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A Scientific Review of the Potential Environmental Effects of Aquaculture in Aquatic Ecosystems

Volume V:

Behavioural Interactions Between Farm and Wild Salmon: Potential for Effects on Wild Populations
(Laura K. Weir and Ian A. Fleming)
Overview of the Environmental Impacts of Canadian Freshwater Aquaculture
(C.L. Podemski and P.J. Blanchfield)
A Scientific Review of Bivalve Aquaculture: Interaction Between Wild and Cultured Species
(T. Landry, M. Skinner, A. LeBlanc, D. Bourque, C. McKindsey, R. Tremblay, P. Archambault, L. Comeau, S. Courtenay, F. Hartog, M. Ouellette and J.M. Sevigny)

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FOREWORD

Context

The Government of Canada is committed to ensuring the responsible and sustainable development of the aquaculture industry in Canada. The Minister of Fisheries and Oceans' announcement of the $75 M Program for Sustainable Aquaculture (PSA), in August 2000, is a clear expression of this commitment. The objective of the PSA is to support the sustainable development of the aquaculture sector, with a focus on enhancing public confidence in the sector and on improving the industry's global competitiveness. Ensuring the sector operates under environmentally sustainable conditions is a key federal role.

As the lead federal agency for aquaculture, Fisheries and Oceans Canada (DFO) is committed to well-informed and scientifically-based decisions pertaining to the aquaculture industry. DFO has an ongoing program of scientific research to improve its knowledge of the environmental effects of aquaculture. The department is also engaged with stakeholders, provinces and the industry in coordinating research and fostering partnerships. As a contribution to the Federal government's Program for Sustainable Aquaculture, DFO is conducting a scientific review of the potential environmental effects of aquaculture in marine and freshwater ecosystems.

Goal and Scope

Known as the State-of-Knowledge (SOK) Initiative, this scientific review provides the current status of scientific knowledge and recommends future research studies. The review covers marine finfish and shellfish, and freshwater finfish aquaculture. The review focuses primarily on scientific knowledge relevant to Canada. Scientific knowledge on potential environmental effects is addressed under three main themes: effects of wastes (including nutrient and organic matter); chemicals used by the industry (including pesticides, drugs and antifoulants); and interactions between farmed fish and wild species (including disease transfer, and genetic and ecological interactions).

This review presents potential environmental effects of aquaculture as reported in the scientific literature. The environmental effects of aquaculture activities are site-specific and are influenced by environmental conditions and production characteristics at each farm site. While the review summarizes available scientific knowledge, it does not constitute a site-specific assessment of aquaculture operations. In addition, the review does not cover the effects of the environment on aquaculture production.

The papers target a scientific and well-informed audience, particularly individuals and organizations involved in the management of research on the environmental interactions of aquaculture. The papers are aimed at supporting decision-making on research priorities, information sharing, and interacting with various organizations on research priorities and possible research partnerships.

Each paper was written by or under the direction of DFO scientists and was peer reviewed by five experts. The peer reviewers and DFO scientists help ensure that the papers are up-to-date at the time of publication. Recommendations on cost-effective, targeted research areas will be developed after publication of the full series of SOK review papers.

State-of-Knowledge Series

DFO plans to publish 12 review papers as part of the SOK Initiative, with each paper reviewing one aspect of the environmental effects of aquaculture. This Volume contains 3 papers: Behavioural Interactions Between Farm and Wild Salmon: Potential for Effects on Wild Populations; Overview of the Environmental Impacts of Canadian Freshwater Aquaculture; and A Scientific Review of Bivalve Aquaculture: Interaction Between Wild and Cultured Species.

Further Information

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BEHAVIOURAL INTERACTIONS BETWEEN FARM AND WILD SALMON: POTENTIAL FOR EFFECTS ON WILD POPULATIONS

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EXECUTIVE SUMMARY

Behavioural interactions between farm and wild fish occur at all three stages mentioned in this review. The ability of farm fish to migrate into rivers following escape from aquaculture in the ocean environment leads to interactions during breeding. As not much is known about salmon during the marine phase of their life cycle, it is difficult to assess how interactions between farm and wild fish will ultimately affect wild populations at this stage. However, farm fish show aberrant migratory patterns, most notably that they may disperse into many rivers and thus may affect more than one wild population. The effects of behavioural interactions between farm and wild fish are most evident during breeding. Farm females and mature male parr represent the most likely means of gene flow from farm to wild populations, which are enhanced by earlier ages at maturity of farm fish because of faster growth rate. However, behavioural interactions on the spawning grounds by large males and females, as well as mature male parr, can negatively influence the reproductive success of wild fish. Pure farm and hybrid offspring in the freshwater environment can effectively compete for food and space with wild individuals, and at this life stage the environmental effects of aquaculture rearing are diminished. Maternal effects heavily influence the success of farm offspring at early juvenile stages, and their survival is usually poor compared to wild fish (e.g. Fleming et al. 2000, McGinnity et al. 2003). In addition, farm juveniles are sometimes less successful at evading predators and are not usually dominant over wild fish in natural environments.

While overall trends suggest that farm and hybrid fish may not behave similarly to wild fish, and indeed have lower survival (e.g., McGinnity et al. 2003), variation among studies reflects the context-dependent nature of determining whether farm fish are successful in the wild. Their effect will depend upon a number of factors, including genetic origin, rearing conditions, the number, timing, magnitude and frequency of escapes, and the state of the wild population (Hutchings 1991). Thus, risk assessment will need to focus on those factors mostly likely to generate exposure to the hazard (e.g. escape), and to influence the risk of harm given an escape and the severity of that harm (e.g., Kapuscinski 2005). It will also need to recognize and incorporate various types of uncertainty. A key outcome of this process should be risk reduction planning and implementation.

KNOWLEDGE GAPS

Despite the growing number of studies on the subject, there remain many areas where little is known about the potential effect of farm fish on wild populations. Our report focuses mainly on the trends among studies investigating differences between farm and wild fish. However, significant variation exists among studies, emphasizing that the outcome of interactions between farm and wild fish is likely context-dependent. Some studies show that the outcome of interactions or the magnitude of differences, between farm and wild fish depends upon the farm strain and wild population under comparison (e.g. Einum and Fleming 1997, Weir et al. 2004). This may be due to a lack of understanding of the interaction between the genetic and environmental effects of aquaculture on farm fish. Elucidating the effects of genetics and environment is important to assess how farm fish of different origin may affect specific wild populations. While some studies indicate that genetic changes may be occurring in some wild populations following farm escape (e.g. Crozier 1993, 2000), there is no documented indication that escaped farm fish are directly causing demographic changes in wild populations, although strong inference can be drawn from two whole-river release experiments that indicate this is likely the case (Fleming et al. 2000, McGinnity et al. 2003). From the population demographic perspective, survival and competition at sea of both wild and farm fish is not well known. In addition, our knowledge of the migratory and straying behaviour of escaped farm fish remains rudimentary despite the fact that aquaculture fish are most likely to escape from sea pens and their first interactions with wild individuals is in the adult migratory phase. While there are substantive data regarding interactions between farm and wild fish in artificial or semi-natural environments, field data documenting farm-wild behavioural interactions in rivers are also lacking, most notably for juveniles. Furthermore, although lifetime fitness over one or more generations has been studied (Fleming et al. 2000, McGinnity et al. 2003), the long-term demographic consequences of decreased farm fish fitness relative to wild in the natural environment have yet to be determined. While significant strides have been made in the state of knowledge regarding farm-wild interactions to allow risk assessment, knowledge gaps remain by which associated uncertainty could be reduced. A formal investigation of knowledge gaps, that includes sensitivity analyses of population dynamic/gene flow models, is needed to determine the types of studies to be undertaken to decrease existing uncertainty.

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OVERVIEW OF THE ENVIRONMENTAL IMPACTS OF CANADIAN FRESHWATER AQUACULTURE

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EXECUTIVE SUMMARY

Worldwide, aquaculture operations have been linked to a number of environmental effects that include nutrient enrichment, habitat alteration, and damage to wild fish populations (Gross 1998). A sound scientific understanding of potential effects on the freshwater environment is required if the industry is to grow in an environmentally sustainable fashion. This document provides an overview of the current state of scientific knowledge of the environmental effects of Canadian freshwater aquaculture activities, and identifies areas for future research. The use and potential environmental influence of chemotherapeutants is outside the scope of this review. World literature that is relevant to aquaculture practices occurring in Canada has been included because the scientific literature dealing expressly with Canadian freshwater aquaculture is extremely limited. Substantial changes in husbandry techniques have occurred in the aquaculture industry and these changes have rendered older publications less relevant to the current experience. Wherever possible, we have limited review to peer-reviewed scientific information published within the last decade.

The effects of aquaculture are complex and related to the production and release of organic waste materials as well as the interactions between cultured species and wild species. The bulk of aquaculture waste constitutes fish metabolic wastes and uneaten feed. Factors affecting waste production include fish size, water temperature, and husbandry practices (i.e., feed composition, ration, and feeding methods). The primary environmental concerns associated with waste generation are the potential for nutrient-induced stimulation of local algal blooms and the creation of hypoxic waters and sediments underlying net pens. The primary mechanism through which escaped fish affect native freshwater fish species is competition for limited resources and predation.

The primary constituent of solid wastes is faecal material with waste feed a secondary and much smaller component (Ackefors and Enell 1990). Faecal production, which is difficult to estimate accurately, ranges from 15% to 30% of applied feed (Costello et al. 1996; Cho and Bureau 2001; Bureau et al. 2003). Waste feed estimates, which are rarely reported, constitute between 3–40% of feed (Weston et al. 1996), and anecdotal reports and modeled predictions suggest that waste feed at Canadian farms is currently approximately 5%. There is a gap in data regarding feed waste. Solid wastes settle to the lake bottom where they are consumed by biota (Johansson et al. 1998) or decompose. The greatest accumulation occurs directly under cages (Enell and Lof 1983), suggesting that direct effects on sediments may be geographically restricted. Sediments beneath fish cages generally show enrichment in phosphorus, nitrogen, organic carbon, and zinc

(Cornel and Whoriskey 1993; Kelly 1993; MacIsaac and Stockner 1995; and Troell and Berg 1997). Although there is extensive literature on the benthic effects of marine aquaculture, few recent publications document the benthic effects of freshwater aquaculture. Few peer-reviewed Canadian studies have been published within the last decade. Effects of fish farm wastes may be similar to those associated with other forms of organic enrichment, including decreased taxa richness and diversity, and increased abundance and dominance of organisms resistant to sedimentation and low oxygen availability (Hynes 1963; Johnson et al. 1993). Generally, effects on the sediments and benthic community are restricted to areas directly under the pens and a small distance away. There are no published studies of the recovery of sediments and sediment-associated communities at former Canadian farm sites. In Scottish freshwater lakes, significant alterations of benthic communities below cage sites were still apparent more than 3 years after cessation of farming (Doughty and McPhail 1995). Recovery of lotic systems from fish farm emissions is generally more rapid than in lentic systems, due to the increased dispersion of wastes by water flow and the relatively swift re-colonization by invertebrate drift (Doughty and McPhail 1995).

Dissolved carbon, nitrogen and phosphorus are released into the water column by solubilization from feed and faeces, and through the gill and urinary excretions of fish (Bureau and Cho 1999). Approximately 3 to 10 kg of phosphorus and 39 to 55 kg of nitrogen are released to the environment for every metric ton of fish that is produced (Ackefors and Enell 1994; Cho et al. 1994; Bureau et al. 2003). The majority of phosphorus in farm wastes is lost to sediments as solids (Enell and Ackefors 1991; Phillips, et al. 1993). Nitrogenous wastes, particularly ammonia and urea, form the largest component of the dissolved waste fraction. In general, detectable increases in water column ammonium or ammonia concentrations are reported in the vicinity of cages (NCC 1990) and in receiving waters downstream of land-based facilities (Selong and Helfrich 1998). There are no published reports of concentrations exceeding local water quality guidelines or causing toxicity, and concentrations downstream of land-based facilities are reported to return to background levels 400 m to 12 km from cages (Selong and Helfrich 1998). Cage farms that are located in shallow basins or basins with poor flushing have often reported detectable increases in total phosphorus, while farms located over deep water and with adequate flushing have generally reported no detectable change. Several studies have reported elevated phosphate in waters receiving effluent from land-based farms (Munro et al. 1985; Trojanowski 1990). The decomposition of solid waste accumulations results in the release of labile P to the water column (Kelly 1992; Kelly 1993). During periods of stratification, phosphorus released from sediments into hypolimnetic water will not be available for primary production. There has been little research into the cycling of P between farm waste accumulations and the water column, and the proportion of this P that is eventually available for primary production is unknown. This knowledge would be of significant value to the sustainable management of the industry.

Decomposition of wastes may result in hypoxia in sediments and the water column (Axler et al. 1998) but these outcomes have been rarely reported. Respiration by cultured fish may produce localized reductions in dissolved oxygen concentrations. Reports of reductions in dissolved oxygen concentrations in the vicinity of net pens are variable, but for the most part reductions are minor and of short duration at sites with adequate water exchange (Weston et al. 1996; Demir et al. 2001; Veenstra et al. 2003). A single study in the primary literature has provided limited data about dissolved oxygen profiles at Canadian cage farms in the last decade (Hamblin and Gale 2002), suggesting that the collection and compilation of these data from Canada is required. The biological and chemical oxygen demand of wastes discharged from land-based aquaculture facilities can reduce dissolved oxygen concentrations in lotic waters for short distances downstream, however there are no recent Canadian data.

Stimulation of pelagic bacterial populations may result from nitrogen, phosphorus, and organic carbon in dissolved metabolic wastes and leaching from faeces and feed. A single study investigating effects on pelagic microbial communities reported no increase in the abundance of bacteria near net pens in British Columbia, but significantly higher production (MacIsaac and Stockner 1995). Microbal stimulation has been observed in lotic waters receiving fish farm effluents. For example, river water and sediments downstream of fish farm effluent outfalls in New England showed a significant increase in bacteria abundance and heterotrophic activity when compared to control sites (Carr and Goulder 1990a).

Studies in Canadian lakes have thus far found no differences in chlorophyll a concentrations between control and farm sites (Cornel and Whoriskey 1993) and only localized effects on periphytic algae (MacIsaac and Stockner 1995). In addition to stimulating production in bacterial populations, the release of nutrients from aquaculture facilities can enhance primary production (Kelly 1993). In Finland, fish farm emissions into a lake resulted in significant increases in chlorophyll a and primary productivity and changes in species composition of phytoplankton (Eloranta and Palomaki 1986). Primary productivity in rivers can be stimulated by discharges from land-based facilities (Carr and Goulder 1990b). For example, Munro et al. (1985) reported a significant increase in epilithic algal biomass, chlorophyll a, and changes in algal species composition downstream of hatcheries in several British Columbia streams.

There are no published studies on the effects of freshwater cage-culture operations on native fish communities in Canada. The potential influences of cage operations on native fish communities include trophic alterations and interactions between native and farmed fish. In Canadian freshwaters, cage-culture generally occurs in oligotrophic systems. Nutrient enrichment of oligotrophic systems can lead to greater in-lake growth of native and stocked fish species (Stockner and MacIsaac 1996). Further trophic changes in native fish species can occur through the consumption of waste feed and faeces. Consumption of wastes by biota may reduce the localized effects of waste build-up under pens but there have been no attempts to quantify this mechanism in Canadian ecosystems.

Cage farming inevitably results in a small number of escaped fish, even in the absence of any catastrophic containment failure. The causes of escape include storm damage, collisions, predator attacks, vandalism and accidental losses associated with fish handling. There are no published estimates of the numbers of farmed fish that escape freshwater net pens in Canada. Studies in other countries have estimated that escaped fish within given freshwaters represent approximately 3% to 5% of total cage production (Phillips et al. 1985). Predation and the competition for limited resources are the principal ways that escaped fish can alter the native fish community. The introduction of a new species, or greater numbers of a species already present, into an ecosystem results in some redistribution of resources among the fish community. The characteristics that favor certain species for aquaculture are the same ones that may allow these species to flourish when introduced into foreign water bodies (i.e., generalists with broad environmental tolerances). However, there are no published studies that provide information on the survival of escaped fish in North American freshwater ecosystems.

Species interactions, especially those from the establishment of self-sustaining introduced species or the alteration of indigenous gene pools, are potentially damaging consequences of aquaculture. The escape of farmed salmonids is not necessarily equivalent to the intentional introduction of the same species for management purposes. Agencies responsible for stocking programs may have different selection criteria and thus prefer different broodstock than that selected for farmed fish. The traits selected for aquaculture programs differ significantly from those required for survival in the wild (Bridger and Garber 2002) and divergence in behavior between native and domesticated fish increases with time in captivity. Interactions between escaped farmed fish and wild fish may be very different than interactions between native fish and stocked hatchery fish that have established self-sustaining populations, depending upon how much selection has occurred in the broodstock. The extent of any permanent effect of escaped farmed species depends on successful reproduction in the wild with other farmed, hatchery, or native fish of the same species, or through hybridization with closely related species. Interbreeding of farmed and native fish or farmed and naturalized stocked fish can produce long-term genetic changes in these populations that can be detrimental (McGinnity et al. 1997; Fleming et al. 2000).

KNOWLEDGE GAPS AND RESEARCH PRIORITIES

The environmental effects of marine aquaculture are fairly well documented, but little research has been done on the environmental effects of freshwater aquaculture on Canadian ecosystems, and such studies have been extremely limited elsewhere. Research is needed in the areas listed below.

- There is need for knowledge about the factors that determine the amount of accumulation or the fate of bottom deposits in freshwater ecosystems. Information regarding current waste feed levels and feed conversion ratios at commercial freshwater finfish facilities in Canada is required to support this research.

- Research is needed to determine what effects freshwater aquaculture activities have on benthic habitats and communities. Research is also required to elucidate the relationship between amount of waste deposition and the severity of effects on benthic communities.

- There is a need to research the recovery of sediments and sediment-associated biota after fish farming has ceased.

- Research is needed to develop an understanding of how phosphorus, nitrogen and carbon from aquaculture facilities cycle in the freshwater environment to determine the ecological consequences of these subsidies.

- There is a need for knowledge about the effects of aquaculture wastes on the species composition, biomass, and productivity of primary producers, microbial communities, zooplankton, and native fish populations.

- Research is needed to determine the role of native (and escaped) fish in the removal and dispersion of phosphorus through consumption of waste feed and faeces. This information will improve the ability to estimate the proportion of waste phosphorus that becomes available to affect primary production.

- There is need for knowledge about the effects of all life-history stages of escaped fish in Canadian aquatic ecosystems. Accurate documentation on the number of escaped fish entering freshwater systems and a determination of the degree and outcome of wild, stocked and farmed fish ecological and genetic interactions is needed to support this research.

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A SCIENTIFIC REVIEW OF BIVALVE AQUACULTURE: INTERACTION BETWEEN WILD AND CULTURED SPECIES

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EXECUTIVE SUMMARY

This paper reviews the present state of knowledge on interactions between wild and cultured species within the context of bivalve mariculture in Canada. It also identifies critical knowledge gaps and recommends research to address these gaps. The literature reviewed includes national and international information covering bivalve aquaculture, bivalve restoration, coastal community and ecology. This review is focused on changes affecting the pelagic community, benthic communities, predator species, genetic structures, and the risk of introducing invasive species.

PELAGIC COMMUNITY AND BIVALVE CULTURE INTERACTIONS

Bivalve aquaculture has two main effects on the pelagic community. First, as grazers, bivalves reduce the phytoplankton biomass that may affect the productivity of other grazing species. Limited information is available on this potential effect of bivalve aquaculture, and to date this has only been demonstrated through the use of ecosystem models. The second main effect of bivalve aquaculture on the pelagic community is via the creation of additional habitat in the water column. This is supported mainly by studies on the effect of shellfish restoration, which clearly show that three-dimensional oyster reefs increase the biomass and possibly productivity of several pelagic species benefiting from food availability or predator avoidance. Although these extrapolations may be logical, direct evidence of these interactions is lacking. Research is recommended to address the:

- effect of bivalve aquaculture on phytoplankton production and the grazing community.
- effect of the epifaunal community associated with bivalve aquaculture on the nekton community.

BENTHIC COMMUNITY AND BIVALVE AQUACULTURE INTERACTIONS

Macrobenthic communities affect rates, directions, and pathways of the exchange of energy and materials between the water column and the sediment, and are critical in regenerating nutrients via benthic-pelagic coupling mechanisms. Shifts in benthic community structure and functioning due to biodeposition, physical alterations, and the presence of fouling organisms have been noted in the proximity of bivalve aquaculture operations, however, the extent of these changes are variable. Preliminary data suggest that bivalve aquaculture may increase coastal productivity. Research recommendations are as follows:

- examinations of the influence of bivalve aquaculture on second order relationships such as growth or reproduction of ecologically and/or commercially important species are required;
- knowledge of interactions related to seagrass communities is incomplete; hypotheses addressing growth rates and distributions of seagrass at near-field and far-field scales need to be tested to provide information for resource managers to effectively protect these areas without unnecessarily hindering the development of this burgeoning industry;
- the spatial scale of resolution on which research questions are based needs to be expanded from the lease-scale to address hypotheses of estuary/bay-wide ecological changes to structure, function, and productivity of benthic communities; and
- the potential for cumulative effects (municipal wastewater processing, fish processing plants, agricultural inputs, pulp and paper effluents, etc.) in conjunction with bivalve aquaculture on benthic ecosystem change needs to be assessed.

PREDATOR EFFECTS RELATED TO BIVALVE CULTURE

Research conducted on the relation between predators and bivalve aquaculture is primarily focused on the effect of predators on cultured bivalves. These studies deal mainly with predator control and exclusion methods. These methods have only been investigated on a local scale; their effects from an ecosystem perspective have not yet been addressed. The effect of aquaculture activities on predator densities is not clearly defined; some studies suggest aggregation of predators while others do not. In studies with increased predator densities, it is unclear if this is due to the aggregation of existing populations or an increase of the population. Research gaps that need to be addressed are as follows:

- effect of predator management methods on targeted and non-targeted species.
- effect of bivalve aquaculture on the abundance and distribution of predators.

EXOTIC SPECIES RELATED TO BIVALVE AQUACULTURE

Historically, the introduction and transfer of bivalves for aquaculture has been one of the most important vectors for the introduction of exotic species around the world. This includes the bivalves that have been intentionally introduced into an area for aquaculture purposes – the "target" species, the animals and plants (both macroalgae and phytoplankton) that grow associated with the introduced bivalves – "hitchhiking" species, and diseases. Introduced bivalves are engineering species and may thus have a large influence on many aspects of the ecology of the receiving area. These changes may further facilitate the introduction and growth of other exotic species. Both target and hitchhiking species may have a variety of cascading effects on the receiving ecosystem. However, research on the subject is extremely limited and many such effects are simply theoretical. Ideally, thorough risk assessments should be done before any introductions and transfers are authorized. Quarantine, disinfection, and other protocols may be used to limit risk. However, the efficacy of such treatments is not always great and other measures should be considered. A number of research needs were identified to better understand and minimize the potential role of bivalve aquaculture in increasing the rate of introduction, spread and effect of exotic species. These include the following:

- preliminary risk analyses, as outlined in the section on management issues, should be done to identify knowledge gaps with respect to exotic species in bivalve culture (the cultured bivalves themselves and hitchhiking species);
- directed research should be used to address these knowledge gaps prior to the introduction of bivalves into a system for aquaculture;
- obtain baseline information on the receiving environment (physical and biological) to make predictions with respect to exotics and to evaluate and understand their influence;
- predict the ability of exotics to establish and spread in the receiving environment; and
- predict the effects of exotic species on receiving ecosystems, including interactions with local species, habitat modifications, energy flow, etc.

More information is needed on the requirements and influence of hitchhiking species in the environment. This is particularly true for a number of currently problematic species (e.g., tunicates). Specifically,

- more information is needed with respect to the natural history of most exotic species;
- more information is needed with respect to the relative importance of natural (currents, dispersion rates, etc.) and anthropogenic (stock transfers, processing, hull fouling, etc.) spread of exotic species;
- remedial measures need be developed to mitigate effects and minimize spread; and
- research is needed to understand the links between the presence of exotic species and other stressors in the environment (e.g., eutrophication, climate change, fishing activities, contamination, etc.).