The Economic Roots of Aquatic Species Invasions

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Across ecosystems and geographic regions, the rate of newly detected biological invasions is increasing, and in the case of individual species this increase is often exponential (Ruiz et al. 2000; Ruiz and Carlson 2003; Fofonoff et al. 2003; Kraus 2003). Invasive alien species have become a real threat to our environment and economy. The economic costs of invading alien species in the United States alone come close to $120 billion per year (Pimentel et al. in press).

Harmful invasions of alien or non-indigenous species often produce devastating impacts on agriculture, recreation, and natural resources (OTA 1993). They threaten biodiversity, habitat quality, and ecosystem function and are now considered among the greatest threats to native species in the United States (Wilcove et al 1998). In combination with other economic activities, the rapid expansion of international trade, travel, and transport have contributed significantly to the increasingly high rate of species invasions. And, as unfortunate as it may seem, "the pressures to increase trade are currently greater than the pressures for precaution in moving biological material across former barriers" (Mooney and Hobbs 2000:426). The following discussion highlights the links between this exponential increase and the unrestricted trade of a growing global economy.

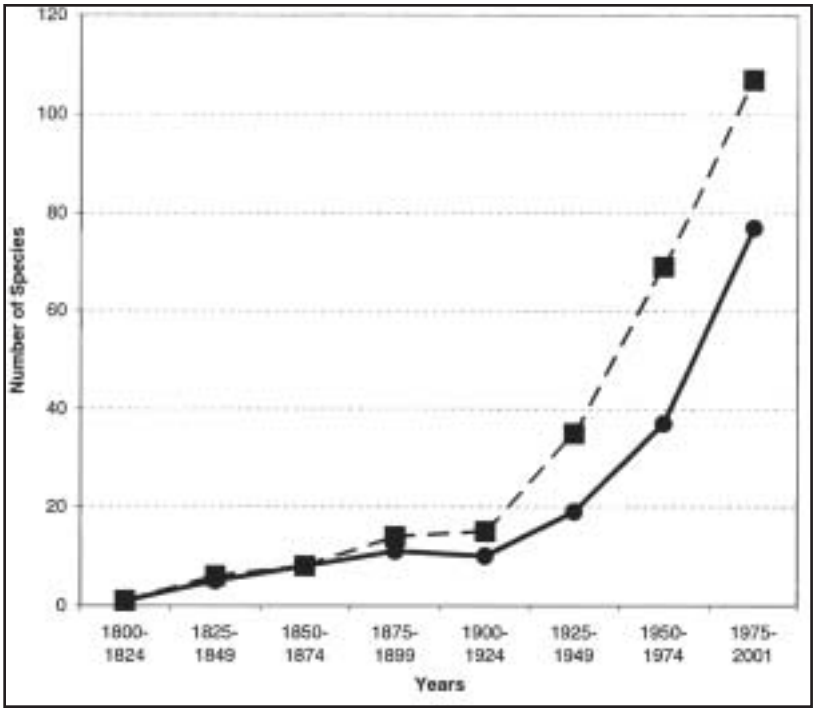
One of the by-products of international trade and travel is the transportation of species beyond their natural geographic range. A species that is not native to a particular ecosystem is referred to as alien, exotic, or non-indigenous. A subset of alien species is considered invasive by virtue of their ability to cause economic or environmental harm, or harm to human health (Executive Order 13112). They generally exhibit characteristics such as rapid growth rate, exceptional dispersal capabilities, large reproductive output, and broad environmental tolerance. Although naturally occurring movement of species has taken place across the surface of the earth for hundreds of millions of years, human activity has greatly increased the velocity of invasion and, by dissolving temporal and spatial boundaries, has enabled many species to relocate that would not normally have had this opportunity. Most arrive in relation to human economic activities either intentionally or unintentionally.

Invasive species move along routes referred to as pathways. Their movement is facilitated by vectors, the means by which the species is moved, such as ships, planes, people, and other organisms. Throughout history, cultures and civilizations have relied on trade to improve relations and increase prosperity. Archaeologists have found evidence of human-assisted movement of species by way of seafaring trade connecting continents early in history. Among the first specialized sailors and merchants were the Phoenicians (ca. 3000 B.C.) who traded articles such as Lebanese cedar and processed dyes (Cameron 1997). Greek sailors and merchants traded basic storable food stuffs such as grain, grapes, olives, wine, and oil. During Roman times, sea trade existed between India and Egypt. And, as early as the sixth century the Vikings were exchanging honey, fur, weapons, and slaves for Arabian silver, which has been found as far west as North America (Het Huis van de Aarde Museum 2005).

Between the eighth and fifteenth centuries Indian Diaspora and Far East trade routes were used not only for economic expansion but also for the expansion of religion. And, by the first half of the seventeenth century the Netherlands had established a fully global trading network (Brummett and Edgar 1999).

Today, transportation of people and cargo via ships and planes has become fast, efficient, and frequent. Increased speed and efficiency of transport enables international trade and feeds aspirations for economic globalization and growth. One shipping company alone can maintain a global network of shipping lines. For example, in 2004 the shipping company Maersk Sealand advertised itself as one of the largest liner shipping companies in the world with over 300 shipping vessels and 950,000 containers traveling around the globe, with feeder vessels, trucks, and dedicated trains available for door-to-door service (www.maersksealand.com).

Figure 1. Invasion rate associated with shipping for nonnative coastal marine species that have become established in North America (from Fofonoff et al. 2003). The black line indicates invasions for which shipping was the sole vector and the dashed line indicates invasions for which shipping was the sole vector or one of multiple possible vectors.



With increases in total volume of trade and the speed and frequency of transportation and delivery come greater risks of introduction, both intentional and unintentional. For example, larger numbers of products bring greater opportunity for unintentional introductions referred to as "hitchhikers," organisms that attach themselves to the product itself, such as insects on plants, or that exist within the transportation medium, such as ballast water. As shipping technology continues to improve, ships take less time to traverse greater distances, which means mortality decreases and organisms that might have once died when contained within a ship's ballast water for a few weeks or a month may now have a better chance of survival given that the journey has been shortened to a number of days. As the rate of non-indigenous, potentially invasive, species introduction accelerates, trade itself begins to look more and more like a sort of "metavector" comprising numerous, individual, yet associated, vectors.

International trade currently represents a growing share of the U.S. economy. Import volume increased from $40 billion in 1991 to around $100 billion in 2001, more than doubling in just a 10-year period (Bureau of Transportation Statistics 2002). Some predict that global trade will double again by the year 2020. All this international trade facilitates the intentional and unintentional transport of biological organisms around the world. For example, rates of introduction to the United States of non-indigenous mollusks and fish recorded since 1790 increased steeply in the 1900s (OTA 1993). Overall the rate of invasion associated with shipping for nonnative coastal marine species established in North America rose from under 20 species in the late 1800s to over 100 species by the mid-1970s (Figure 1; Fofonoff et al 2003).

Approximately 42% of the plants and animals federally listed as threatened or endangered species are at risk because of alien and invasive species (Pimentel et al. in press). Invasive species were a contributing factor in 68% of North American fish extinctions over the past century (Miller et al. 1989).

The National Invasive Species Council's working group on pathways identifies three major categories of pathways for the introduction of alien and invasive alien species: (1) transportation, (2) living industry, and (3) miscellaneous. Within the category of transportation, pathways related to aquatics include: the movement of water, such as ballast water, sediments and dredge spoil materials; items used in the shipping process, such as the ships themselves, which are subject to hull fouling; and "hitchhikers" attached to seaweed (National Invasive Species Council 2003). Historically the dominant vectors for marine invasions into North America have been shipping and fisheries. Most introductions of non-indigenous aquatic species result from discharging contaminated ship ballast water and from fouling of the ship's hull, anchor chain, etc. (Fuller et al. 1999).

Perhaps the most notorious example of a species entering through a transportation pathway is the zebra mussel (*Dreissena polymorpha*). This invasive species entered the United States through the St. Lawrence Seaway as planktonic larvae, probably in the ballast water of a bulk cargo vessel coming from a Black Sea port (Holeck et al. 2004). Since discovery in 1988, zebra mussels have spread from the Hudson River on the east to Oklahoma in the west, and from Ontario and Quebec in the north to Louisiana in the south. Zebra mussels are small bivalves that cluster in colonies of hundreds of thousands per square yard and clog the openings of underwater pipes, often closing them off altogether.

Additionally, invasions are facilitated by the mail, Internet, and overnight shipping companies. In particular the Internet is a very difficult pathway to control. Although recognized as a

federally-prohibited weed, giant salvinia (*Salvinia molesta*) is still available for purchase on the Internet.

Within the council working group's category of "living" industry, pathways related to aquatics include: the food industry (both seafood and freshwater), and the non-food industries transporting animals and other organisms such as aquaculture, the pet/aquarium trade, the bait industry (see Thompson and Alam later in this series), research, and public education and enjoyment such as zoos and public aquariums. Through any of the living industry pathways, species can be intentionally released, escape, or hitchhike with people, products, and services. The plant trade is often a vehicle for species introduction through nurseries and pet stores.

Two examples of species introduced through living industry pathways are the lionfish (*Pterois volitans*/miles complex) and the water hyacinth (*Eichhornia crassipes*). The venomous lionfish is native to Indo-Pacific waters and has established itself off the southeast coast of the United States. As early as 1994, lionfish were observed off the east coast of Florida. Several individuals were unintentionally released in this region when a private aquarium was destroyed by Hurricane Andrew in 1992 (Hare and Whitfield 2003). Dispersal along the Atlantic coast was likely helped by Gulf Stream transport of eggs and larvae.

Water hyacinth, another example of a highly invasive aquatic species, began charting its course around the globe in 1884. This plant originally came from the Amazon basin in South America and is today a serious pest in North America, tropical Africa, and Southeast Asia. In certain parts of tropical Africa, riverboat transport has become impossible because this water weed has completely blocked whole river systems. The control cost to seven African countries runs about $20-50 million per year (McNeely et al. 2003).

Within the council working group's category of miscellaneous pathways, those related to aquatics include interconnected waterways and inter-basin transfers. A good example of introduction by interconnected waterways is the sea lamprey (*Petromyzon marinus*). This eel-like species is native to the Atlantic Ocean. It entered the Great Lakes through the Hudson River and the Welland Canal in 1829 and was later discovered in Lake Eerie in 1921 (Mooney and Hobbs 2000). The sea lamprey attaches itself to other fish and with its suctorial mouth extracts blood and other body fluids.

In order to address the problem of biological invasions, some important legislation has been passed. In 1990 the Nonindigenous Aquatic Nuisance Prevention and Control Act (NANPCA) called for a national program to prevent and respond to problems caused by the unintentional introduction of nonindigenous aquatic species into U.S. waters and it established the multi-agency Aquatic Nuisance Species Task Force to carry out its mandates. A reauthorization took place in 1996 in the form of the National Invasive Species Act (NISA). Currently a second reauthorization, the National Aquatic Invasive Species Act (NAISA), is under review by Congress.

NAISA represents a major re-write of NANPCA. It requires a standard for ballast water management and appropriation of funds for the National Oceanic and Atmospheric Administration, the U.S. Geological Survey, and the Smithsonian Institution to establish baselines and invasion rates, as well as improved tools for early detection. It also focuses on rapid response to incipient infestations, establishing a separate non-year fund administered by the U.S. Fish and Wildlife Service to assist states to respond to newly detected species. It allocates funding for setting up a screening mechanism for intentional introductions. It also encourages examining new pathways besides the historical focus on ballast water. And, it mandates more and better research on the topic.

It is crucial that efforts continue with prevention, specifically risk identification and assessment, further research on pathways, and continued exploration of avenues available through regulation. We need to strengthen outreach at all levels and continue to support research specifically in invasion ecology. And, we need to continue to support research specifically in invasion ecology. For management of invasive species at the field level to be successful, we must encourage a greater understanding of early detection/rapid response, control and management, and restoration techniques.

Invasive species have been recognized as one of the most significant drivers of environmental

change worldwide. And, as we have seen biological invasions are facilitated by the increasingly expanding network of commercial highways underlying international trade, travel, and transport. It is crucial that we address these pathways. However, even if urgent measures are taken, it is likely that the number of species invasions in the United States will increase in conjunction with the growth of the economy and the sectors that constitute or represent pathways for invasive species.

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