# Ballast water risk assessment: principles, processes, and methods

Simon C. Barry, Keith R. Hayes, Chad L. Hewitt, Hanna L. Behrens, Egil Dragsund, and Siri M. Bakke

Barry, S. C., Hayes, K. R., Hewitt, C. L., Behrens, H. L., Dragsund, E., and Bakke, S. M. 2008. Ballast water risk assessment: principles, processes, and methods. – ICES Journal of Marine Science, 65: 121–131.

Two methods of assessing the risk of species introduction by ballast water are discussed, species-specific and environmental similarity assessments, each for alignment with four proposed principles of risk-based resource management: (i) society accepts that low risk scenarios exist; (ii) risk assessment is capable of identifying low risk scenarios; (iii) risk mitigation strategies exist; and (iv) mitigation costs are less than the cost of performing risk assessment. All four principles were met in some circumstances for both methods. Species-specific ballast water risk assessment is best suited to situations where the assessment can be restricted to a limited set of harmful species on journeys within bioregions where ballast water is a small component of natural genetic exchange. Environmental similarity risk assessment is appropriate for journeys that start and end in locations which have very little or no natural genetic exchange, such as journeys between non-contiguous bioregions. Because a large number of species are not assessed individually, environmental match assessments necessarily will be restricted to fundamental variables such as temperature and salinity. A number of bioregion classifications have been identified in the world's oceans, some of which at a scale that may be appropriate for ballast water management. The suitability of any particular classification, however, needs further examination.

**Keywords:** biological invasions, biological regions, environmental similarity risk assessment, species-specific risk assessment.

Received 6 July 2006; accepted 16 December 2007; advance access publication 14 February 2008.

*S. C. Barry: CSIRO Mathematics and Information Sciences, GPO Box 664, Canberra, ACT 2601, Australia. K. R. Hayes: CSIRO Marine Research, GPO Box 1538, Hobart, Tasmania 7001, Australia. C. L. Hewitt: National Centre for Marine and Coastal Conservation, Australian Maritime College, Private Mail Bag 10, Rosebud, Victoria 3939, Australia. H. L. Behrens, E. Dragsund, and S. M. Bakke: Det Norske Veritas, Veritasveien 1, 1322 Høvik, Norway. Correspondence to S. C. Barry: tel: +61 2 6216 7157; fax: +61 2 6216 7111; e-mail: simon.barry@csiro.au*

## Introduction

The translocation of terrestrial pests and diseases has been a significant agricultural, trade, and environmental issue for many years. There are now many international arrangements in place that identify the need to manage the movement of these generally unwanted organisms around the globe (e.g. International Plant Protection Convention, IPPC, 1952; Office International des Épizooties, OIE, 2007; Convention on Biological Diversity, CBD, 1992). The risks and threats posed by the translocation of marine species, however, have only received significant attention in the past 25 years, coincident with the United Nations Convention on Law of the Sea (UNCLOS, 1982).

Ballast water and hull fouling associated with maritime activity are responsible for the vast majority of accidental marine translocations around the world (Carlton, 1985, 2001; Carlton *et al.*, 1995; Eno *et al.*, 1997; Cranfield *et al.*, 1998; CIESM, 2002; Hewitt, 2003a; Lewis *et al.*, 2003; Robinson *et al.*, 2005). Examples of economically and environmentally significant introductions include zebra mussels (*Dreissena polymorpha)* into the US, Northern Pacific sea stars (*Asterias amurensis*) into Australia, and a macroalga (*Undaria pinnatifida*) into the Mediterranean (Bax *et al.*, 2003). The nature of ballast water transport in these regions is diverse. Shipping within the Mediterranean Sea, for example, translocates water relatively short distances, whereas bulk international trade to Australia and the US can involve large quantities of ballast water moving long distances through multiple jurisdictions. This wide variety of shipping operations needs to be considered when formulating procedures for ballast water management.

The International Maritime Organization (IMO), recognizing the importance of ballast water as a vector, has been striving for many years to manage ballast water discharges through its Marine Environmental Protection Committee (MEPC). This effort recently culminated in the new International Convention for the Control and Management of Ship's Ballast Water and Sediments (BWM Convention; IMO, 2004; Firestone and Corbett, 2005). Regulation B-4 of the new convention stipulates that vessels should conduct ballast water exchange as far as possible from the nearest land (ideally 200 nautical miles, but at least 50 nautical miles) in water at least 200 m deep. Regulation A-4 provides exemptions to these provisions so long as the exemptions are, *inter alia*, granted based on a risk assessment. Regulation A-4 recognizes that vessels operating in some regions, such as enclosed seas, or on short journeys may have difficulty in complying with Regulation B-4. Regulation A-4 allows these otherwise non-compliant vessels to comply with the Convention and to discharge unmanaged ballast water.

This manuscript is motivated by Regulation A-4 of the new convention and its associated guidelines (MEPC, 2005). We briefly explore four principles that underpin risk assessment for natural resource management, before evaluating two major approaches to ballast water risk assessment. By examining these approaches against the fundamental principles, we identify approaches to ballast water risk assessment that are biologically rational. Throughout, we use the term "ballast water risk" to mean the introduction and establishment of an organism outside its native range via ballast water transport, and we consider the assessment of risk between the uptake and discharge locations (typically ports).

## Risk assessment requirements

When comparing different approaches to ballast water risk assessment, we found it useful to describe four fundamental requirements that should be satisfied before risk assessment is used to manage any natural resource problem.

(i) Society recognizes the risk, believes that low risk scenarios exist, and are willing to express risk-acceptance criteria for them.
(ii) The risk assessment is capable of distinguishing high risk from low risk scenarios.
(iii) Risk mitigation strategies are available.
(iv) The costs of risk assessment are less than the costs of risk mitigation.

In summary, we require that society can accept that low risk scenarios exist, that the assessment technique can identify the risk, that if the risk is identified, there is something that can be done about it, and finally that the cost of assessing the risk is smaller than the mitigation cost. We discuss these requirements in more detail below.

### Existence of low risk scenarios

Risk assessment becomes a moot point if society does not recognize the risk or does not believe that low risk scenarios exist. This may be expressed by a zero-risk tolerance and an unwillingness to specify relevant risk-acceptance criteria. Dread and unfamiliarity may underlie such a stance (Slovic, 1987), but it usually becomes apparent through a deep-seated distrust of the assessment process and rejection of well-corroborated evidence of low risk. Unfortunately, ecological risk assessment is typically fraught with uncertainty, and it is rarely afforded the luxury of well-corroborated evidence. Hence, zero-risk tolerance stances can be hidden within an apparently rational scientific debate (Hayes, 2003). If such a stance is adopted by society, then a risk assessment will not provide a solution, but it may expose society's beliefs and facilitate the development of its attitudes over the longer term.

### Capable of distinguishing high and low risk scenarios

The risk assessment must be theoretically capable of distinguishing high and low risk scenarios. If it cannot, then clearly it is an ineffective and inefficient management tool. There are several ways in which risk distinction or resolution is lost in a risk assessment. The most common example of this is when the uncertainty associated with the assessment is so great that the confidence limits on the risk estimate span societies' high risk/low risk acceptance criteria. This can easily be the case in bioinvasion risk assessment, owing to the complexity of the systems involved, and is evident in one of the first quantitative assessments of ballast water risk (AQIS, 1994).

### Practical risk mitigation exists

It is important that practical risk mitigation strategies are available—if they are not, risk assessment becomes largely an academic exercise which neither protects the environment nor helps allocate limited funds in a manner that maximizes societal benefit.

### Assessment costs less than risk mitigation costs

The expense of conducting ecological risk assessment, gathering the data to support the assessment, and monitoring to verify the predictions of the assessment, can only be justified if the costs of risk mitigation are non-negligible, and outweigh the costs associated with the assessment. If mitigation costs are much smaller than the assessment costs, then risk management should simply proceed, obviating the need for the risk assessment (see, for example, Field *et al.*, 2004).

## Ballast water risk assessment methods

To date, at least eight ballast water risk assessments have been developed within several national and international contexts (Table 1). These assessments demonstrate two major approaches to ballast water risk assessment: species-specific and environmental similarity.

### Species-specific risk assessment

By definition, species-specific risk assessments provide information about the particular risk of a nominated species. This risk is calculated with direct consideration of the characteristics of the organism. Species-specific approaches to risk assessment use data on port infestation status and life history to assess the likelihood of translocation. The main difference between species-specific and other approaches is in how the former assess whether a species can establish and spread in a new environment.

There are two main approaches to this issue. The first uses distributional information from the native range to estimate the response of the species to the environment. This model is then used to assess species survival in the recipient range. Examples of this approach in terrestrial systems are given by Guisan and Zimmerman (2000), and an example of its application in invasive species research is given by Carpenter *et al.* (1993).

The second approach is to use information on life history and physiological tolerance to define a species' physiological limits and thereby to estimate its potential to survive or to complete its life cycle in the recipient environment. A common criticism of the first approach is that it is not as useful for prediction because a species' native range may also be constrained by biotic interactions. Many examples exist where species have invaded outside their native range for particular environmental variables. Modelling life history more closely is an attempt to limit these prediction failures by more carefully characterizing the species response to the environment. At least two ballast water risk assessment systems adopt a predictive species-specific approach that mimics the process of introduction (Table 1), and both model life history rather than relying on comparisons to the species' native range.

By their nature, species-specific risk assessments require a lot of data. Typically, they require locality records of the presence or absence of the species with which they are concerned (hereafter referred to as target species), life-history information, and the physiological tolerances (e.g. temperature and salinity) of each life stage (Hayes and Hewitt, 2000, 2001). Other information needed could include behavioural and reproductive

**Table 1.** Ballast water risk assessment systems currently in use or development.

| Name | Method summary | Approach | EV[a] | Endpoint | Time unit[b] | Purpose | Date | Reference |
|---|---|---|---|---|---|---|---|---|
| Australian Decision Support System | Models four steps in the bioinvasion process: source port infection, vessel infection, journey survival, and survival in the recipient port | Species-specific, quantitative | 1 | Target species life cycle completion in recipient port | Monthly | Identify low risk routes, vessels, and tanks | 1997 – ongoing | Hayes and Hewitt (2000, 2001) |
| Globallast | Environmental similarity between localities, weighted by target species presence in the donor location and inoculation factors | Environmental similarity, semi-quantitative | 37 | Identify and rank high and low risk ports | Seasonal | Enhance awareness and recommend ballast water management strategies between ports | 2002 – 2004 | Clarke *et al.* (2003) |
| Norwegian ballast water risk assessment | Alt 1. Environmental match between donor and source localities<br>Alt 2. Models four steps in the bioinvasion process: source port infection, vessel infection, journey survival, and survival in the recipient port | Species-specific, quantitative | 2 | Target species life cycle completion in recipient port | Monthly | Identify low risk routes, vessels, and tanks | 1998 – ongoing | Behrens *et al.* (2002); Haugom *et al.* (2002) |
| Nordic ports risk assessment | Environmental match between donor and source localities and listing of potentially hazardous species | Environmental similarity and species-specific, qualitative | 5 | N/A—Hazard analysis | Annual | Identification of high risk routes and species in NORDIC countries | 1998/1999 | Gollasch and Leppakoski (1999) |
| Ports Corporation of Queensland | Environmental similarity between localities, weighted by target species presence in the donor location and inoculation factors | Environmental similarity, semi-quantitative | 37 | Identify and rank high and low risk ports | Seasonal | Enhance awareness and recommend ballast water management strategies between ports | 1995 – 1997 | Hilliard *et al.* (1997a, b); Hilliard and Raaymakers (1997) |
| Dinoflagellate bioeconomic risk assessment | Estimates probability of establishment, bloom, and impact of a toxic dinoflagellate species | Species-specific, quantitative | 1 | Tourism and aquaculture impact | Annual | Economic impact of *Gymnodinium catenatum* on aquaculture and tourism | 1993/1994 | AQIS (1994) |
| German ballast water risk assessment | Environmental match between donor and source localities and listing of potentially hazardous species | Environmental similarity and species-specific, qualitative | 2 | N/A—Hazard analysis | Annual | Identification of high risk routes and species in German coastal waters | 1992 – 1996 | Gollasch (1996) |
| Great Lakes risk assessment | Species-based tolerance and taxa concentrations in vessels with no-ballast on board (NOBOB) | Quantitative | 2 | Journey survival of target species | Per journey | Estimate risk associated with NOBOB vessels entering the Great Lakes | 2002 | MacIzaac *et al.* (2002) |

[a]Number of environmental variables used in the assessment.
[b]Period over which risk is assessed.

characteristics, such as predation patterns, fecundity, and habitat preferences. The information requirements are largely driven by the assessment endpoint (Table 1). Species-specific assessments that strive to calculate the probability of survival in a new location will typically require less information than those that aim to calculate the probability of establishment and potential impacts of target species.

Species-specific assessments also require analyst(s) *a priori* to identify target species. Virtually all methods to date discriminate target species from non-target species based on the characteristics of successful historical invasions and invaders (see, for example, Lodge, 1993; Ricciardi and Rasmussen, 1998; Hayes and Sliwa, 2003a; Nyberg and Wallentinus, 2005). These criteria, however, can never wholly protect against species that are benign in their native region, but become pests in another (e.g. *Carcinus maenas*, *Codium fragile tomentosoides*, *Membranipora membranacea*; see Hewitt, 2003b; Schaffelke and Hewitt, in press). Another, more subtle problem may arise through taxonomic uncertainty, particularly in species that exhibit strains, ecotypes, or other equivalent subspecies classification. Examples include the tropical/temperate ecotypes of the Pacific oyster (*Crassostrea gigas*) and the toxic/non-toxic strains of the *Alexandrium* species complex (Hewitt, 2002; Aquenal Pty Ltd, 2004).

### Environmental similarity risk assessment

In contrast to species-specific approaches to risk assessment, ballast water risk assessments based on environmental similarity rely only on comparing the physical conditions of the source and destination locations. This approach is based on the observation that many species adapted to local conditions die or grow poorly when translocated to very dissimilar environments (van den Hoeck, 1982, 1984; Yarish *et al*., 1986). The risk assessment is therefore predicated on the premise that the likelihood of survival and establishment of any species that is repeatedly transferred between locations can be determined by the degree of physical similarity between these locations (Hilliard *et al*., 1997b; Hilliard and Raaymakers, 1997).

Although there is no single definition of environmental similarity, it is typically derived by using standard metrics such as the Gower or Euclidean distance (Legendre and Legendre, 1998), measured on multivariate environmental variables that are deemed relevant to the survival and/or reproduction of an organism. Typically, the environmental variables are standardized to have unit variance, so that each variable has equal weight in the analysis. This is particularly necessary when the variables are measured on different scales (Hilliard *et al*., 1997b; Clarke *et al*., 2003).

The main advantage of the environmental-similarity approaches developed to date (Table 1) is that they do not require target-species information. The major complications of the approach are: (i) they do not directly calibrate the relationship between environmental distance and establishment or invasion success; and (ii) the inclusion of environmental variables that are unrelated to invasion risk, for some or all potentially invasive species, can dilute significantly the sensitivity of the environmental distance measure (see Appendix).

## Methods evaluation

Many biological and physical processes act to restrict where and when ballast water risk assessment will satisfy society's needs. Some of these become evident by evaluating different risk assessment methods against the requirements discussed above.

### Existence of low risk scenarios

Although there have been no specific surveys of any particular society's attitudes to marine pests, it is reasonable to make analogies to terrestrial systems. With terrestrial biosecurity, the aim is for transparent, science-based decision-making. Additionally, all national systems that we are aware of recognize that zero-risk trade would have prohibitive cost, and that the advantages of trade are significant (FAO, 1996; OIE, 1996). National tolerances vary, but typically there is acceptance that the threat of incursion of harmful species should be small, and that any significant incursions should be managed adequately.

We suggest that society is willing to accept that there may be low ballast water risk scenarios, and that these low risk scenarios do not necessarily have to be zero risk, provided they have a scientific basis. Both species-specific and environmental similarity approaches to risk assessment have a scientific basis and are therefore likely to be acceptable.

We suggest that there are two low risk scenarios that society may accept for ballast mediated translocations: (i) where the ballast water vector represents a very small component of the natural exchange of organisms between two locations, and does not significantly contribute to the translocation of known harmful species; and (ii) where the likelihood of a novel species establishing in the recipient location is physiologically unlikely. Neither of these scenarios presents a zero risk.

Our first scenario presupposes the existence of coastal biomes, provinces, or regions that are sufficiently similar (biologically) for translocations of native species within the region to be deemed acceptable. A number of such biogeographical divisions ("bioregions"), at a variety of scales, has been identified for global marine ecosystems (Ekman, 1953; Briggs, 1974, 1995; Michanek, 1979; Springer, 1982; Sherman, 1993; Kelleher *et al*., 1995; Longhurst, 1998; Watling and Gerken, 2004). The boundaries of these bioregions are usually fuzzy, merging in an overlap zone or "zootone" (Yatsu, 1995), where there is a coexisting mixture of species from adjacent regions. Sharp boundaries at which the distribution of a large number of species terminate or start ("disjunctions") are relatively rare in the marine environment (but see Gaines and Gaylord, 2005).

Notable bioregional classifications to date, at a scale that may be appropriate to ballast water management, include large marine ecosystems (Sherman, 1993; Duda and Sherman, 2002), the bioregions of the World Conservation Union (Kelleher *et al*., 1995), and the Watling and Gerken "provincial" classification (Watling and Gerken, 2004; Figure 1). Each of these classification systems was created for a particular purpose, and few efforts at reconciling the differences have been made. It is important to note that bioregion boundaries exist at a variety of scales (Lourie and Vincent, 2004), for a variety of physical (Gaines and Gaylord, 2005) and biological (Welsh, 1994) reasons, and they can involve complex interactions between physical oceanography, an organism's physiological tolerance, and competition for space and resources. The suitability of a particular bioregional scheme for ballast water management needs to be carefully examined in light of this complexity.

The second scenario is largely self-evident. Translocation of species from one location to another, where they are unable to survive or complete their life cycle, is unlikely to threaten societal

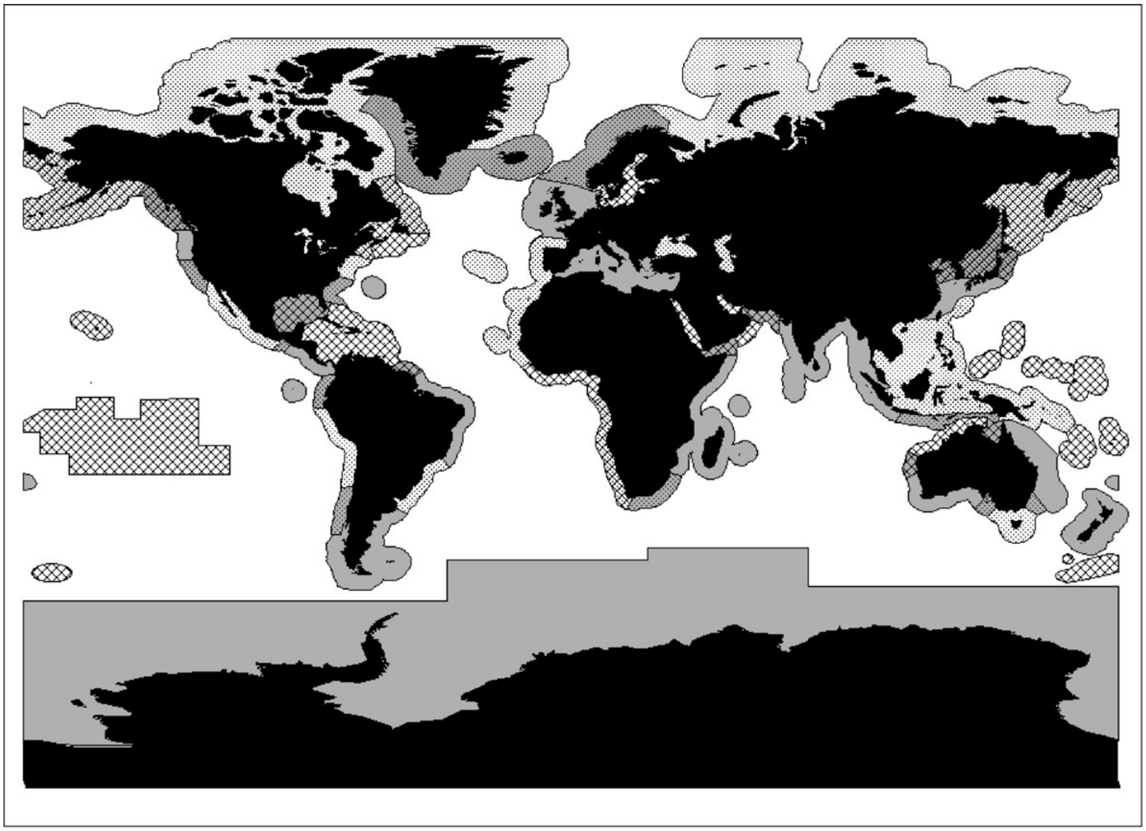

**Figure 1.** Bioregions based on the Watling and Gerken (2004) Coastal Marine Regions of the World (http://marine.rutgers.edu/OBIS/biogeo/watling.htm), adjusted to include "zootones" and core regions using the IUCN Bioregions (Kelleher *et al.*, 1995). Bioregions are represented by grey-shaded, cross-hatched, or half-tones, with overlaps identified by combinations.

values (human health, economic, or environmental) in coastal regions.

## Capable of distinguishing high and low risk

The direct empirical evidence for both species-specific and environmental similarity risk assessments being able to accurately characterize risk is limited (though see Patil *et al.*, 2004). This is due to the ethical prohibition on performing translocation experiments and the limited research funding in this area. Our assessment of the performance of these approaches is therefore largely based on our combined operational experience and analogy to terrestrial systems. The techniques are assessed at two levels: first, whether the techniques would be expected to work if perfect data were available; second, the difficulty in collecting data and making the systems operational.

In our experience, species-specific approaches can identify low risk scenarios if the number of target species is limited (Barry and Bugg, 2002). Hence, we believe that species-specific risk assessments are capable of resolving risk levels for journeys that start and end within biogeographical boundaries, if they are restricted to a few (in our experience $<12$) target species. Environmental similarity approaches, on the other hand, may be useful where the number of potential target species is very large or unknown, and there is no or very little natural exchange of organisms between locations, i.e. between non-contiguous biogeographic regions. We recommend the use of non-contiguous bioregions in this context to protect against the uncertainty associated with the various mechanisms that create bioregion boundaries and the overlap zone typical of most contiguous bioregions. However, although we believe that environmental similarity risk assessment may be suitable for some trans-biogeographic journeys, we suspect that the resolution could be low because of the need to protect against all species (see below).

It is not scientifically controversial to report that if a species is not present or cannot be entrained then it does not represent a ballast water threat. Therefore, this component of the species-specific approach is not problematic if data are available. The prediction of where a species can survive or complete its life cycle presents greater challenges. Simple use of native range tolerances can lead to under- and over-prediction, because other factors not included in the analysis (such as competition) can have positive or negative impacts on the species. Examples can be found in Mack (1996). More-sophisticated techniques based on life history and experimentation may improve the analysis, but it must be remembered that all approaches are simple models, and their predictions cannot ever be perfect. In the absence of perfect knowledge, an approach to this issue is to use uncertainty in the calculations to introduce conservatism. The appropriate extent of uncertainty to introduce is best assessed by expert opinion on a case-by-case basis.

In both cases, issues remain about the representativity of the data and the consistency of the conditions under which it is measured. Experience from the ballast water decision support system in Australia (Barry and Bugg, 2002; Hayes and Sliwa, 2003b) reveal that the available data are fragmented. Although careful and coordinated study can determine robust port infection status (Hayes *et al.*, 2005a) and planktonic duration times, the development of robust species tolerance data is often more difficult. This is because of the complicated variation and interactions between genotypes, the environment, and the cost and difficulties associated with laboratory trials. The conclusion from this is that the confidence we have that a species is in the port and it is available for uptake is limited to our effort to measure these parameters, rather than any unknown factors of the system. The prediction that a species will survive in a different environment, however, usually entails more fundamental uncertainty that must be carefully evaluated.

A feature of species-specific risk assessments is the occurrence of saturation. As the number of species included in the assessment increases, the number of low risk scenarios decreases. This phenomenon is entirely justified if the species assessments are accurate. The difficulty arises when the assessments are conservative through a lack of data. In extreme cases, very few low risk scenarios remain (Barry and Bugg, 2002).

Evidence to support the use of environmental similarity is similarly limited. Although it is not controversial to state that a large enough change in the environment will lead to failure to establish or spread, how large this change should be is unknown, and will vary between species. This is an active area of debate in the marine pest policy world, but little of it appears in the referenced literature.

Current approaches (Table 1) that use environmental similarity do not address what is high and what is low risk in terms of absolute environmental distance. We argue that any system that is used to make a binary decision, e.g. to provide exemption from treatment or not, must address this issue. There are a number of approaches to this. The use of native ranges to assess appropriate environmental distance is vexed for the same reasons discussed under native range correlation. Moreover, the fact that organisms are sufficiently morphologically similar to be categorized as a species may also be problematic here because this may not reflect significant physiological differences between individuals within a species. The existence of ecotypes is well understood; many translocation experiments in terrestrial systems have demonstrated this. Examples can be found in ecology and forestry (Clausen *et al.*, 1940). More direct evidence for determining the appropriate cut-off for environmental similarity might be found in empirical records. For example, systematic surveys of Australian ports (Hewitt, 2002, 2003a; Ruiz and Hewitt, 2002) show no significant history of species translocations between northern hemisphere temperate ports and tropical Australian ports, despite large volumes of ballast water being discharged (Hayes *et al.*, 2005b). Of course, there might be other complicating factors, such as the level of disturbance of the recipient environment, so this type of evidence could theoretically provide the basis for appropriate cut-offs and help justify risk assessments. To date, however, we are unaware of any such analysis.

An additional difficulty with environmental similarity is the question of optimal data requirements. The risk-discrimination power of environmental similarity can be degraded when non-significant or inaccurate variables are included in the analysis (see Appendix). Therefore, we suggest that only variables that are truly predictive of invasion success and robust to error be included. In our opinion, these are variables such as salinity and temperature. Additionally, a change of synchronization of seasons could undermine the accuracy of an environmental similarity risk assessment. For example, a plant could change from a summer annual in temperate locations to a winter annual in tropical locations.

Given this discussion, we believe that it is prudent for environmental similarity only to be considered for more extreme environmental distances, and not for fine-scale risk estimation.

## Practical risk mitigation exists

The new BWM Convention (IMO, 2004) requires that all ships built before 2009 must conduct ballast water management equivalent to ballast water exchange, until 2014 (or 2016 depending on size). Ships completed in or after 2009 must meet a ballast water performance standard (again with some size-related exceptions). The efficacy of ballast water exchange as a bioinvasion risk mitigation strategy has been argued by various authors (Carlton, 1985, 2001). The consensus opinion is, however, that if performed properly it will reduce significantly the number of coastal organisms in the ballast tank, and hence the risk of translocation (Dickman and Zhang, 1999; Wonham *et al.*, 2001; Boelens, 2002). The BWM Convention has also agreed to ballast water performance standards (Regulation D-2) that phase in after 2009, as ballast water exchange at sea is phased out (Regulation B-3).

## Management costs less than risk assessment costs

Species-specific risk assessments rapidly become expensive as the data requirements increase. The approaches typically need to assess infestation status in ports and to collect species information that is robust enough to support the assessments. Further, as the number of species increases, the probability of low risk will decrease, especially where there is conservatism as a consequence of a lack of data (Barry and Bugg, 2002). Therefore, a full species-specific risk assessment for the entire world would be an enormous ecological challenge as well as involving significant ongoing expense. The environmental similarity approach, in contrast, has low recurrent costs.

A recent analysis of the costs and benefits associated with ballast water management suggests that the costs associated with ballast water exchange (initial costs) are determined by how far off the standard route a ship must divert to perform exchange, with associated costs of fuel (pumping) and delay. The capital costs of onboard treatment to meet Regulation B-4 (permanent costs) are estimated to range between AU$1 million and AU$5 million per vessel, with a small additional variable cost of 0.06–4.66 cents per tonne of ballast water treated (Centre for International Economics, 2006). The combined costs to the Australian economy of both initial and permanent ballast water management for coastal shipping, accumulated to the year 2025, are estimated to be between AU$455 million and AU$155 million, depending on whether exchange is mandatory or risk-based (species-specific approach for seven species) before the implementation of permanent treatment arrangements (Table 2). Similar values for risk assessment approaches based on environmental similarity are not available, but would be higher as long as an assessment was equally as effective.

It is important to note that considerable uncertainty exists in both the estimates of initial and permanent costs, and the benefits of mandatory and risk-based exchange requirements. A sensitivity analysis, however, suggests that if Australian coastal vessels perform species-specific (seven species), risk-based exchange 12 nautical miles from the coast before the implementation of

**Table 2.** Cost estimates (Net Present Value million AU$) for the implementation of the IMO Ballast Water Convention requirements for coastal Australian shipping between 2007 and 2025 for (top) all vessel exchanges, and (bottom) exchanges by high-risk vessels only (source: Centre for International Economics, 2006).

| Costs | 50/200 nautical miles | 12 nautical miles | 3 nautical miles |
|---|---|---|---|
| Mandatory exchange | | | |
| Exchange costs | 209.7 | 109.7 | 87.5 |
| Treatment costs | 3.3 | 3.3 | 3.3 |
| Capital costs | 31.7 | 31.7 | 31.7 |
| Depreciation costs | 41.4 | 41.4 | 41.4 |
| Inspection costs | 2.8 | 2.8 | 2.8 |
| Economy flow-on costs | 165.9 | 107.9 | 95.0 |
| Total | 454.9 | 295.8 | 261.7 |
| Risk-based exchange | | | |
| Exchange costs | 63.9 | 24.4 | 15.7 |
| Treatment costs | 3.3 | 3.3 | 3.3 |
| Capital costs | 31.7 | 31.7 | 31.7 |
| Depreciation costs | 41.4 | 41.4 | 41.4 |
| Inspection costs | 9.6 | 9.6 | 9.6 |
| Economy flow-on costs | 81.4 | 58.5 | 53.4 |
| Total | 231.3 | 168.9 | 155.2 |

permanent ballast water treatment methods, there is a 90% chance that the accumulated net benefit will be between AU$60 million and AU$290 million (Centre for International Economics, 2006). This value would increase dramatically if vessels were to perform exchange 50 nautical miles from the coast, and would diminish if more species were added to the target list. These analyses will still be relevant with permanent treatment technologies. If treatment is rapid and low cost, then the benefits of risk assessment may be low. If it involves significant delay of vessels, then it may be attractive in some circumstances.

## Discussion

There are at least 1500 marine and estuarine species that have ballast-water- or hull-fouling-mediated invasion histories (Hayes *et al*., 2005b). Australia alone has at least 338 marine species that are non-native, cryptogenic, or of unknown invasion status (Hayes *et al*., 2005b). The number of species that has no history of invasion is larger again. Given current knowledge, a species-specific risk assessment that attempts to address the ballast water risks associated with this many species will quickly exhaust all resources and saturate.

We anticipate that species-specific risk assessments are theoretically capable of distinguishing high and low risk scenarios for cases where a small number of species are involved. The journeys that are most likely to meet these criteria are those that start and end within biogeographic regions. In particular, we argue that if ballast water represents a small component of genetic movement between locations, then it is low risk for adverse translocation of the native species, so they do not need to be assessed. In this case, we only need to assess the non-native species.

In practice, the number of non-native species in a port may still be large. For example, San Francisco Bay (USA) is thought to contain 212 non-native species whereas Port Phillip Bay (Australia) is thought to contain at least 99 non-native species (Hewitt *et al*., 1999, 2004). If all these species are to be managed, it is likely that principle 4 will quickly be violated. An alternative approach is to argue that most non-native and cryptogenic species have little if any discernible impact on their environment (Williamson, 1996; Hewitt, 2003b; Hayes *et al*., 2005b; but see Crooks and Soulé, 1999). Therefore, a species-specific risk assessment will best satisfy our principles if we only consider a limited set of harmful target species between pre-defined ports, where ballast water is only a small component of natural genetic exchange between the two locations.

In the species-specific approach, the efficacy of the assessment is critically determined by both the target list and the distribution of the species. We anticipate that most target species will be identified through empirical methods based on previous invasion history and previous/current impact. Arguments that invasive potential cannot be predicted are countered by noting that the assessment is done for environments with similar biological composition.

Species-specific risk assessment is less principled for journeys between locations that have little natural genetic exchange. In this case, the ability to identify high and low risk scenarios is significantly reduced because of (i) the increased potential for unidentified harmful species, and (ii) the assessment may saturate, and the cost of supporting the assessment could become larger than the cost of mitigation, as the number of species assessed rises. Risk assessments based on environmental similarity are possible in this context, but they must be carefully designed to discriminate high and low risk vessels. In this approach, environmental similarity risk assessments for journeys between locations must provide appropriate protection for the destination environment. This means that the assessment should only include variables such as temperature and salinity that are relevant to the invasion success of all species in the source region. Assessments that contain large numbers of variables (Table 1) are much more likely to dilute the true environmental distance between two regions (Appendix). Determining what environmental distance constitutes low risk is an important, but as yet, unresolved issue.

We believe we have identified the two possible scenarios where risk assessment may potentially be applied, based on a set of simple requirements. The choice of appropriate method and the selection of the correct levels of precaution is a matter for policy. From our experience, the lack of data in this field will possibly lead to significantly precautionary approaches. Given this lack of data, it is likely that any practical system will have adaptive elements. As new data arise, existing policies could be reviewed. We accept that designing a practical system that can be easily implemented and communicated to all users will require further development, and is outside the scope of this manuscript. However, we argue that the ideas presented here should form the basis of a case-by-case development of any practical system.

## Acknowledgements

We thank Roger Mann and Nic Bax for helpful comments on earlier drafts, and the members and Chair (Stephan Gollasch) of the ICES/IOC/IMO Working Group on Ballast and Other Ship Vectors for their assistance in constructing Table 1. We also thank the referees for their constructive comments, which improved the final manuscript.

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## Appendix

Environmental similarity risk assessments measure the environmental distance between two locations. Currently, however, there is no firm guidance on which environmental measures are significant predictors of establishment or invasion success. Analysts are free to choose which environmental variables to include and which to exclude, and methods to date suggest that there is considerable differences between emergent approaches (see Table 1).

The inclusion of uncorrelated environmental variables that are unrelated to invasion risk in an environmental similarity risk assessment will dilute significantly the true environmental signal and so reduce the resolution of the assessment. As an example, consider the environmental distance ($d$) between two locations, given as

$$d = \sqrt{\sum_{i=1}^{n} (x_{1i} - x_{2i})^2}, \qquad \text{(A1)}$$

where $x_{1i}$ and $x_{2i}$ are the values for the $i$th variable for the source and destination location, respectively. As an extreme example, consider that only the first variable is truly related to the probability of invasion success, and that all other variables have no bearing on the successful survival or establishment of a non-native species. In this case, we can write

$$d = \sqrt{(x_{11} - x_{21})^2 + \sum_{i=2}^{n} (x_{1i} - x_{2i})^2}. \qquad \text{(A2)}$$

Here, only the first variable ($i = 1$, e.g. temperature) is correlated with invasion success. The term $\sum_{i=2}^{n} (x_{1i} - x_{2i})^2$ is noise, which obscures the information in $d$. Adding additional variables rapidly dilutes the true signal, decreasing the signal to noise ratio (Figure A1). Note that in Figure A1 we assume that the values $x_i$ are standard normal deviates. This is consistent with the standardized variables used in many environmental distance metrics.

The effect is similar when there is error in $x$, i.e. the variable does not represent the true nature of the location. This is equivalent to including non-significant variables. The impact of the error on the analysis will depend on its magnitude. Because of this effect, care should be taken to use truly predictive variables that are also an accurate reflection of the state of the location.

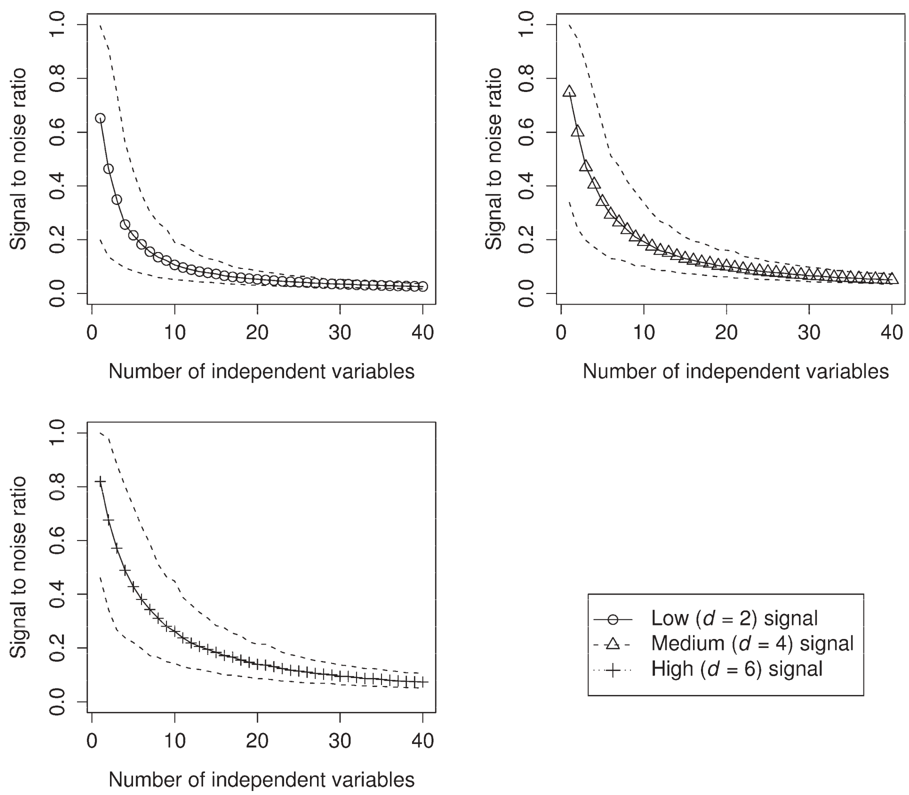


**Figure A1**. Signal to noise ratio with 95% confidence limits for three values of small, medium, and large environmental distance ($d$).

Finally, it is noteworthy that the choice of variables also influences the ability of environmental similarity risk assessments to distinguish high risk scenarios from low risk scenarios. For example, the substratum in a port may not be important to planktonic species, so large distances based on this variable would dilute the true environmental distance for planktonic species. The choice of variables is therefore dependent on the purpose of the system. If it is designed to exclude a set of species, their requirements should be used to determine the appropriate variables. If the system is to exclude a large set of unknown species, then it must necessarily choose variables that are directly relevant to invasion risk across all species.

doi:10.1093/icesjms/fsn004