Closing the Pathways of Aquatic Invasive Species across North America:

Overview and Resource Guide

Commission for Environmental Cooperation 2003

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Preface

This paper is a contribution to the Commission for Environmental Cooperation's (CEC) project entitled, "Closing the Pathways of Aquatic Invasive Species across North America." Through this project, the CEC intends to provide its member countries with the information and mechanisms that they need to protect North America's marine and freshwater ecosystems from the adverse effects of invasive alien species (IAS). Ultimately, the CEC hopes to inspire and assist in the development of a North American strategy for preventing and managing the movement of IAS along the pathways by which they are introduced into marine and freshwater environments.

As of January, 2004, the CEC had held three meetings on IAS:

- *Preventing the Introduction and Spread of Aquatic Invasive Species in North America*. 28-30 March 2001, Montreal, Canada (Reaser 2003)
- *Closing the Pathways*[1] *of Aquatic Invasive Species across North America*. 18-19 January 2003, San Diego, California
- Round Table: *An unwelcomed dimension of trade: the impact of alien invasive species in North America*. 4-5 December 2003

The reference materials associated with these meetings can be found on the CEC website[2]. Based on the deliberations at these meetings, the CEC has recommended five priority areas for regional cooperation:

- Identify IAS of common continental concern and their pathways;
- Develop a North American Invasive Species Information Network;
- Develop and distribute tools for raising awareness and empowering decision-makers;
- Identify tools to provide economic incentives to engage the industrial and economic sectors; and
- Create a regional directory of legal institutions and frameworks for the three North American countries.

This paper provides an overview of the status and trends of IAS and their pathways of invasion into the marine and freshwater systems of North America. It is not intended to serve as thorough scientific review, but to provide participants in the CEC's activities with sufficient background to: 1) understand the cause and consequences, as well as status and trends, of biological invasion in North America's aquatic and marine systems; 2) understand the need for bi- and tri-lateral cooperation to prevent and manage introductions of IAS; 3) identify opportunities for such cooperation; and 4) contribute to and support well-informed policy decisions that will help minimize the spread of IAS into and within North America.

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[1] The use of the word "pathway" in this CEC project addresses both "pathways" and "vectors" as used in this paper.
[2] www.cec.org/programs_projects/conserv_biodiv

The following terms and definitions are used[3]:

Non-native species - a species, subspecies or lower taxon, introduced outside its natural past or present distribution; includes any part, gametes, seeds, eggs, or propagules of such species that might survive and subsequently reproduce. These organisms are sometimes called “exotic,” “alien,” or “non-indigenous” species.

Invasive alien species (IAS) – a non-native species whose introduction and/or spread harms or threatens to harm biological diversity, economies, or human health.

Introduction – the movement by human agency, indirect or direct, of a non-native species outside of its natural range (past or present). This movement can be either within a country or between countries or areas beyond national jurisdiction.

Intentional introduction - the deliberate movement and/or release by humans of a non-native species outside its natural range.

Unintentional introduction - all other introductions which are not intentional.

Establishment - the process of a non-native species in a new habitat successfully producing viable offspring with the likelihood of continued survival.

Pathways - the physical means or agent by which IAS are relocated (e.g., hulls of ships and equipment used for water sport; sometimes referred to as vectors) and routes by which IAS are moved from one location to another. Because they follow the patterns and trends of globalization, pathways are ever expanding and changing.

[3] The terminology used to define IAS and describe associated processes is still evolving and can differ considerably among contexts (e.g., countries, ecosystem types, and pathways).

The Problem

Invasive alien species (IAS) are non-native species whose introduction and/or spread harms or threatens to harm biological diversity, economies, or human health. IAS are among the top three drivers of environmental change globally (Mooney and Hobbs 2000, Sala et al. 2000, McNeely et al. 2001) and may soon surpass habitat loss as the main cause of ecological disintegration worldwide (Vitousek et al. 1997, Chapin et al. 2000). There is no doubt that IAS can cause severe ecological damage (Mack et al. 2000); in North America, they have caused harm to approximately half of the species listed under the U.S. Endangered Species Act (Wilcove et al. 1998) and are a contributing factor in 68% of the region's fish extinctions over the past century (Miller et al. 1989). Furthermore, it is clear that the impacts that IAS have on biodiversity and ecosystem services can impede environmental conservation, sustainable development, and economic growth (McNeely 2001, McNeely et al. 2001). Pimentel et al. 2000) estimates that IAS have already cost the U.S. more than $100 billion annually. Even the most well protected natural areas are being invaded worldwide (Chapin et al. 2000, Simberloff 2000a, Parkes et al. 2002, Tye et al. 2002, O'Dowd et al. 2003).

International and national responses to the IAS problem have thus far been inadequate to counter their increasing toll on the environment and society (McNeely et al. 2001, Reaser et al. 2003a). In North America, however, the Commission for Environmental Cooperation (CEC) has made it a priority to provide its member countries with the information and mechanisms that they need to protect the region's marine and freshwater ecosystems from the adverse effects of IAS. Ultimately, the CEC hopes to inspire and assist in the development of a North American strategy for preventing and managing the movement of IAS along the pathways by which they are introduced into marine and freshwater environments.

Aquatic systems have proven particularly susceptible to biological invasion (Claudi and Leach 1999; Lodge 2001). Sala et al. (2000) believe that freshwater systems may be the most IAS-impacted ecosystems globally. The impacts of IAS on marine systems are not as well studied as other ecosystems. However, a growing body of well-document case studies indicates that marine systems, such as coral reefs, are both vulnerable to and are being detrimentally impacted by IAS (e.g., Coles and Eldredge 2002, Eldredge and Carlton 2002, Eldredge and Reaser 2002, Hewitt 2002, Hutchings 2002, Lambert 2002, Paulay et al. 2002, Smith et al. 2002).

Causes

The globalization of trade, travel, and transport is greatly increasing the rate at which organisms are transported around the world, as well as the number and diversity of species being moved (McNeely et al. 2001). A wide variety of ecological and socio-economic factors influence the ability of a non-native organism to establish, spread, and cause harm (Table 1). In most cases, the translocation of biological organisms does not present a problem; either the organisms do not survive in their new conditions without deliberate care or their populations are small and easily managed (Mack et al. 2000).

However, about 1 out of every 1000 organisms is introduced into a new environment where it thrives and becomes invasive (The "10s" rule; Williamson and Brown 1986, Williamson 1996)[4]. *Intentional introductions* of IAS occur when non-native organisms are introduced into the natural environment for specific reasons (e.g., aquaculture production or "freeing" of pets and research subjects) and later cause harm. *Unintentional introductions* take place when harmful non-native species are imported as "hitchhikers" on people and products and disperse into the environment or when they escape from captivity (McNeely 2001).

IAS have been introduced into every country and every country facilitates biological invasions: some request goods and services from afar, while others supply products to meet these demands. In 2001, world import and export markets were valued at US$6270 billion and US$6155 billion, respectively (World Trade Organization 2002). Increasingly, people are traveling the world for business and pleasure. Commercial services (including travel, transport, and other services) totaled US$1443 billion in imports and US$1458 billion in exports worldwide in 2001 (World Trade Organization 2002). Despite good intentions, developed countries occasionally facilitate the introduction of IAS to other countries through development assistance programs, military operations, famine relief projects, and international financing (Reaser et al. 2003a). Land-use and climate change can also facilitate biological invasion by making habitats more challenging for native species and more hospitable to IAS (Mooney and Hobbs 2001). Because disturbed habitats often favor rapid colonizers, they are particularly vulnerable to the invasion of non-native species (Mack et al. 2000).

Aquatic and Marine Pathways

In large continental countries, organisms sometimes cause harm when they are relocated within national borders. In North America, some of the earliest known introductions of this kind occurred in the late 1800s when fish were transported from coast to coast (Benson 1999). For example, crayfish and other freshwater organisms native to the southeastern United States have been relocated to the western United States to serve as game species or forage for game species. In many instances, these newcomers have proven to be voracious predators, competitors, and/or vectors of disease and parasites (Reaser et al. 2003a). The long-term result has been a significant reduction in the freshwater biodiversity of western watersheds (Fuller et al. 1999, Claudi and Leach 1999, Carlton 2001). Nevertheless, North America's most challenging IAS problems occur when non-native species are brought into the countries of the region (e.g., Fuller et al. 1999, Carlton 2001). In the Great Lakes Basin alone, at least 139 non-native species from other regions of the world (esp. Baltic Sea) have been established since the early 1800s (Glassner-Shwader 1998).

Approximately half of the non-native animal species and more than 80% of the plants introduced into freshwater systems in the U.S. originated outside of North America (Benson 1999). The number of species introductions into freshwater systems of Canada

[4] In North American freshwater systems a rule of "twos" or "threes" might be more accurate (Minns and Cooley 1999).

and Mexico are lower, but still significant (Contreras-Balderas and Escalante 1984, Crossman 1991). Evolutionarily isolated freshwater systems throughout North America are particularly vulnerable to the impacts of IAS (Magnuson 1976). The rate of introduction of marine species in U.S. waters (and likely the Canada and Mexico) has exponentially increased over the last 200 years and continues to rise. Between 1961 and 1995, a new species was established in the San Francisco Bay on average every 3.5 months (Carlton 2001).

In freshwater and marine systems, intentional introductions of potentially invasive non-native species can result from the stocking of fish and game, as well as forage for these species; releases of live bait, pets, plants and animals from aquaria and garden ponds, research subjects, biological control agents, food fish; and releases from aquaculture and mariculture facilities (Fuller et al. 1999, Lodge 2000, Aquatic Nuisance Species Task Force 2003). Fishing in reservoirs is currently a $28-billion-a-year industry in the U.S. (American Sportfishing Association 2001, cited in Heinz Center 2002). More than 200 fish species have been stocked in the North American waters for sportfishing (Benson 1999). Gamefishes in particular are almost always carnivorous and their introductions can have cascading effects throughout the aquatic community (e.g., Li and Moyle 1999). A review of intentional introductions of non-native species into freshwater systems of North America can be found in Crossman and Cudmore (1999a), as well as Dextrase and Coscarelli (1999).

Potentially invasive non-native species can be unintentionally introduced into aquatic and marine systems by boats (e.g., hull fouling and ballast water), when recreational equipment (e.g., boats, fishing and scuba gear) contaminated with non-native organisms is moved from one body of water to another, when intentionally introduced species carry non-native pathogens or parasites, or when animals escape from captivity and take up residence in the natural environment (Fuller et al. 1999; Aquatic Nuisance Species Task Force 2003). Under some circumstances, the removal of dams might release IAS formerly held in reservoirs into the associated watershed (Heinz Center 2003).

Table 2 provides a list of common *pathways* for biological invasion into freshwater and marine systems in North America, as well as examples of specific introductions via these pathways into Canada, the United States, and Mexico. The pathways of introduction are diverse and follow the patterns and trends of regional transport, trade, and travel. Benson (1999) includes tables summarizing the patterns of introduction of non-native species into the freshwater systems of the United States. For Mexico, a summary of non-native species introductions can be found in Contreras-Balderas and Escalante (1984), and Contreras-Balderas (1999) provide an annotated checklist of non-native species and their pathways of introduction. Crossman (1991) reviews the introduction of non-native species into freshwater systems of Canada. Carlton (2001) provides an overview of marine pathways for IAS introduction into the United States in particular, although many of the findings are also relevant for Mexico and Canada.

Rarely are human activities or their consequences limited to a single location within aquatic or marine environments. Once introduced into marine and freshwater systems, IAS can enter other parts of the watershed and interconnected waterways in three ways: 1) people can relocate the organisms via the same types of pathways mentioned above (and in Table 2), 2) barriers isolating IAS in one waterway can be overcome due to flooding or the purposeful releases of water for various natural resources management purposes (e.g., canal and reservoir management), and 3) some IAS (e.g., various frog, crayfish, insects, and plant species) can self-disperse throughout the system.

Consequences

One of the most significant barriers to the development and implementation of policies and programs that effectively prevent the movement and introduction of IAS has been the paucity of reliable quantitative information on their ecological and socio-economic impacts. These data are needed to help decision makers understand the scale and complexity of the problem and to enable stakeholders to determine the costs versus the benefits of their actions (Perrings 2000, McNeely et al. 2001, Pimentel 2002, Reaser et al. 2003a,b).

The following section provides case studies of ecological and socio-economic impacts of biological invasions into marine and freshwater systems of North America. Whenever possible, information on the type of organism(s), locations, pathways, and socio-economic impacts has been provided. While the impacts of IAS are typically classified as environmental, economic, and human health-related, these categories should not be regarded as mutually exclusive. IAS often have synergistic and cascading impacts, influencing numerous aspects of environmental and human well-being over long periods of time. The impacts of IAS on any ecosystem can in fact (Reaser and Meyerson 2003):

- Occur at any level or across levels of biotic organization (see Table 3);
- Occur in any type of ecosystem and at the interface of ecosystems;
- Result from direct and/or indirect influences of the IAS;
- Occur immediately or years after the introduction (i.e., only after prolonged lag time since arrival);
- Persist for the short- or long-term;
- Act synergistically to magnify or amplify other impacts on the system (including habitat destruction, see Sala et al. 2000);
- Be so subtle that they are not readily perceived, but be cumulative over time; and/or
- Interact and have cascading effects (i.e., effects that trigger additional effects throughout the system).

Case Studies

Case study: Numerous species of aquatic weeds have entered North American aquatic systems through a wide variety of pathways (Table 2). Hydrilla (*Hydrilla verticillata*) and Eurasian water-milfoil (*Myriophyllum spicatum*), for example, have dramatically altered aquatic systems (e.g., changing sedimentation rates, oxygen and light levels) and impeded boating, fishing, and other recreational activities (Benson 1999). Aquatic invasive plants are particularly a problem in the southeastern U.S., and the U.S. spends approximately US$100 million annually to control aquatic invasive plants (U.S. Congress 1993). California has expended nearly US$1 million per year for the last 20 years to remove hydrilla from freshwater systems and Florida spends more than $14 million annually in control efforts (Glassner-Shwayder 1998)[5].

Case study: Multiple species of mosquitoes (e.g., *Aedes aegypti*, *A. albopictus*, *A. bahamensis*) have entered and become establish in North America's freshwater systems, particularly in the southeastern U.S. Most have likely come in with used tires, but they are also known to be shipped with commodities such as lucky bamboo (Chester Moore, personal communication). Some of these species are known disease vectors (e.g., malaria, dengue fever, West Nile virus) and substantial sums of money are being spent on prevent and control programs. (McCann et al. 1996, Meyerson and Reaser 2003b).

Case study: The zebra mussel (*Dreissena polymorpha*) entered the U.S. in the early 1990s, most likely through ballast water. In just a few years, the native mussels of Lake St. Clair disappeared (Nalepa 1994), and shifts in native fish and aquatic plant assemblages, as well as water quality, have occurred where the zebra mussel has established (Napela et al. 1999). The zebra mussel often occurs in large groupings and clogs water intake valves. As of 1995 it had already cost 339 facilities more than US$69 in expenses for prevention and remediation (O'Neill 1996). Using just market values, Leung et al. (2002) estimate that society could benefit by spending up to US$324,000 annually to prevent the invasion of zebra mussels into a single lake hosting a power plant. However, in 2001, the U.S. Fish and Wildlife Service spent only US$825,000 to manage all aquatic IAS in all U.S. lakes.

Case study: The sea lamprey (*Petromyzon marinus*) invaded Lake Erie and the upper Great Lakes through the Welland Canal. This species, in association with the predacious alewife (*Alosa pseudoharengus*) which entered the Great Lakes after the completion of the Welland and Erie canals, caused the decline and near extinction of native lake trout (*Salvelinus namaycush*) in the Great Lakes. The U.S. Department of State spends approximately US$10 million annually to reduce the impact of the sea lamprey on Great Lakes fisheries. It has been estimated that, if not properly controlled, the sea lamprey could cost the Great Lakes region more than US$500 million annually in lost fishing revenues and indirect costs (U.S. Congress 1993).

Case study: In 1991, a strain of cholera bacteria was transported via ballast water into Mobile Bay, Alabama where it threatened the Gulf of Mexico shellfish industry and human health. Health alerts and the temporary closure of oyster beds caused a decline in regional consumer demand for a wide variety of shellfish (Glassner-Shwayder 1998).

[5] For a survey of literature on the economic impact of aquatic weeds, see http://www.aquatics.org/pubs/economics.htm

Recently, mariculture fisheries in the Gulf of Mexico have also suffered from shrimp viruses (Carlton 2001).

Case study: The Chinese mitten crab (*Eriocheir sinensis*) was intentionally introduced into the San Francisco Bay in 1992 and soon became abundant (Carlton 2001). It burrows into river banks and dikes weakening shoreline structures, blocks fish screens (Cohen and Carlton 1997), and is host to the oriental lung fluke, a parasite that can affect humans and other mammals (Glassner-Shwayder 1998). Mitten crab control and research in California cost the U.S. federal government US$1 million in 2000-2001 (Carlton 2001).

See Moyle (1986) and Claudi and Leach (1999) for a review of IAS in freshwater systems of North America, as well as Taylor et al. (1984) and Fuller et al. (1999) for a review of non-native freshwater fishes in the United States. A detailed review of the status, pathways, and ecological and economic impacts of IAS introduction of IAS into aquatic systems in Florida can be found in McCann et al. (1976, 1996). See Carlton (2001) for a review of introduced species in U.S. coastal waters and Goldburg et al. (2001) for a review of the environmental impacts of mariculture in the United States. See Moyle (1986) for a historical perspective on freshwater and marine introductions in North America.

Addressing the Problem

The vulnerability of freshwater and marine ecosystems to the impacts of IAS has led some resource managers to consider the protection and restoration of these systems an impossible task. However, there are a growing number of examples of successful IAS eradication and control programs in freshwater and marine environments (Wittenberg and Cock 2001), and greater awareness of the problem is increasing the capacity of countries to prevent the movement and introduction of IAS (McNeely 2001).

In general, the strategies that any government needs to have in place in order to minimize the impacts of IAS are well known. The following section defines the goals and outlines the general processes for IAS prevention and management.

Goals for addressing the problem of IAS include:

Prevention: Keeping an IAS from being introduced into a new ecosystem. Ideally, this usually means keeping non-native organisms from entering a new country.

Early Detection: Locating IAS before they have a chance to establish and spread. This usually requires effective, site-based inventory and monitoring programs.

Eradication: Killing the entire population of IAS. Typically, this can only be accomplished when the organisms are detected early.

Control: The process of long-term management of the IAS population size and distribution when eradication is no longer feasible.

Control and eradication methods can take one or more of three forms (see below). Integrated pest management (IPM) is their combined application:

(i) *Mechanical Control*: The physical removal of organisms – pulling aquatic weeds or hunting nutria (*Myocastor coypus*), for example. The process requires a long-term investment of human resources.

(ii) *Chemical control*: Using chemicals to kill organisms – poisons for wildlife and herbicides for plants, for example. The processes can be quite costly and typically requires repeated applications. Chemical control is rarely an option in open water systems.

(iii) *Biological control*: The introduction of a highly specific predator, parasite, or pathogen that will attack the IAS. This process is not likely to result in eradication of the organism but often can reduce the population of the IAS to tolerable levels. The initial costs associated with research and development may be high, but the long-term costs once applied are low and relatively little maintenance is required.

Restoration: The process of re-establishing natural populations and ecosystem functions. In theory, restoration increases the ecosystem's resistance to future invasions. For discussion on IAS resistance issues, see Mueller-Dombois (1981), Loope and Mueller-Dombois (1989), Simberloff (1995, 2000), and Chapin et al. (2000). However, once IAS have established within an ecosystem, they can indefinitely impede the ability of the ecosystem to return to its pre-invaded state. For example, due to their stabilizing influence on river banks, large woody plants (e.g., *Tamarisk* sp.) can prevent a channel from resuming its former course (Shafroth et al. 2002).

These goals are best accomplished through a strategic, holistic approach that incorporates the following processes:

- Risk assessment and risk management
- Research
- Inventory and monitoring
- Education and outreach
- Policy and regulation
- Information management
- International cooperation and capacity building

International cooperation and capacity building are crucial, as typically IAS are an international problem. However, these processes are probably the "weakest link" in any country's efforts to minimize the spread of IAS (Reaser et al. 2003a).

The following resources provide guidance for developing and implementing effective, strategic programs for the prevention, eradication, and/or control of IAS.

Several of them provide case studies or provide suggestions for overcoming socio-political, financial, scientific, technical, and technological challenges to the implementation of IAS prevention and management programs. Table 4 provides additional guidance and resources that can help the CEC and other stakeholders minimize the impacts of IAS on freshwater and marine ecosystems.

Global

- *Guidelines for the Prevention of Biodiversity Loss Caused by Alien Invasive Species* (IUCN 2000)[6].

- *Guiding Principles for the Prevention, Introduction and Mitigation of Impacts of Alien Species that Threaten Ecosystems, Habitats or Species* (Convention on Biological Diversity Decision VI/23)[7].

- *Global Strategy on Invasive Alien Species* (McNeely et al. 2001).

- *A Guide to Designing Legal and Institutional Frameworks on Alien Invasive Species* (Shine et al. 2000). Includes information on agreements relevant to freshwater and marine ecosystems generally, as well as regionally.

- *Review of the Efficiency and Efficacy of Existing Legal Instruments Applicable to Invasive Alien Species* (Convention on Biological Diversity 2001).

- *Code of Conduct for Responsible Fisheries* (Food and Agricultural Organization 1995).

- *Invasive Alien Species: A Toolkit of Best Prevention and Management Practices* (Wittenberg and Cock 2001). Includes case studies specific to freshwater and marine ecosystems.

- *Invasive Species and Wetlands*. (Howard 1999).

- *Turning the Tide: Eradication of Invasive Species* (Veitch and Clout 2002). Proceedings of the International Conference on Eradication of Island Invasives. Exclusively focused on island issues.

- *Results of an Experts Consultation on the Ecological and Socio-economic Impacts of Invasive Alien Species on Island Ecosystems* (Meyerson and Reaser 2003a).

- *Invasive Species: Vectors and Management.* (Ruiz and Carlton 2003).

Regional

- *Invasive Species in the Pacific: A Technical Review and Draft Regional Strategy*.

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[6] http://www.issg.org/IUCNISGuidelines.html#Guidelines.
[7] http://www.biodiv.org/decision/defaults.asp?lg=dec=VI/23.

(Sherley 2000).

- *Introduced Species in U.S. Coastal Waters*: *Environmental Impacts and Management Priorities* (Carlton 2001).

Marine Aquaculture in the United States: Environmental Impacts and Policy Options. (Goldburg et al. 2001).

For further information on specific laws and voluntary codes of conduct relevant to IAS in freshwater and marine systems of North America, see Dextrase and Coscarelli (1999), Lodge et al. (2000), Carlton (2001), and the website of the National Invasive Species Council[8].

Any plan to eradicate or control IAS in freshwater and marine ecosystems needs to consider the potential impacts of the proposed actions on those ecosystems and the people that depend upon them. If undertaken without an adequate consideration to ecosystem linkages, eradication and control programs can create additional problems and lose their necessary public and institutional support as a result. For example, if not species-specific or properly handled and applied, some pesticides can threaten animal (wild and domestic) and/or human health. And, although purposeful introductions of organisms for biological control have led to notable successes in controlling IAS, biocontrol agents have occasionally become invasive (Meyerson and Reaser 2003a).

Conclusions

The process of biological invasion is complex and fraught with uncertainties. It is, thus, a challenge for ecologists, economists, and other scientists to develop and implement rigorous risk analysis frameworks and environmental impact assessments for IAS. Furthermore, because the issue of IAS is new to many sectors and governments, there is a paucity of data to incorporate into appropriate analyses. For these reasons, it can be very difficult to project the vulnerability of ecosystem to IAS, as well as to determine the impacts that IAS may have had or that may be in progress. Nevertheless, studies that are available lead experts to conclude that IAS are now among the most significant drivers of population declines and species extinctions in freshwater ecosystems and threats are increasing for marine ecosystems as well. Clearly, IAS can also have significant socio-economic impacts either directly (e.g., on human health) or indirectly through their effects on ecosystem goods and services. The invasion of non-native species is a consequence of human activities and an issue that affects all sectors of society. People thus need to be recognized as both the facilitators of the problem and the means by which solutions can be achieved (McNeely 2001).

The response measures needed to prevent and minimize the impacts of IAS on freshwater and marine ecosystems are generally known. However, all of the countries of North America lack scientific and technical information, infrastructure, and human and

[8] http://www.invasivespecies.gov

financial resources necessary to adequately address the problems caused by IAS. The patterns and trends of invasion into North America have and will continue to follow the patterns and trends of international commerce and the movement of people into and within the region. Furthermore, the process of biological invasion and the severity of its consequent impacts are likely to be facilitated by land use and climate change.

Although the prevention, eradication, and control of IAS in freshwater and marine ecosystems present scientific, political, and ethical challenges, the problem can be dramatically reduced through concerted action. The CEC's stakeholders need to be made aware of the problem and motivated to address it. Scientifically-based information and effective tools need to be provided to regional policy makers and resource managers so that well-informed decisions can be enacted. Co-operative programs need to be forged among the three governments and other institutions to enable the problem to be addressed in a strategic, holistic, and timely manner. It also important for the governments of North America to cooperate with and raise the capacity of their trading partners to prevent the movement of IAS into the region (Reaser et al. 2003).

No program to minimize the spread and impact of IAS within North America will be successful, however, unless it effectively addresses the factors that ultimately drive invasion processes. IAS are a by-product of human values, beliefs, and behaviors. They are a symptom of a society that is choosing immediate gains over long-term, irreconcilable losses. The governments of North America must recognize that the way in which they choose to conduct business and measure standards of living will either magnify or minimize the problem (Reaser 2001).

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Table 1. Ecological and Socio-economic Factors that Influence the Risk of Introduction, Establishment, and Spread of IAS in Freshwater and Marine Ecosystems.

Notes: This table provides examples of relevant factors and is not an exhaustive list. Each species and ecosystem will be influenced by a unique set of factors, many of which will be inter-related. Many of the ecological and socio-economic factors listed can contribute to or result from environmental disturbances. This table was first published in Reaser and Meyerson (2003).

Factors	*Introduction*	*Establishment*	*Spread*
Ecological	Species vagility or transportability (including ability to survive transit)		Species vagility or transportability
	Ability to escape into the environment (unintentional introductions)	Climate (and the stochasticity within climate which is weather)	Climate (and the stochasticity within climate which is weather)
		Resource (food, habitat, etc.) availability	Resource (food, habitat, etc.) availability
		Ability to avoid predation, competition, pathogens and parasites	Ability to avoid predation, competition, pathogens and parasites
		Ability to produce viable offspring	Ability to produce viable offspring
		Ability to establish mutualisms	Ability to establish mutualisms
Socio-economic	Demand for goods and services (esp. imports)	Demand for goods and services (i.e. cultivation or animal husbandry)	Demand for goods and services (i.e., tendency for cultivation or animal husbandry)
	Modes, frequency, capacity and, routes, along pathways (Table 2)	Existence of effective IAS early detection programs	Types, routes, timing of pathways (Table 1)
			Timing of IAS detection and response
			Methods used for eradication or control, as well as timing and scale the response to invasion

Table 2. Common and Likely Pathways for the Introduction of Invasive Marine and Freshwater Species in North America.

Note: See Carlton and Ruiz (2003) for a review of issues concerning IAS pathways.

Vector	***Means of Introduction***[9]	***Examples in NA***
Aquaria (Pets)	1. (I/U) Aquaria plants and pets escape/released into the environment 2. (U) Pathogens associated with aquaria plants/pets escape into the environment or impact humans	1.Hydilla (*Hydrilla verticillata*), Brazillian waterweed (*Egeria densa*), dotted duckweed (*Spirodela punctata*) have been introduced in various locations in North America (Benson 1999). Introduced grass shrimp (*Neocaridina denticulate sinensis*) compete with native shrimp in Hawaiian streams (Staples and Cowie 2001). The Mediterranean sea weed (*Caulerpa taxifolia*) was apparently dumped into a lagoon near San Diego (Anderson and Keppner 2001). 2.The red-eared slider (*Trachemys scripta elegans*) was popular in the pet trade until concerns arose over transmission of salmonella (Staples and Cowie 2001). 1-2. See review in Courtney (1999), Crossman and Cudmore (1999b), and Mackie (1999; molluscs).
Aquaria (Public)	1. (I/U) Display organisms escape/released into the environment 2. (I/U) Organisms transported with display species escape/released into the environment	
Bait	1. (I/U) Live bait and/or its live packaging (e.g., seaweed) released/escaped into the environment 2. (U) Organisms associated with live bait/ packaging released into the environment with escaped/release of bait/packaging	1.Numerous species of crayfish, for example rusty crayfish (*Orconectes rusticus*) and red swamp crayfish (*Procambarus clarkii*) been moved outside there native ranges as bait/forage and negatively impacted numerous aquatic species (Capelli 1982, Lodge 2000) and can carry serious human diseases (Staples and Cowie 2001). 2. The European shorecrab (*Carcinus maenas*) entered the San Francisco Bay when seaweed associated with bait worms from Maine was discarded (Cohen et

[9] I = intentional introduction; U = unintentional introduction

		al. 1995). 1-2. See Goodchild (1999) and Litvak and Mandrak (1999) for a review.
Biological Supply	1. (I/U) Plants and animals intended for scientific study and their associated organisms released into the environment	
Boats & Ships	1. (U) Organisms released when ships discharge ballast water 2. (U) Organisms attached to interior or exterior structures and equipment (e.g., anchors)[called "fouling organisms"] released into the environment 3. (U) Organisms contaminating cargo (e.g., wood products) released into the environment	1. Alligatorweed (*Alternanthero philoxeroides*), water-lettuce (*Pistia stratiotes*), zebra mussel (*Dreissena polymorpha*) (Benson 1999). See Carlton (1999), Mackie (1999b; mollusks), and Whitby et al. (1999; mibrobes) for overview. 2. Likely cause on introduction on the soft coral (*Carijoa riisei*) in Hawai'i which threatens reefs (Staples and Cowie 2001). See Meyerson and Reaser (2003a) for a Call to Action for hull fouling. 1-2. See Wiley and Claudi (1999) for a review.
Canals	1. (U) Movement of organisms through canal systems (e.g., irrigation, sea level, or lochs)	1. Sea lamprey (*Petromyzon marinus*) caused decline and near extinction of native lake trout in the Great Lakes and alewife (*Alosa pseudoharengus*) accelerated the decline of some species through competition and predation (Benson 1999). See Crossman and Cudmore (1999c) and Mills et al. (1999) for a review.
Dams	1. (U) Release of organisms upstream and/or downstream when dams are removed	See discussion in Graf (2003), Freeman et al. (2002)
Drilling Platforms	1. (U) Organisms attached to structures and equipment relocated or swim freely alongside during transport 2. (U) Organisms released when ballast water is discharged	
Dry Docks	1. (U) Organisms attached to structures relocated 2. (U) Organisms released when ballast water is discharged	
Education	1. (I/U) Organisms used for classroom study escape/released into the environment 2. (I/U) Organisms associated with study specimens escape/released into the environment	
Floating Debris	1. (U) Organisms moving on garbage (e.g., bottles, nets, packaging) relocated	
Fisheries & Game (recreational)	1. (I/U) Release of organisms for sporting purposes, including organisms intended to serve as their forage. Also includes	1. Brown trout (*Salmo trutta*) have had a negative impact on several species of native trout,

	associated organisms (e.g., pathogens that are unintentionally released) 2. (U) Escape of fisheries stocks (incl. shellfish), game species, and their associated organisms during transport, or during transplantation and holding for growth or refreshening (rejuvenation) 3. (U) Introduction of organisms associated with relocated fishing gear (e.g, lines, nets, floats, trawls, dredges) 4. (I/U) Introduction of aquatic plants and associated material to enhance habitat fisheries/game stocks 5. (U) Release of organisms (esp. pathogens and parasites) from waste produced by processing of fish/game	including the golden trout (*Oncorhynchus aquabonita*) in California (Courtney and Williams 1992, Dextrase and Coscarelli 1999). American bullrogs (Rana catesbeiana) have been introduced out of their native range into other parts of North America where they have had profound impacts on native species, including endangered species (Orchard 1999). Nutria (*Myocastor coypus*) were introduced into North America for fur-farming. They destroy aquatic ecosystems[10]. Deadly parasitic fish leeches (*Myzobdella lugubris*) have been introduced into freshwater systems in Hawai'i along with exotic fish (Staples and Cowie 2001).
Food (aquaculture & mariculture)	1. (U) Escape of fisheries/game stocks and their associated organisms from holding facilities/transport containers 2. (I/U) Release of fisheries/game by private citizens for propagation and harvest. Includes associated organisms. 3. (I/U) Organisms associated with food packaging (e.g., seaweed) released into the environment when packaging is discarded	1. Numerous species, common carp (*Cyprinus carpio*) and blue tilapia (*Orechromis aureus*), for example (see Courtney and Williams 1992, Dextrase and Coscarelli 1999) 2. The Northern snakehead (*Channa argus*) caused a media frenzy and rapid management response when introduced into a pond in the state of Maryland (US)[11]. In Hawai'i, the Asiatic freshwater clam (*Corbicula fluminea*) was introduced into Hawai'i where it clogs irrigation lines and broken shells in taro cut farmers fee and the Tahitian prawn (Macrobrachium lar) carries a parasite that can cause deadly encephalitis in humans (Staples and Cowie 2001). 1-3. See Patrick (1999), Mackie (1999c; Molluscs), and Golburg et al. (2001; US) for a review.
Gardening (esp. ponds, bogs)	1. (I/U) Introduction of plants and animals and their associated organisms into ornamental water gardens	1. Water hyacinth (*Eichhornia crassipes*), parrot feather (*Myrioplhyllum aquaticum*), water-cress (*Nasturtium officinale*), torpedo grass (*Panicum repens*) (Benson 1999). See review in Courtney (1999)

[10] http://www.invasivespecies.gov/profiles/nutria.shtml
[11] http://www.invasivespecies.gov/profiles/snakehead.shtml

		and Crossman and Cudmore (1999b).
Pest Control	1. (I/U) Release of organisms as biological control agents. Includes their associated organisms.	1. Mosquitofish (*Gambusia affinis*) and grass carp (*Ctenopharyngodon idella*) have occurred in all three countries of North America (Dextrase and Coscarelli 1999). The cane toad (*Bufo marinus*) has been introduced into Hawai'i to control crop pests (Staples and Cowie)
Restoration	1. (I/U) Introduction of organisms (esp. plants and fish) and their associates for habitat restoration/conservation purposes 2. (U) Release of IAS associated with re-introduced or established native species	1. Purple loosetrife (*Lythrum salicaria*) (Benson 1999)
Water Diversion Projects (see also canals and dams)	1. (U) Movement of organisms into new aquatic system as a result of projects designed to redirect the flow of water	1. Multiple species entered the Great Lakes through the Garrison water diversion project (Wright and Franzin 1999). See Crossman and Cudmore (1999c) and Mills et al. (1999) for a North American review.
Water Sports (see also boats, fisheries, & bait)	1. (U) Introduction of organisms associated with relocated sporting gear (e.g., SCUBA tanks, rafts, inner tubes, surfboards)	

Outline adapted by Jamie K. Reaser from Carlton, J. 2002. Introduced Species in U.S. Coastal Waters: Environmental Impacts and Management Priorities. Pew Oceans Commission.

Table 3. Components of Biodiversity That Could Be Affected by IAS[12]

Components of Biological Diversity

Levels of Biodiversity	**Composition**	**Structure (temporal)**	**Structure (spatial: horizontal and vertical)**	**Key Processes**
Genetic diversity	• Minimum viable population (avoid destruction by inbreeding/ gene erosion) • Local cultivars • Living modified organisms	• Cycles with high and low genetic diversity within a population	• Dispersal of natural genetic variability • Dispersal of agricultural cultivars	• Exchange of genetic material between populations (gene flow)
Species diversity	• Species composition, genera, families, etc., rarity/ abundance, endemism/ exotics • Population size and trends • Known key species (essential role) • Conservation status	• Seasonal, lunar, tidal, diurnal rhythms (migration, breeding, flowering, leaf development, etc.) • Reproductive rate, fertility, mortality, growth rate • Reproductive strategy	• Minimal areas for species to survive • Essential areas (stepping stones) for migrating species • Niche requirements within ecosystem (substrate preference, layer within ecosystem) • Relative or absolute isolation	• Regulation mechanisms such as predation, herbivory, parasitism • Interactions between species • Ecological function of a species
Ecosystem diversity	• Types and surface area of ecosystems • Uniqueness/ abundance • Succession stage, existing disturbances and trends (= autonomous development)	• Adaptations to/ dependency on regular rhythms: seasonal • Adaptations to/ dependency of on irregular events: droughts, floods, frost, fire, wind • Succession (rate)	• Spatial relations between landscape elements (local and remote) • Spatial distribution (continuous or discontinous/ patchy) • Minimal area for ecosystem to survive • Vertical	• Structuring process(es) of key importance for the maintenance of the ecosystem itself or for other ecosystems

[12] Developed by the Convention on Biological Diversity. See Appendix 4 of Decision VI/7 (Identification, monitoring, indicators and assessments). http://www.biodiv.org/decisions/default.asp?lg=0&dec=VI/7.

			structure (layered, horizonts, stratified)	

Table 4. Guidance and Resources for Preventing and Mitigating the Impacts of IAS on Freshwater and Marine Ecosystems

Note: See the National Invasive Species Management Plan[13] for an overview of prevention and control efforts in the United States.

Guiding Principle[14]	**Guidance/Comments**	**Resources[15]**
1. Precautionary approach	• Raising the capacity of governments to conduct risk analyses and share access to relevant information needs to become a priority	• See FAO (1996). • *Globalisation and IAS*[16] • *Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve*[17,18] • See Li et al. (1999), Kolar and Lodge (2002), Leung et al. (2002) for discussions on risk analysis in aquatic and marine systems of North America.
2. Three-stage hierarchical approach	• Preventative measures are particularly challenging to implement in open freshwater and marine ecosystems because of their connectivity and lack of adequate legal frameworks • Priority needs to be given to preventing the movement of IAS along pathways of invasion (Table 2), including efforts to minimize the movement of IAS within the same country	• See information on pathways in Table 2 • See 13
3. Ecosystem approach	• Thus far, measures to deal with IAS have largely taken a species by species approach	• See 13
4. The role of States	• The governments of North America need to develop within country strategies as well as bi- and multi-lateral strategies within North America and between trading partners in other regions of the world	• See *Thematic Reports on Alien Species*[19]
5. Research and monitoring	• Numerous information gaps	• See 8

[13] http://www.invasivespecies.gov
[14] http://www.biodiv.org/decisions/defrault.asp?lg=0&dec=VI/23
[15] This is not an exhaustive list of resources, but is intended to provide information on the major "gateways" of information and examples of activities specifically directed IAS on islands.
[16] http://odin.dep.no/ud/norsk/publ/rapporter/032121-220009/index-hov006-b-f-a.html
[17] http://hawaiireef.noaa.gov/comment/sdcom/washdc.html
[18] http://www.oceanconservancy.org/dynamic/press/kits/owcKit/nwhi.pdf
[19] Principles developed by the Convention on Biological Diversity. See http://www.biodiv.org/world/reports.asp?t=ais.

	exist for assessing, preventing, and mitigating the impacts of IAS in freshwater and marine ecosystems • There are very monitoring programs for IAS in freshwater or marine ecosystems anywhere in the world • Voucher specimens should be deposited in well-managed collections for future reference	• The Sea Grant program[20] supports research in the North America and works with other regions. Between 1991-2000 the program distributed US$29.3 million in research and education funds (Carlton 2001).
6. Education and public awareness	• Historically, IAS have been seen as only a problem in terrestrial agricultural systems • In 2001-2003, the CEC held two workshops to raise awareness of the causes and multiple consequences of IAS within the region • Education and public awareness needs to have a strong focus on those governing the pathways of IAS introduction • The multi-cultural aspect of the countries of North America needs to be considered when designing education programs meant to influence people's relationships to the environment and IAS in particular	• See 4 • *Guidebook of Introduced Marine Species of Hawaii*[21] • In the United States, the Aquatic Nuisance Species Taskforce (ANSTF)[22] and National Invasive Species Council (NISC)[23] have education and outreach programs • Glassner-Shwayder (1998) for information regarding the Great Lakes • The Sea Grant program[24] has relevant activities in the North America and works with other regions
7. Border control and quarantine measures	• See 2	• See 2
8. Exchange of information	• See 6	• See 6 • *The Global Invasive Species Database*[25] • *Centre for Research on Introduced Marine Pests*[26] • *FishBase*[27]

[20] http://www.nsgo.seagrant.org/
[21] 2002. Hawaii Biological Survey, Bishop Museum. http://www2.bishopmuseum.org/HBS/invertguide/index.htm
[22] http://anstaskforce.gov/
[23] http://www.invasivespecies.gov
[24] http://www.nsgo.seagrant.org/
[25] http://www.issg.org/database/welcome/
[26] http://crimp.marine.csiro.au/
[27] http://www.fishbase.org

		• *Aquatic Invasions Research Database*[28] • *Plants Database*[29] • *North American Biodiversity Information Network (NABIN)*[30] • *Inter-American Biodviersity Information Network (IABIN)*[31]
9. Cooperation, including capacity-building	• The need to overcome the particular challenges faced "free trade" countries such as those in North America makes programs of cooperation particularly important	• Reaser (2003) • *Ramsar Convention on Wetlands* Resolution VIII.18[32]
10. Intentional introduction	• Historically, led to the most significant impacts • All other comments relevant	• All other resources relevant
11. Unintentional introduction	• Currently, likely to have at least as great, if not far greater, impacts • All other comments relevant	• All other resources relevant
12. Mitigation of impacts	• Due to their high-level of vulnerability to IAS, early detection and rapid response are particularly important in freshwater and marine ecosystems • Closed aquatic systems can provide opportunities for eradication and control of species in ways that would not be possible in open freshwater and marine systems • There are a growing number of example of successful eradication, containment, and control of IAS in freshwater ecosystems	• Carlton (2001) • *Turning the Tide: Eradication of Invasive Species* (Veitch and Clout 2002) • See Sherley (2000) • See National Research Council (1992) for a review of restoration of aquatic ecosystems
13. Eradication	• See 12	• See 12 • See also Simberloff (2001)
14. Containment	• See 12	• See 12
15. Control	• See 12	• See 12

[28] http://invasions.si.edu/aird.htm
[29] http://plants.usda.gov/
[30] http://www.cec.org/nabci
[31] http://www.cricyti.edu.ar/INSTITUTOS/iadiza/ojeda/iabin.html
[32] http://www.ramsar.org/key_res_viii_18_e.htm