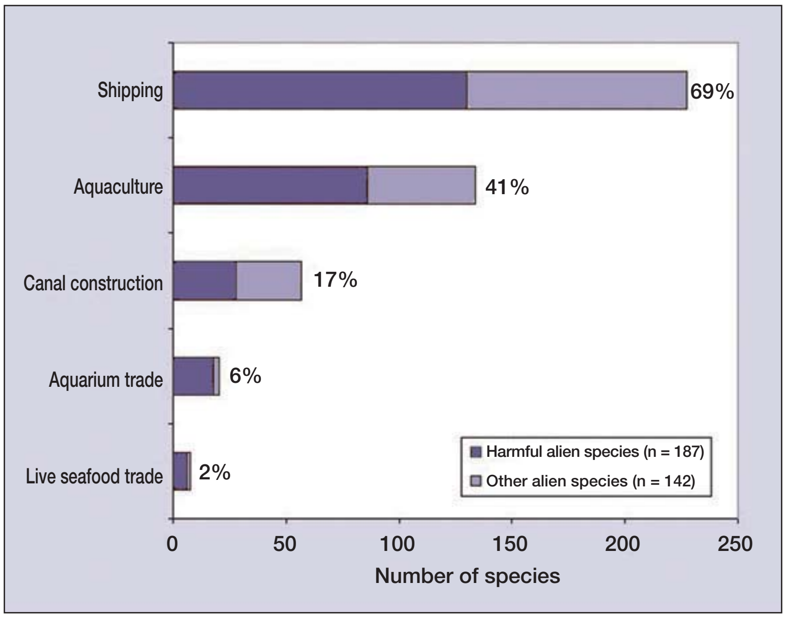

Figure 3. *Number of marine alien species known or likely to be introduced by the most common human-assisted pathways, with the proportion scored as high ecological impact (3 or 4) shown in a darker shade. Percent of total number of species in assessment (n = 329) is indicated.*

Identifying research and information needs

We documented more information on well-studied regions (eg US, Europe, Australia) than on other areas. Regions with a small number of invasions reported may contain few, if any, invasive species, but it is likely that at least some of these gaps are the result of a lack of research, monitoring, and/or public reporting of information.

A large number of ecological and economic impacts of alien species have been documented by others in regions identified as highly invaded on our map (eg San Francisco Bay, Cohen and Carlton 1998; Hawaiian Islands, Smith *et al.* 2003; North Sea, Eno *et al.* 1997; Mediterranean Sea, Galil 2006). It is probable that alien species are also affecting regions that appear, on our map, to be less invaded. To see if shipping data could act as a proxy indicator for identifying areas where invasions may have gone undetected, we compared our data on harmful species introduced via shipping in well-

Table 1. Key pathways for most invaded ecoregions

Ecoregion	*Number of harmful species (% of total)*	*Pathways (% of harmful species)*[*]
Northern California	56 (66%)	Shipping (71%); aquaculture (71%)
North Sea	47 (64%)	Shipping (83%); aquaculture (57%)
Western Mediterranean	43 (66%)	Shipping (77%); aquaculture (55%)
Oregon, Washington, Vancouver	41 (65%)	Aquaculture (73%); shipping (68%)
Levantine Sea	36 (50%)	Canal (61%); shipping (58%)
Puget Trough/Georgia Basin	35 (64%)	Aquaculture (74%); shipping (69%)
Celtic Seas	33 (66%)	Shipping (76%); aquaculture (67%)
Aegean Sea	31 (53%)	Shipping (55%); canal (52%)
Southern California Bight	31 (72%)	Shipping (81%); aquaculture (71%)
Hawaiian Islands	31 (42%)	Shipping (68%); aquaculture (39%)

[*] Species may be known or likely to be transported via more than one pathway

studied regions (US excluding Alaska, temperate Europe, Australia, New Zealand) with separate shipping indicators (number of ports and shipping cargo volume) in a recent year (2003) by ecoregion (Halpern unpublished). We found statistically significant correlations between these shipping indicators and the number of harmful species reported (using a generalized linear model for number of ports – number of harmful species: $t = 6.94$, SE = 0.0019, df = 32; for shipping cargo volume – number of harmful species: $t = 5.81$, SE = 5.2×10^{-10}, df = 32). Thus, the magnitude of shipping activities could potentially predict the risk for harmful invasions. These shipping measures do not account for the origin of incoming ships, susceptibility to invasion, changes in shipping patterns and volume (Drake and Lodge 2004), or variation in quarantine standards and shipping operations. Should such refinements to shipping data become available, it is likely that even stronger relationships would be observed.

Given the correlation between shipping indicators and harmful invasions, regions with high port traffic but few reported invasions probably contain more marine invaders than we have documented. Notably, we would expect this to include east and southeast Asia. Data may not have been collected in these regions, or results may not be easily available to researchers in other parts of the world. It is our hope that the establishment of global data repositories or networks on invasive species (eg Global Invasive Species Information Network; www.gisinetwork.org) will encourage more detailed research and the release of additional information.

Together with more thorough geographic coverage, better reporting of ecological impacts would help to close the most substantial and immediate information gaps. Our database includes only those species with documented ecological impacts. Several hundred invasive species known to exist in places like the Mediterranean Sea (Mooney and Cleland 2001) and San Francisco Bay (Cohen and Carlton 1998) were excluded because impact information was not reported. These particular systems are already highly invaded, but a more complete assessment of impacts would improve understanding of likely effects in other regions where those species are found. We are making our database freely available online, to encourage further submissions; this will improve reporting and refine our knowledge of global invasion patterns.

Conservation and policy applications

Using data collected in this assessment, we can identify global patterns and draw preliminary conclusions that may be applied to conservation and policy efforts. Here, we discuss several ways in which our database could be used to inform policy decisions.

Informing regional strategies

The database allows us to examine patterns of the known presence of marine invasive species and the distribution of their threat. The number of harmful species in each ecoregion provides an indication of the level of degradation from past invasions as well as, perhaps, the pressure from future invasions. This information could help policy makers to understand the trade-offs as they choose how to implement decisions and invest resources.

Prioritizing pathways for prevention efforts

Identification of the most common pathways for introduction of harmful marine species (Figure 3) can inform and support international policies aimed at preventing such introductions. Our results, based on the largest dataset compiled to date, clearly confirm earlier studies (eg Ruiz *et al.* 1997; Minton *et al.* 2005) and point to shipping as a major global pathway. This provides a powerful, objective argument in support of ongoing efforts to improve ballast water management practices (eg International Maritime Organization's Ballast Water Convention and Management Programme; http://globallast.imo.org). Even so, the major impacts of ship-fouling species suggest that ballast water agreements alone may be insufficient. We also confirm earlier studies describing the role of aquaculture operations in marine invasions (eg Naylor *et al.* 2001). Stricter, industry-wide control measures could be developed and legal and enforcement structures strengthened to restrict intentional and accidental introductions of harmful species.

Our assessment data can also be used by policy makers in specific regions (Table 1). For example, in the two ecoregions that extend along the coastlines of Oregon and Washington State, including the Puget Sound, aquaculture has been the most common pathway for introduction (71% of non-native marine species documented in these ecoregions were introduced by aquaculture). Most of these introductions probably occurred accidentally, through oyster farming (with introduced species hitchhiking on shells or equipment). Of the 33 species known to be associated with oyster farming, 55% are harmful, and most are difficult if not impossible to remove or control (26 of 28 species scored for management difficulty received a score of 3 or 4). In this region, policy makers, conservation practitioners, and the aquaculture industry should continue to work together to prevent any future invasions, by improving practices and perhaps limiting new operations.

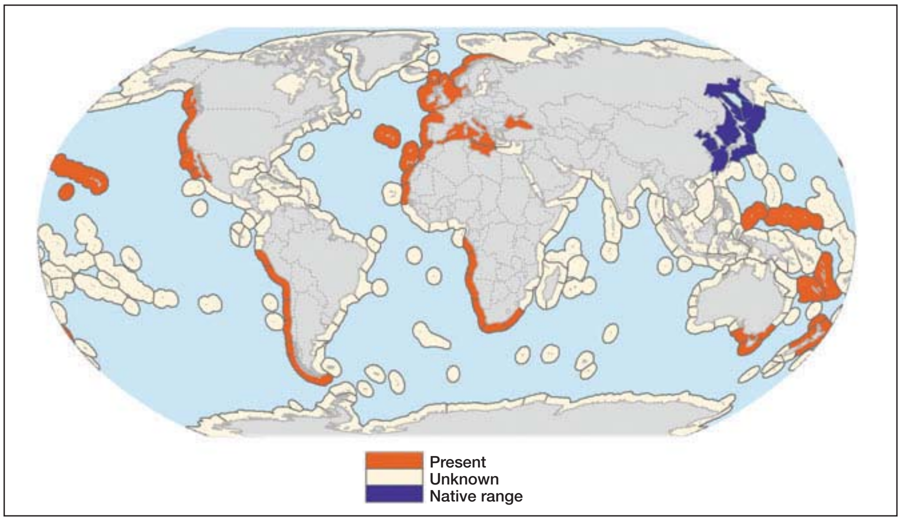

Figure 4. *The Pacific oyster* (Crassostrea gigas) *has been intentionally released and cultured in coastal waters around the world. It can dominate native species and destroy habitat (ecological impact = 3). The map shows the oysters' distribution; its invasive range is indicated in orange, its native range in blue.*

Our data could inform biosecurity measures by helping to identify species that have not yet invaded an ecoregion or realm but have had considerable impact in similar habitats elsewhere. Our use of biogeographic units will be of value in identifying "similar" vulnerable ecoregions, and more refined data about ship movements and habitat suitability would further support such work (see Hayes *et al.* 2002).

Informing introduction decisions

Species are often introduced to new habitats for their economic benefits or to meet development needs (eg aquaculture). There may be an initial economic gain, but if a species becomes invasive, it can cause serious, unforeseen economic and ecological damage. These risks of invasion have often not been factored into decisions on species introductions (Naylor *et al.* 2001).

Our impact scores offer guidance on the merits of these intentional introductions. For example, oysters have been deliberately introduced into coastal waters worldwide, to be cultured for food. One species in particular, *Crassostrea gigas*, has been introduced in at least 45 ecoregions (Figure 4). Its high ecological impact score (3) should cause decision makers and regulators to reconsider plans for introduction of this oyster into new areas. While its harvest brings economic gains, the ecological impact of introductions of this species are potentially dramatic. Oysters play a role in many estuarine ecosystem processes; altering their abundance or distribution causes complex changes. Furthermore, when oyster populations are supplemented with alien oysters, other alien species can piggyback on their shells (Ruesink *et al.* 2005). Global information about distribution and impacts could inform risk assessments and decisions about whether, and how, species should be introduced in the future.

■ Conclusions

The new invasive species database provides a powerful tool for understanding the patterns and processes of marine invasions. The current data holdings already represent the most comprehensive collection of information on marine invasions worldwide. By quantifying impacts and describing pathways of invasion, our data framework improves our ability to assess threats and impacts and allows valid and consistent assessments between locations, habitats, or taxonomic groups. Work is continuing to expand this assessment of marine invasive species and similar analyses are underway for terrestrial and freshwater species.

Initial findings confirm earlier studies and point to shipping and aquaculture as the most critical pathways for marine invasions globally. At the same time, regional differences in dominant pathways are highlighted.

The information we have compiled can begin to inform the large-scale strategies necessary to prevent future introductions. This global perspective allows researchers and regulators to better consider where and how invasive species are likely to be introduced and invade in the future. This can help to inform risk assessments and decisions about potential future introductions, as well as the development of species- and pathway-specific regulations and geographically targeted policies.

We have also identified some disparities in information resources on marine invasive species. In particular, there is clearly under-reporting of both microorganisms and low-impact invasive species, and there appears to be a geographic gap in our knowledge regarding large parts of east Asia, where invasions are highly likely, but little published information exists. We hope that these observations may catalyze and encourage efforts to make decentralized data available and direct future research efforts.

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