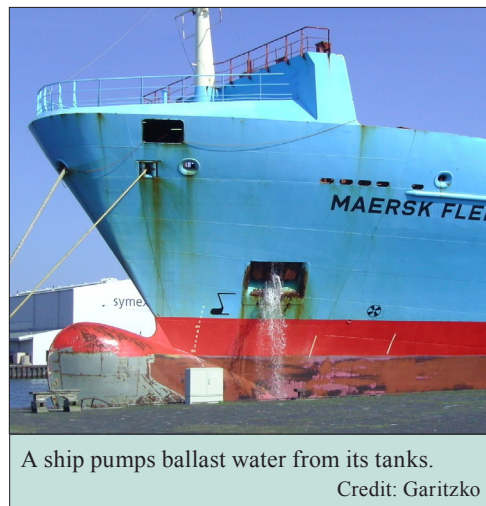


## Assessing the Relationship between Propagule Pressure and Invasion Risk in Ballast Water

The release of invasive species from the ballast water of ships to U.S. waterways has caused extensive environmental and economic impacts (on the order of \$1 billion since 1989 for zebra and quagga mussels alone). To limit the spread of invasive species, the Environmental Protection Agency and the U.S. Coast Guard are developing plans to regulate the concentration of living organisms discharged from ballast water. These plans assume there is a relationship between organism concentration in ballast water and the establishment of invasive species (known as the risk-release relationship). Although there is strong support for such a relationship, determining the exact number of organisms that could be expected to launch a new population is complex. Establishing an initial benchmark to reduce concentrations of organisms in ballast water below current levels, and then selecting various risk-release models to analyze much-needed experimental and field-based data would help inform future decisions about ballast water discharge standards.

Each year commercial shipping vessels make more than 90,000 visits to U.S. waterways, bringing with them containers of cargo—and tanks of ballast water. This water, taken up from coastal port areas at the beginning of the voyage, fills the ballast tanks of ships to provide stability during transit and is released when the ship reaches its destination. However, a variety of aquatic organisms, ranging from microscopic plants and animals to mussels, crabs, and even schools of fish, can also enter the tanks as they are filled. Once released, often in regions they would never



A ship pumps ballast water from its tanks.

Credit: Garitzko

have reached by natural means, these organisms can establish populations with significant impacts on the environment, economy, and society.

Increasing world trade and a growing global shipping fleet composed of larger and faster vessels, combined with a series of prominent ballast-mediated invasive species outbreaks over the past two decades, have

prompted national and international interest in the management of ballast water. Over the past ten years, ballast water exchange (see box) has been the primary method of mitigating the

**Ballast water:** To maintain stability during transit along coasts and on the open ocean, ships fill their ballast tanks with water. This water is taken from coastal port areas and is transported with the ship to the next port of call. Commercial ships discharge an average of 196 million gallons of ballast water to U.S. waters every year.

**Ballast water exchange:** A method of reducing the concentration of coastal organisms transported among global regions by transferring the water from a ship's ballast system to the environment, with a simultaneous or subsequent uptake of water to refill the ballast. This usually takes place in open ocean waters, because coastal organisms are considered less likely to survive in oceanic conditions, and the oceanic species that will enter the ships ballast are considered unlikely to survive in coastal waters.

transfer of coastal species around the globe. In an effort to find a more effective method of preventing the transfer of coastal species in ballast waters, the U.S. Environmental Protection Agency and the U.S. Coast Guard are developing regulations to limit the density of organisms in ballast water discharged to U.S. waters. These agencies requested that the National Research Council convene a committee of experts to provide technical advice to help inform the process of setting limits for living organisms in ballast water.

### Factors Affecting Invasion

Plans to manage invasion risk by setting limits for living organisms in ballast water assume there is a quantifiable relationship between the number of organisms in the water discharged (propagule pressure, see box), and the probability that the organisms will establish a population in their new environment (called the risk-release relationship). There is strong support for such a relationship across a diverse range of habitats, geographic regions, and types of organisms.

However, determining the precise nature of the risk-release relationship—the exact dosage of organisms that could be expected to launch a new population—is complex. The relationship varies enormously with different species, with time, and in different environments. Although organism density is a key component in the success of an invasive species, it is just one of scores of variables that can influence invasion outcome. Other factors include the identity of the organism, its source and history, the frequency and quality of deliveries, as well as the traits of the recipient region. For these reasons, the committee concluded that any method of predicting invasion outcomes based upon

**Propagules:** Any living bacterial material, such as cells, spores, eggs, larvae, or mature organisms, transported from one location to another.

**Propagule pressure:** A general term expressing the quantity, quality, and frequency with which propagules are introduced to a given location. Propagule pressure is a function of a suite of variables reflecting the nature of the species and the transport vector.

**Invasion Risk:** The probability that an introduced group of organisms will establish a self-maintaining population in their new environment.

only one factor is likely to suffer from a high level of uncertainty.

### Understanding the Risk-Release Relationship

In order to reach a more detailed understanding of the risk-release relationship, models could help predict and compare the invasion risk associated with different discharge standards. Models are often used in environmental management, because they provide a framework to help predict and compare the outcome of various decisions, and can be updated as new information becomes available.

The committee considered a variety of models that could be used to describe the risk-release relationship, and evaluated their strengths, weaknesses, and data needs. The models range from descriptive models that simply describe the shape of the relationship, to mechanistic models that describe the biological processes underlying the relationship. The models also consider single or multiple species.

Unfortunately, there are very few analyses of the risk-release relationship that have tested multiple models and quantified uncertainty. This is partly because the existing data on invasions and organism density in ballast water (from historical invasion records or more recent ballast surveys) are substantially mismatched in time and patchy in time, space, and taxonomy. Statistical modeling has been applied to these datasets, but the data are not sufficient in present form to characterize a biologically meaningful relationship, much less to estimate the associated uncertainty in order to confidently identify the invasion probabilities associated with particular discharge standards.

The analyses that do exist have attempted to use proxy variables; for example, several studies have used the number of ship arrivals as a proxy for organism density. However, even if a relationship is found between vessel arrivals and invasions, this relationship may be spurious and not causal. If reliable proxies could be established, this would represent an efficient and cost-effective approach; however, there is no evidence that any proxy variable used thus far is a reliable stand-in for organism density.

### The Path Forward

The committee concluded that establishing a benchmark discharge standard (such as the

### Box 1. Zebra and Quagga Mussels



Zebra mussel with siphons open for feeding, initiating a process that results in increased growth of plants and algae.

Credit: NOAA

Zebra and quagga mussels (*Dreissena polymorpha* and *D. bugensis*) are small mollusks native to the freshwater rivers and lakes of Eastern Europe and Western Asia. They were introduced to the Great Lakes in the 1980s, as larvae in the ballast water of ships that traveled from Europe or Asia. Zebra and quagga mussels are now established in all the Great Lakes and all of the large navigable rivers in the eastern United States, in many small lakes in the Great Lakes region, and in Nevada and California.

Increasing populations of mussels have caused extensive environmental damage. The shellfish can colonize water pipes, growing so large that they block water flow. This can reduce water intake in heat exchangers, condensers, fire fighting equipment, and air conditioning and cooling systems. The mussels can

also firmly attach themselves to solid objects such as buoys, docks, and boats—which can then transport the mussels throughout the waterway. Zebra and quagga mussels also attach themselves to the shells of native mussels, reducing populations of these species.

Zebra and quagga mussels have had major impacts on the ecosystems they have invaded. For example, they primarily consume phytoplankton, but also filter other suspended materials, such as bacteria and silt, from the water column. As a result, the waters of the Great Lakes are becoming more transparent, allowing light to penetrate further and increasing the growth of photosynthetic organisms.



Zebra mussels cover a current meter in Lake Michigan (left) and infest the walls of a lock on the Arkansas River (right).

Credits: NOAA (left), Laurie Driver, U.S. Army Corps of Engineers (right)

Additional information from USGS zebra mussel factsheet.

D-2 standard from the International Maritime Organization) to reduce concentrations of organisms in ballast water below current standards would be a logical first step to reducing invasion risk. Following the setting of an initial benchmark, a risk-release model or models should be selected as the foundation for the data gathering and analysis effort.

In the short term, mechanistic single-species models could be used to look at the risk-release relationship. This would be a conservative approach if a hypothetical “best candidate” invasive species was used, that is, one with characteristics optimized for invasion. Single-species models allow for the clarification of model structures and assumptions without the added complications of multi-species releases; however, these models are not representative of the real world because they are constructed to represent a one-time introduction of a known initial number of individuals. In reality, ballast

water is discharged repeatedly and contains many different species.

In the longer term, more robust statistical models of the risk-release relationship would be helpful in determining ballast water discharge standards. Currently, the greatest challenge in this approach is the insufficient scope and scale of the available data.

### Gathering Data

To date, there has been no concerted effort to collect and integrate the data necessary to provide the robust analysis of risk-release relationship needed to evaluate the invasion probability associated with particular discharge standards. That is, there are no regular monitoring programs in place to measure invasions in the nation’s waterways, nor to measure organism density in ballast water. In order to advance a robust understanding of the risk release relationship, a two-track approach should



The Chinese mitten crab (*Eriocheir sinensis*) is native to northern China and Korea, but after arriving in the United States—likely in ballast water—this invasive species established a population in San Francisco Bay in the early 1990s. Chinese mitten crabs spend most of their lives in fresh water, returning to marine water only to spawn. This life cycle, coupled with the spatial separation of low salinity estuaries along the west coast, may have helped limit the spread of Chinese mitten crabs beyond San Francisco Bay.

Additional information from Smithsonian Environmental Research Center. Photo credit: Stephan Gollasch

be pursued to obtain both experimental and field-based data.

### **Experimental Data**

Experiments could be used to estimate the effect of organism density on establishment

success providing a solid basis for initial discharge standards and providing data to help validate models. To support the short-term use of single-species mechanistic models, researchers should focus on those species and environmental conditions most likely to maximize invasion, in order to provide a conservative estimate of invasion probability. Serious consideration and explicit criteria should be used in order to select the appropriate organisms and conditions. If these experiments are pursued aggressively, results could be obtained in three to five years.

### **Field-based Data**

In addition to experiments, gathering field-based data would help ground-truth the models, providing a critical validation step for the results obtained from experimental efforts. Several locations should be selected to include different coasts, ship traffic patterns, source regions, and environmental conditions. Suggested locations include San Francisco Bay, Chesapeake Bay, and Tampa Bay. At each location, measures of organism density in the ships' ballast and invasion rate would be made repeatedly over a minimum of a ten-year period in order to provide a data set for independent analysis and validation of experimental results.

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The National Academies appointed the above committee of experts to address the specific task requested by the U.S. Environmental Protection Agency and U.S. Coast Guard. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.



For more information, contact the Board on Water Science and Technology at (202) 334-3422 or visit <http://dels.nas.edu/wstb>. Copies of *Assessing the Relationship between Propagule Pressure and Invasion Risk in Ballast Water* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; [www.nap.edu](http://www.nap.edu).

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