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# Pathway of effects of escaped aquaculture organisms or their reproductive material on natural ecosystems in Canada

# Séquence des effets liés aux organismes d'élevage évadés ou à leur matériel de reproduction sur les écosystèmes naturels au Canada

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## ABSTRACT

The purpose of this document is to provide an overview of the pathways of effects of escaped aquaculture fish (specifically finfish and bivalves) on natural ecosystems in Canada. Escape, survival, dispersal and reproduction of aquaculture organisms have been noted in many areas in Canada, although the scale of escapes in Canada is not known. In general, escaped fish have poor survival, foraging, and reproductive capacity relative to wild conspecifics. However, substantial evidence indicates escaped Atlantic salmon can affect wild conspecifics through juvenile competition resulting in decreased productivity of wild juveniles, and through hybridization resulting in partial transfer of culture phenotypes to wild populations. However, the potential for escaped fish to affect wild populations through predation, marine competition, reproductive interference, and disease transfer pathways has been poorly studied. As well, a high degree of uncertainty exists for other escape species (e.g., marine finfish, other salmonids) due to insufficient evidence and uncertainty regarding extrapolation of existing information from other species and ecosystems. For shellfish, information from outside of Canada suggests that release of farmed bivalves can cause ecological disruptions where they are non-native. Effects are expected to be very context-specific and can be influenced by health of the receiving environment, geography, species and strain types, climate, life-stages released, among others. Overall, there is significant potential for escaped aquaculture organisms to impact natural ecosystems in Canada and this potential can be influenced by numerous environmental and genetic factors. However, the effects escaped fish may have on overall community dynamics or ecosystem function are not yet known.

# RÉSUMÉ

L’objectif du présent document est de fournir un aperçu des séquences des effets des poissons d’élevage évadés (particulièrement les poissons à nageoires et les bivalves) sur les écosystèmes naturels au Canada. On a remarqué dans de nombreuses régions du Canada l’évasion, la survie, la dispersion et la reproduction d’organismes d’élevage, bien que l’étendue des évasions au Canada ne soit pas connue. En général, les poissons évadés ont de faibles capacités de survie, de recherche de nourriture et de reproduction par rapport à leurs congénères sauvages. Cependant, on dispose de suffisamment de preuves pour montrer que le saumon atlantique évadé peut avoir des effets sur ses congénères sauvages au moyen de la compétition entre les juvéniles entraînant une baisse de la productivité chez les juvéniles sauvages et au moyen de l’hybridation entraînant le transfert partiel des phénotypes d’élevage vers les populations sauvages. Cependant, la possibilité que les poissons évadés aient des effets sur les populations sauvages en raison de la prédation, de la compétition maritime, de l’interférence reproductive et des séquences de transfert de maladies n’a pas fait l’objet de nombreuses études. De plus, dans le cas d’autres espèces évadées, il existe un degré élevé d’incertitude quant aux autres espèces évadées (p. ex. poissons de mer, autres salmonidés) en raison de preuves insuffisantes et du caractère incertain des prédictions dérivées des données existantes concernant d’autres espèces et écosystèmes. En ce qui concerne les mollusques et crustacés, des données provenant de l’extérieur du Canada indiquent que les évasions de bivalves d’élevage peuvent causer des perturbations écologiques dans les écosystèmes où elles ne sont pas des espèces indigènes. On s’attend à ce que les effets soient très particuliers au contexte et pourraient être influencés par la santé du milieu récepteur, la géographie, l’espèce et les types de souche, le climat, les étapes du cycle de vie des espèces évadées, entre autres. Dans l’ensemble, il est fort probable que les organismes d’élevage évadés aient une incidence sur les écosystèmes naturels au Canada et que cette possibilité puisse être influencée par de nombreux facteurs environnementaux et génétiques. Cependant, les effets que les poissons évadés pourraient avoir sur l’ensemble de la dynamique communautaire ou la fonction de l’écosystème ne sont pas encore connus.

# INTRODUCTION

In Canada, many wild stocks of finfish and shellfish are dwindling, primarily due to habitat alterations, overfishing, and introduction of non-native species. In the last few decades, there has been increased emphasis on aquaculture production to provide a reliable supply of finfish and shellfish for market, and to relieve pressure on wild populations. The impacts of aquaculture and aquaculture-related activities or stressors on natural ecosystems in Canada are currently under investigation. A national Framework for Aquaculture Environmental Management (FAEM) is being developed to provide the basis for a coherent national approach to support the sustainability of the aquaculture sector in Canada. This framework addresses environmental effects of activities associated with the suspended and bottom culture of finfish and shellfish on four components of Canadian aquatic ecosystems: fish health, fish communities, fish habitat, and water quality. For the purposes of this document, fish refers to finfish, shellfish and other aquatic invertebrates, plankton, and macrophytes, although only effects of finfish and bivalve aquaculture escapes will be addressed. Identified stressors associated with aquaculture that may affect aquatic ecosystems include: alteration in light; release of chemicals and litter; release of pathogens; release or removal of fish; release or removal of nutrients, non-cultured organisms and other organic material; physical alteration of habitat structure; and noise. Identifying Pathways of Effects (POE) of these stressors on aquatic ecosystem components, including development of state-of-knowledge descriptions of stressor-effects, and descriptions of risk, is a key component to developing sustainable aquaculture practices in Canada. The purpose of this document is to identify potential POEs of escaped farmed organisms (i.e., release of fish) on natural aquatic ecosystems in Canada, the strength of scientific literature supporting these POEs, as well as the strength of knowledge regarding exposure and effects of escaped fish, and what knowledge gaps should be addressed to improve our understanding of POEs of escaped aquaculture organisms. This document is not intended to be an inclusive examination of all available literature, but is intended to provide a broad overview of known and potential pathways of effects of escaped aquaculture organisms. Potential mitigation procedures for the escape of aquaculture species are not addressed in this document but will be addressed in a future project.

In 2008, aquaculture products in Canada totalled 144,009 tonnes and were valued at $727 million. Of this, farmed salmon (Atlantic, Coho, and Chinook Salmon) made up the largest proportion (104,0701 tonnes, $621 million, as of 2003 Atlantic salmon comprised approximately 85% of salmon production), followed by mussels (20,006 tonnes, $27 million), oysters (8635 tonnes, $13 million), trout (Rainbow, Brook 5843 tonnes, $28 million), and clams (1629 tonnes, $13 million) (http://www.dfo-mpo.gc.ca/stats/aqua/aqua08-eng.htm, see Table 2 for a complete list of culture finfish and shellfish covered in this document). As bivalves comprise almost all of the current Canadian shellfish aquaculture industry, only bivalves were considered in the shellfish group. While the main focus of FAEM is on net-pen and other non-land-based aquaculture, we have included escapes from hatcheries that supply finfish to be held in net-pens, as these can represent a significant source of escapes. Escape of farmed organisms into Canadian waters has been noted in all major groups of farmed species (e.g., freshwater and anadromous salmonids, non-native shellfish). These escapes can be direct through accidental release of organisms from holding facilities or movement away from areas of introduction, or indirect through release of reproductive material resulting in feral offspring of contained farmed organisms. Since the early 1990's, the potential for these escaped organisms to cause effects to natural ecosystems has been suggested (e.g., Gausen and Moen 1991). In particular, the impacts farmed escapees may have on wild populations, many of which are already threatened, are currently being explored. The majority of this research has focused on the effects of escaped Atlantic salmon on wild conspecifics, primarily in Europe, although effects of escaped Atlantic salmon on native salmonid populations in Eastern and Western North America have received some attention. Little work has examined the impacts of other marine or freshwater finfish and bivalve escapes on natural ecosystems in Canada. Additional information on specific effects of escaped aquaculture organisms can be found in numerous scientific and government reviews (e.g., Jonsson 1997; Gross 1998; Lacroix and Fleming 1998; Youngson and Verspoor 1998; DFO 1999; Huntingford 2004; Naylor et al. 2005; Ruesink et al. 2005; Johannes 2006; Jonsson and Jonsson 2006; Landry et al. 2006; McKindsey et al. 2006; McVicar et al. 2006; Podemski and Blanchfield 2006; Tymchuk et al. 2006b; Weir and Fleming 2006; Ferguson et al. 2007; McKindsey et al. 2007; Cook et al. 2008; Hutchings and Fraser 2008; Thorstad et al. 2008; Trippel et al. 2009).

## OVERVIEW OF AQUACULTURE PRACTICES

Over 60% of Canadian aquaculture products consist of farmed salmon, primarily Atlantic salmon, but also Coho, Chinook, Steelhead, and Sockeye salmon. Salmon are anadromous, and their culture reflects this lifestyle. In general, salmon juveniles are raised in freshwater, land-based hatcheries, and transferred to marine net-pens (Atlantic, Chinook, Coho, and Steelhead) or salt-water land-based facilities (Sockeye) for grow-out to market. The majority of Atlantic salmon production takes place in British Columbia and New Brunswick, with lesser amounts farmed in Newfoundland and Nova Scotia. All production of semelparous Pacific salmon (Coho, Chinook) takes place in British Columbia, although Steelhead production takes place in British Columbia, Saskatchewan, New Brunswick, Nova Scotia and Newfoundland. Other species held in marine net-pens on a small scale are emergent commercial species Atlantic cod (New Brunswick, Newfoundland) and Sablefish (British Columbia).

Rainbow trout is the largest commercial freshwater finfish product in Canada, and is farmed in every province. Other farmed freshwater salmonids include Brook trout and Arctic charr. In general, freshwater salmonid juveniles are raised in hatcheries and then transferred to freshwater net-pens or land-based facilities for grow-out. Freshwater net-pen facilities are used in Newfoundland, Prince Edward Island, Ontario, Saskatchewan, and British Columbia, although the majority are located in the North channel of Lake Huron, Ontario (see Podemski and Blanchfield 2006).

The largest contributor to commercial bivalve production in Canada is the Blue mussel, followed by the Pacific oyster. Other species of significant commercial importance in Canada include the American oyster, Mediterranean mussel, Manila clam, and various scallop species (see Table 2). Stocks of bivalves used and methods for culture differ between Atlantic and Pacific Canada. In Atlantic Canada, the majority of farmed bivalves are native species, and seed supply is taken from local wild stocks, with only minor use of hatchery-produced bivalve seed. In contrast, in Pacific Canada the majority of commercial bivalves are non-native species and seed supply is primarily from hatchery-raised stocks. Grow-out conditions vary between species but take place in the marine environment for all species listed in Table 1. In general, pre-adult and adult organisms are contained in bags, cages, nets, or mesh socks which are placed directly on the beach, on tables, trays or rafts, or hung from long-lines within the marine environment, depending on the species (see McKindsey et al. 2006). The exceptions to these are clam species, and occasionally American oysters, that are directly seeded onto the beach without being enclosed in a culture apparatus.

## OVERVIEW OF RELEASE OF AQUACULTURE ORGANISMS

Data on the scale of escapes of aquaculture species to Canadian waters is considered incomplete, and such data consists primarily of Atlantic and Pacific salmon escapes from net-pen operations (see Table 1). There are two ways that aquaculture species may escape from aquaculture holding facilities to Canadian water systems. The main way is direct escape through accidental release of organisms from holding facilities (potentially in all species), or through migration of farmed organisms away from their area of culture (clam species where adult life stage is mobile. Escape of various finfish species can occur as occasional high magnitude escape events (e.g., >10,000 individuals) from net-pens through major damage to the net-pen or handling errors, or frequent, small magnitude escapes from net-pens or land-based hatcheries due to incomplete containment of the organisms (i.e., “trickle” escapes). Provincial regulations regarding the reporting of known escapes vary among different provinces, although most provinces using marine net-pen culture have some form of reporting regulations. The transparency of the regulations also varies among provinces (i.e., British Columbia allows public assess to summary escape numbers while New Brunswick does not). However, trickle escapes are rarely noted, and quantifying the magnitude of escapes is often unfeasible. The scale of escapes of farmed fish in Canada is not accurately known, and any estimates based on reported escapes are certain to be underestimated. For example, Morton and Volpe (2002) reported 10,826 escaped Atlantic salmon were caught in marine waters in British Columbia over 17 days in 2000, which represented 34% of the total number of reported escapes in 2000 (31,855, see Table 1).

Estimates of average escapes from finfish aquaculture have not been developed for Canadian aquaculture, but recent estimates of escapes from other countries range from <1% to up to 6% of total net-pen production, depending on the country and species considered (Moe et al. 2007; Thorstad et al. 2008; Norwegion-Fisheries-Directorate 2009). Several programs and studies have attempted to understand the scale of Atlantic salmon escapes by monitoring the number of aquaculture escapees in Canadian marine and freshwater systems. In British Columbia, the Atlantic Salmon Watch Program (ASWP) operated by DFO in association with British Columbia Ministry of Agriculture and Lands, monitors reported catches of Atlantic salmon in commercial and sport-fishing industries in British Columbia, Alaska, Washington (http://www.pac.dfo-mpo.gc.ca/science/aquaculture/aswp/index-eng.htm). On the East Coast, DFO has monitored the number of escaped farmed salmon in some rivers in the Maritime Provinces and Newfoundland (see Morris et al. 2008). As well, the Atlantic Salmon Federation (ASF) has monitored wild and escaped farmed Atlantic salmon in the Magaguadavic River, New Brunswick since 1997 (http://www.asf.ca/projects.php?id=7). This river, located in the Bay of Fundy, contains several aquaculture-related hatcheries, and is located near numerous net-pen sites. Since 1992, numbers of returning wild Atlantic salmon to the Magaguadavic River have decreased (from a maximum of >600 to a minimum of <10), while numbers of returning farmed Atlantic salmon have increased (from a minimum 0 to a maximum of >1000, although 2005-2009 saw <20 farmed adult returns). As well, the number of wild smolts migrating downstream were less than those of farmed smolts (from land-based hatchery escapes) from 1996-2004, although wild smolts outnumbered farmed smolts in 2005 (see ASF 2007; Morris et al. 2008). Even with monitoring programs, the numbers of escaped salmon are presumed to be underestimated. Provincial aquaculture Code of Practices have likely helped decrease the proportion of salmonids escaping over recent years due to improved net construction and employee training, among others. However, the number of finfish produced has increased, resulting in continued expected release of salmonids.

Atlantic cod may have greater potential for escape from net-pens than salmon species. While there are no known reports of Atlantic cod escapes in Canada, up to 6% of all Atlantic cod held in net-pens in Norway between 2000-2005 were reported to have escaped, which constituted a higher proportion of production than for Atlantic salmon (Moe et al. 2007). This may be due to propensity of Atlantic cod to bite on and through netting and their willingness to enter openings (Moe et al. 2007).

*Table 1. Number of farmed salmon known to have escaped to the marine environment in British Columbia from 1987 to 2003 (from BCMAL 2006), and Eastern Canada from 1984 to 2005 (from Morris et al. 2008). n/a indicates escape numbers are not available, or none were reported.*

| | British Columbia | | | | Atlantic Canada |
|---|---|---|---|---|---|
| **Year** | **Atlantic** | **Chinook** | **Coho** | **Steelhead** | **Atlantic** |
| 1984 | n/a | n/a | n/a | n/a | 500 |
| 1987 | 0 | 22,422 | 0 | 32,576 | n/a |
| 1988 | 0 | 2000 | 0 | 0 | n/a |
| 1989 | 0 | 390,165 | 0 | 0 | n/a |
| 1990 | 0 | 165,000 | 0 | 0 | n/a |
| 1991 | 6650 | 229,500 | 0 | 0 | n/a |
| 1992 | 9546 | 59,632 | 0 | 0 | n/a |
| 1993 | 9000 | 12,113 | 0 | 0 | n/a |
| 1994 | 62,809 | 2300 | 0 | 0 | 20,000-40,000 |
| 1995 | 51,883 | 5000 | 1000 | 0 | 120,000 |
| 1996 | 13,137 | 0 | 0 | 0 | n/a |
| 1997 | 7,472 | 38,956 | 0 | 0 | n/a |
| 1998 | 80,975 | 1900 | 0 | 0 | 71,300 |
| 1999 | 35,954 | 0 | 0 | 0 | 56,500 |
| 2000 | 31,855 | 36,392 | 0 | 0 | 45,000 |
| 2001 | 55,414 | 0 | 0 | 0 | n/a |
| 2002 | 11,257 | 9098 | 0 | 0 | n/a |
| 2003 | 30 | 9 | 0 | 0 | 6500 |
| 2005 | n/a | n/a | n/a | n/a | >160,000 |
| **TOTAL** | **375,982** | **974,487** | **1000** | **32,576** | **>480,000** |

The other method of escape is indirectly through release of reproductive material in broadcast or pelagic spawners such as bivalves and Atlantic cod. In bivalve species where seed is taken directly from local or nearby wild populations (i.e., most bivalves in Atlantic Canada), such release would be difficult to quantify and would not be expected to impact natural ecosystems as much as non-native species or native species with a genetic history of domestication. However, there are reports of naturalized populations of non-native Pacific oysters, Manila clams, and Blue and Mediterranean mussels in British Columbia, demonstrating the potential for spread of these species through broadcast spawning. As well, Jørstad et al. (2008) found farmed Atlantic cod spawned in Norway while contained in their net-pens, and the consequent larvae released made up 20% of the local wild population. Pelagic or broadcast spawners may release viable gametes and larvae to natural water systems while contained in culture apparatus, potentially including land-based facilities that have direct connection to suitable water systems.

## SCOPE OF REVIEW

### Activities causing stressor (release of aquaculture organisms)

The primary mechanism for farmed finfish to escape is through site and stock management activities (i.e., storm-associated damage, stocking/fish transport, net changing, grading, harvesting, defouling, on site housing, mortality removal, feeding, disease, predator and pest management, etc.). In freshwater and marine net-pen culture of salmonids, reported escapes are generally episodic and have been caused primarily by storm or flood damage, vandalism, predator attacks (seals, sea lions, dogfish, etc.), gear failure, accidents during fish handling or transfer, as well as through industrial equipment issues, specifically boat collisions with net-pens (see Podemski and Blanchfield 2006; Morris et al. 2008). Net tears are the primary cause of large magnitude escapes and can be caused by storms, predator attacks, inadequate maintenance (e.g., chafing of nets from contact with abrasive equipment, deterioration of nets with age, failure to remove dead finfish and debris, etc.), and boat collisions (see BCMAL 2006). On the East coast (including Maine), the known causes of net-pen escapes from 2000-2005 were 30% storms, 30% vandalism, 5% gear failure, 4% boating accidents and 4% handling error (see Morris et al. 2008). In British Columbia, the known causes of net-pen escapes from 1996-2000 were 42% net failures (14% from predator attacks), 39% handling errors, 15% boat collisions, and 4% system failures (see Thorstad et al. 2008). Unaccounted for trickle escapes from both net-pens and land-based hatcheries can also occur through incomplete containment, and through slow-growing finfish slipping through increased mesh size in net-pens (Morton and Volpe 2002). As well, there is historical precedent for illegal release of surplus hatchery smolts in unauthorized attempts to boost wild numbers (see Carr and Whoriskey 2006).

Bivalve species, Atlantic cod, and other pelagic or broadcast spawners can escape indirectly through release of viable gametes that are fertilized in the water column. This can occur when organisms are held in pens, cages, etc. within the water column, or potentially if held in land-based facilities where overflow water is released directly into suitable aquatic environments. In bivalves where larval phases represent the primary dispersal phase, this may result in farmed populations establishing in bays and estuaries beyond the aquaculture site. Clam species that are mobile and seeded directly on the benthos can migrate away from the area of introduction, although the extent of dispersal through this means is expected to be small. Other bivalve species may be released from holding apparatus through containment failures. In most cases, bivalve adults are effectively sessile and will not migrate beyond the site of release. Scallops may migrate away from release site through clapping of their valves, although there is no evidence of extensive migration by this means (see Fay et al. 1983; Hart and Chute 2004).

This report exclusively examines the effects of farmed organisms that have escaped from their culture apparatus. Ecosystem effects of aquaculture organisms occurring while the organisms and their reproductive material are contained in their culture apparatus are discussed in other sections of the Science Advisory Report (e.g., Chamberlain and Page in press; Grant and Jones in press; McKindsey in press). As well, POEs of finfish that are intentionally released into Canadian waters for recreational fishing, stock enhancement, or nuisance weed control are not included in this report. This report focuses on the effects of released aquaculture organisms on native components of Canadian ecosystems. However, in some cases intentionally introduced non-native species have social and/or economic importance in different regions (e.g., established populations of Brown trout and Rainbow trout in some places in Eastern Canada are important to recreational fishing industries). Incorporating the importance of effects of escaped fish on these non-native species to the overall ecosystem health is problematic, although instances where escaped fish may pose unique impacts to socially or economically important non-native species is noted.

**Scope of species examined**

Species examined in this report include all species of significant commercial importance in Canada, as well as several emergent or minor commercial species with potential for significant escape events (e.g., species held in net-pens in natural ecosystems, see Table 2). Aquaculture species lists were obtained from DFO (http://www.dfo-mpo.gc.ca/aquaculture/aquaculture-eng.htm, accessed April 15, 2009). Species that are currently held in small numbers in land-based facilities or outdoor ponds (e.g., wolfish, Sockeye salmon, percids) or that are not expected to survive in Canadian aquatic environments (e.g., tilapia) are not included in this report.

*Table 2: Marine finfish, freshwater finfish, and bivalves farmed on commercial or research scales for the food market in Canada with potential for escape to natural aquatic ecosystems in Canada.*

| **Common name** | **Species** | **Location of use**[1] | **Native (N) or non-native (E)** | **Type of culture** |
|---|---|---|---|---|
| *Marine finfish* | | | | |
| Atlantic salmon | *Salmo salar* | Atlantic and Pacific coasts (BC, NB, NS, PE, NL) | N (Atlantic); E (Pacific) | Freshwater hatchery, marine net-pens |
| Chinook salmon | *Oncorhynchus tshawytscha* | Pacific coast (BC) | N | Freshwater hatchery, marine net-pens |
| Coho salmon | *Oncorhynchus kisutch* | Pacific coast (BC) | N | Freshwater hatchery, marine net-pens |
| Steelhead salmon | *Oncorhynchus mykiss* | Atlantic and Pacific coasts (BC, SK, NB, NS, NL) | N (BC); E (rest) | Freshwater hatchery, marine net-pens |
| Atlantic cod | *Gadus morhua* | Atlantic coast (NB, NL) | N | Saltwater hatchery and marine net-pens |
| Sablefish | *Anoplopoma fimbria* | Pacific coast (BC) | N | Saltwater hatchery and marine net-pens |
| *Freshwater finfish* | | | | |
| Rainbow trout | *Oncorhynchus mykiss* | BC, AB, SK, MN, ON, QC, NB, NS, PE | N (BC, AB); E (rest) | Freshwater hatcheries and net-pens or land-based tanks |
| Brook trout | *Salvelinus fontinalis* | QC | N | Freshwater hatcheries and net-pens or land-based tanks |
| Arctic charr | *Salvelinus alpinus* | YK, MN, ON, QC, NS, PE | E (MN); N (rest) | Freshwater hatcheries and |

| Common name | Species | Location of use[1] | Native (N) or non-native (E) | Type of culture |
|---|---|---|---|---|
| | | | | net-pens, ponds or land-based tanks |
| *Bivalves* | | | | |
| American oyster | *Crassostrea virginica* | Atlantic coast | N | Marine grow-out |
| Pacific oyster | *Crassostrea gigas* | Pacific coast | E | Saltwater hatcheries and marine grow-out |
| Blue mussel | *Mytilus edulis* | Atlantic and Pacific coasts | N (Atlantic); E (Pacific) | Saltwater hatcheries and marine grow-out |
| Mediterranean mussel | *Mytilus galloprovincialis* | Pacific coast | E | Saltwater hatcheries and marine grow-out |
| Manila clam | *Tapes philippinarum* | Pacific coast | E | Saltwater hatcheries and marine grow-out |
| Bar / Surf clam | *Spisula solidissima* | Atlantic coast | N | Direct seeding on marine benthos |
| Geoduck clam | *Panopea abrupta* | Pacific coast | N | Saltwater hatcheries and direct seeding on marine benthos |
| Quahaug | *Mercenaria mercenaria* | Atlantic coast | N | Direct seeding on marine benthos |
| Soft-shelled clam | *Mya arenaria* | Atlantic coast | N | Direct seeding on marine benthos |
| Sea scallop | *Placopecten magellanicus* | Atlantic coast | N | Marine grow-out |
| Bay scallop | *Argopecten irradians* | Atlantic coast | E | Marine grow-out |
| Iceland scallop | *Chlamys islandica* | Atlantic coast | N | Marine grow-out |
| Japanese scallop (and hybrid with Weathervane scallop) | *Patinopecten yessoensis* and *P. caurinus* hybrids | Pacific coast | E | Saltwater hatcheries and marine growout |

[1] AB=Alberta, BC=British Columbia, MN=Manitoba, NB=New Brunswick, NL=Newfoundland and Labrador, NS=Nova Scotia, ON=Ontario, PE=Prince Edward Island, QC=Quebec, SK=Saskatchewan, YK=Yukon

## Type/source of literature used

The literature sourced in this document are primarily peer-reviewed scientific documents and reviews identified through various search engines (BIOSIS, Web of Science, ASFA). As well, government documents, reports, and websites from provincial, federal, and international agencies were used as appropriate. The potential impacts of escaped aquaculture fish have been well reviewed in the scientific and government literature, and much information was obtained from these documents. Much of the relevant scientific literature involves use of laboratory studies to examine potential interactions between cultured (farmed or hatchery) and wild finfish. However, phenotypic effects of culture (e.g., altered growth rate, behaviour, etc.) are generally products of both exposure to the culture environment (environmental effects) and direct or indirect selective breeding (genetic effects). Significant environmental x genotype interactions have been observed when examining fitness of farmed or hatchery finfish relative to wild finfish (e.g., Ayles and Baker 1983; Devlin et al. 2006; Tymchuk et al. 2007). As such, farmed and wild finfish are not expected to behave or interact equally if housed in farmed versus natural environments. Consequently, our literature review focused on studies using natural or semi-natural environments (i.e., laboratory-based conditions supplemented with natural substrate, prey, etc.), but included laboratory studies as appropriate to build up the best possible estimates of the POEs of escaped aquaculture fish. Few studies have specifically examined biological effects to local populations or ecosystems from escaped aquaculture fish, but instead infer overall effects through comparisons of aquaculture and wild performance or interactions. Potential measureable ecosystem endpoints for each POE of escaped aquaculture fish are given in Figures 2-7, and appropriateness and practicality of these endpoints are discussed in the section on Measurable Endpoints.

The majority of studies examining potential effects of escaped aquaculture individuals have considered Atlantic salmon. This report will focus on escaped Atlantic salmon on the East and West coasts of Canada as a model for determining POEs of aquaculture escapes on native and non-native natural ecosystems in Canada, respectively. Where POEs for other species of interest may differ from the Atlantic salmon are noted for each group of farmed organisms (i.e., other salmonid species, marine finfish species, and bivalve species), as are the strength of evidence, knowledge gaps, uncertainties, and recommended research for determining POEs of various escaped farmed species. It should be noted that while the emphasis of this document is on the possible effects of escaped Atlantic salmon, this does not necessarily equate to greatest relative effects to the ecosystem from escaped Atlantic salmon. Rather, it is moreover a reflection of the relative investment in research in Atlantic salmon versus other finfish or bivalves. For example, a growing number of authors and organizations have questioned the relative value of using exotic bivalve species for aquaculture and restoration purposes, given the great impact of these species on the environment (e.g., Ruesink et al. 2005; Forrest et al. 2009). In particular, the Pacific oyster, *Crassostrea gigas*, has been singled out as a particularly undesirable species for aquaculture and other purposes, given its great impact on local communities and processes in the greater ecosystem. Specifically, the World Wildlife Fund discussion paper on bivalve aquaculture suggests that no new introductions of the species should be permitted outside of areas in which it is already present (WWF 2009). Similarly, the International Council for the Exploration of the Sea (ICES) has recently released an “Alien Species Alert” for the bivalve (Miossec et al. 2009). The scope of information regarding effects of escaped fish of different farmed groups is discussed in each relevant section and summarized in the section Summary of Effects of Aquaculture Escapes.

## LINKAGES BETWEEN ACTIVITY, STRESSOR (AQUACULTURE ESCAPES) AND EFFECTS

The potential for and magnitude of effects to natural ecosystems in Canada caused by escaped fish is dictated by the potential for susceptible ecosystems to be exposed to escaped fish, the potential for escaped fish to cause negative effects to such ecosystems, and the resilience of the ecosystem to such effects (i.e., the health of the ecosystem). The potential for exposure, health of receiving environments, and potential for negative effects shall be considered separately below. Exposure is considered a function of the probability and magnitude of fish to escape, survive in, disperse through, and reproductively establish in natural ecosystems (Exposure to Stressor, see below). The sensitivity of ecosystem components to escaped fish varies greatly and is influenced by numerous factors including the health of the ecosystem relative to the number of escaped fish present (i.e., the proportion of wild and escaped fish). Ecosystem components that escaped fish have potential to cause negative effects to include fish health, fish communities (through trophic and reproductive effects, fish habitat, and water quality. Schematics of the steps required for specific POEs are given in Figures 2-7. These schematics focus on Atlantic salmon, as the POEs are best defined for this species of escaped farmed organism.

The ability of escaped farmed fish to cause harm to Canadian ecosystems will be considered as an integration of the potential for ecosystems to be exposed to escaped fish, the health of the ecosystem, and the potential for escapees to cause negative effects to such ecosystems. Types of aquaculture escapes in Canada can be grouped into three categories based on whether fish are farmed in native or non-native habitat, and the degree of genetic domestication: 1) domesticated fish with escape potential to native habitat (i.e., Atlantic salmon and cod in Eastern Canada, Pacific salmon and Sablefish in British Columbia, Rainbow trout in British Columbia, Alberta, all other freshwater finfish in Table 2, minor bivalves in Pacific and Atlantic Canada); 2) domesticated fish with escape potential to non-native habitat (i.e., Atlantic salmon in British Columbia, Rainbow trout in provinces other than British Columbia, Alberta, most bivalves Pacific Canada); and 3) wild-collected fish with escape potential to local or nearby native habitat (most bivalves in Atlantic Canada).

Other factors expected to influence the POEs of escaped farmed fish on Canadian ecosystems include species of escape, wild species and strain exposed, life-stage or time of escape, length of time in the natural environment, environmental conditions at the site of release including similarity to environment of aquaculture parent strain, number of escaped fish in proportion to susceptible wild populations, number of generations (generation time) in captivity, and genetic structure of escaped and wild fish populations, among others. The known influence of the above factors on POEs to ecosystems components is addressed in each section below.

## EXPOSURE TO STRESSOR

The numbers of farmed finfish or shellfish released to Canadian waters is not fully known, but for finfish release it is estimated to range from <1% to 6% of total stock. The potential for fish to escape will be influenced by numerous factors including species farmed (e.g., Atlantic cod are more likely to escape than salmonids), siting of farms (e.g., escapes from storm damage may be greater in exposed areas than sheltered areas), standards and maintenance of farm equipment, etc. The fate of escaped fish is often not known. However, river monitoring in both Atlantic and Pacific salmon have identified surviving escaped salmon. In the Atlantic region, escaped Atlantic salmon have been found in 75% of surveyed rivers close to hatcheries in New Brunswick (Carr and Whoriskey 2006), and in 87% of surveyed rivers within 300 km of aquaculture sites on the East Coast of North America (Morris et al. 2008). In British Columbia, escaped adult Atlantic salmon have been found in >80 rivers and feral juveniles have been found in 3 rivers (Volpe 2000; Volpe et al. 2000; Thorstad et al. 2008). The known rivers exposed to escaped salmon is likely underestimated as not all rivers have been surveyed, and few have been surveyed for a significant amount of time. The length of time escaped farmed organisms will survive in Canadian waters, their spatial distribution beyond point of entry, and their ability to become reproductively established, will influence the spatial and temporal potential for and magnitude of effects to natural ecosystems in Canada. However, the ability of escaped fish to survive in, reproduce in, and migrate through natural waters systems is difficult to predict as it may be influenced by species, generation time in captivity, generations of artificial selection, life-stage of release, length of time in the natural environment, time of year of release, presence of predators, competitors for adequate food and habitat, ocean currents, and whether released to native or non-native habitat.

## Potential for Survival of Escaped Aquaculture Species in Canadian Aquatic Ecosystems

### Atlantic salmon

The majority of studies examining survival, migration, and reproduction of escaped farmed species have focused on Atlantic salmon and less so on other salmonids. The majority of studies report escaped farmed salmonids generally have lower survival in both freshwater and marine natural systems compared to wild conspecifics, due to both genetic effects of domestication and environmental effects of rearing in culture (Heggberget et al. 1993; Fleming et al. 2000; McGinnity et al. 2003; Lacroix and Stokesbury 2004; Saloniemi et al. 2004). This may be due in part to decreased predator avoidance (Fresh et al. 2003; Fritts et al. 2007; Tymchuk et al. 2007; Houde et al. 2009b) and decreased competitive ability of some farmed finfish (Metcalfe et al. 2003; Orlov et al. 2006), although farmed or hatchery salmonids had equal survival in a natural setting in one experiment (Einum and Fleming 1997), and greater survival than wild conspecifics with competition in the absence of predation in a semi-natural environment (circular tank enriched with water flow, gravel, logs, etc., Tymchuk et al. 2007).

Overall evidence indicates survival of finfish escaped from marine net-pens in Canada is expected to be less than that of wild finfish at a similar life stage (reviewed in Weir and Fleming 2006), and high winter and spring mortality of escaped Atlantic salmon, presumably from seal predation, has been noted in the Atlantic (Whoriskey et al. 2006). Marine survival may be influenced by time of release, where late summer and autumn releases may have lower survival than releases later in the winter (Hansen 2006). As well, generation time in captivity can greatly affect survival. For example Jonsson et al. (1991) found Atlantic salmon hatchery smolts obtained from wild parents had marine survival 50% of that of wild smolts, while Lacroix and Stokesbury (2004) found escaped Atlantic salmon smolts with a long history of domestication had only 20% marine survival of wild smolts. Survival may also be influenced by whether released to local and/or native habitat. For example, St. John strain farmed Atlantic salmon may have greater survival if released to habitats within its area of origin (i.e., the Bay of Fundy), rather than outside its area of origin (Hutchings and Fraser 2008), and Atlantic salmon released in the Pacific where they are non-native are expected to have lower survival than if released to the Atlantic (see MacCrimmon and Gots 1979).

### Other Finfish

Survival potential of other farmed species has been poorly examined, but is expected to be equal to or lower than wild conspecifics, based on studies in Atlantic salmon. In a recent study, Rainbow trout released from an experimental farm in a small freshwater lake had high annual mortality (50%), with no trout surviving for longer than 3 years (Blanchfield et al. 2009). Studies in semi-natural conditions found domestic Rainbow trout had greater survival than wild trout when in competition for food resources with one another, but lower survival than wild trout in the presence of predation (Tymchuk et al. 2007). While survival of escaped finfish is thought to be low, clearly a significant number of escaped finfish do survive for measurable time in Canadian waters.

### Bivalves

The survival of escaped farmed bivalves (i.e., those that drop off culture apparatuses, clams that migrate from culture sites, or larvae released through broadcast spawning), has not been well addressed, but is expected to be influenced by local conditions such as bottom-type, presence of predators, local currents, etc.

## Potential for dispersal of escaped aquaculture species through Canadian aquatic ecosystems

Escaped farmed organisms in theory will have a capacity to disperse similar to wild conspecifics, with some variation. Wild salmon, Atlantic cod and Sablefish undergo extensive marine migration, and salmon have further migration of up to several hundred kilometres into freshwater to spawn. Wild freshwater salmonids generally home to one lake or river system, although are occasionally known to enter new freshwater systems. Adult phases of most commercially important bivalves are functionally sessile or have limited movement, and the primary mode of dispersal is through the larval phase. The extent that larvae will disperse is most affected by the length of time of larval development, which varies between species from a few weeks to several months. Larvae dispersal will also depend on oceanic currents at site of release.

### Atlantic salmon

Studies examining the effects of culture rearing and domestication on migration potential have focused on salmonids – primarily Atlantic salmon. In general, tracking studies of escaped Atlantic salmon in natural environments report them to have aberrant migration patterns relative to wild salmon. Migration of escaped salmon in natural environments can be influenced by life-stage of release, time of release, and local oceanic currents (reviewed in Weir and Fleming 2006). Escaped salmon have lower marine dispersal than wild salmon (Hansen and Jacobsen 2003), and marine migration of escaped Atlantic salmon tend to be within a 500 km range of the point of release, although migration up to 2000-5000 km have been reported (reviewed in Thorstad et al. 2008). Escaped salmon are less able to home to freshwater rivers of imprinting than wild salmon, and tend to enter more than one river (Heggberget et al. 1993). This may be due to effects of culture on homing ability, and/or diminished imprinting when raised in culture rather than natural ecosystems. Atlantic salmon released as pre-adults tend to follow local currents and enter nearby rivers when ready to spawn (Hansen 2006; Whoriskey et al. 2006). Atlantic salmon escaped as parr or smolts are more likely to home to their river of imprinting than those released at later life-stages (reviewed in Thorstad et al. 2008), and mature salmon released at sea tend to enter freshwater systems close to the site of release (reviewed in Weir and Fleming 2006). Time of release may also affect homing pattern. Salmon released in late summer and winter may have decreased homing ability compared to those released at other dates (Hansen and Jonsson 1991). Farmed salmon reportedly enter rivers later than wild salmon (Gausen and Moen 1991; Fleming et al. 1997). Once in the river, escaped adult salmon have been reported to go higher in the river, remain lower in the river, move more, and be more randomly distributed than wild salmon (Webb et al. 1991; Webb et al. 1993a; Webb et al. 1993b; Økland et al. 1995; Thorstad et al. 1998). Little is known of natural freshwater distribution of parr escaped from poorly contained land-based hatcheries, although Carr and Whoriskey (2006) found all juvenile salmon that could be reliably identified as escaped parr were located at sites near hatcheries, while wild parr were located at sites away from hatcheries.

### Other Finfish

The effects of culture on migration in species other than Atlantic salmon have been poorly studied. Escaped Rainbow trout tend to have short-term high site-fidelity to net-pens with some excursions (reviewed in Podemski and Blanchfield 2006), and Bridger et al. (2001) found escaped triploid Steelhead salmon had high site fidelity, although eventually dispersed to the site of the local salmon hatchery. Levings et al. (1986) found hatchery Chinook fry spent approximately half the time in an estuary as wild fry. Blanchfield et al. (2009) showed that escaped Rainbow trout exhibited variable fidelity, ranging from complete net-pen site dependence over two years to near absence to the net-pen site in a small lake. As well, Uglem et al. (2008) found simulated escapes of Atlantic cod in Norway dispersed rapidly and randomly over a large area, while wild cod remained more stationary at one location.

### Bivalves

The main stage of bivalve dispersal is the larval stage. The extent that bivalve larvae released from culture sites will disperse has not been well addressed, but will depend on numerous factors including reproductive output of farmed individuals (i.e., quantity of larvae released), species and season (i.e., length of time of larval development), and local currents, among others. Wild-harvested bivalve species farmed in native habitat will likely have comparative reproductive output to wild cohorts, if maintained in the marine environment to reproductive maturation, while the reproductive output of non-native culture bivalves will likely depend on numerous factors including similarity of holding environment to optimal reproductive conditions. The dispersal distance of larvae may be small in some areas for species with short larval life-spans (e.g., Manila clam, Mediterranean mussel, and Blue mussel have larval life-spans of 2-4 weeks) and/or in areas of localized currents, although may be extensive for species with long larval life-spans (e.g., Geoduck clam has larval life-span of 7 months) and/or widespread currents. Offspring of non-native Pacific oysters farmed in Brazil were found up to 100 km away from oyster farms (Melo et al. 2009), indicating significant spread of this exotic is possible under appropriate conditions. In South America, the Mediterranean mussel, first observed in the 1970's, has been spreading at an average rate of approximately 115 km per year with the prevailing northerly Benguela Current and at about 25 km per year against it, it has now extended its range to approximately 2000 km along the west coast of South Africa and Namibia (Griffiths et al. 1992; Branch and Steffani 2004). Similarly, by studying the dispersal from an aquaculture site in Port Elizabeth, South Africa, McQuaid and Phillips (2000) found Mediterranean mussel to spread – in low numbers – over 223 km in 4 years at a rate of about 42 and 19 km per year to the east and west, respectively. However, approximately 90% of the mussels that dispersed from the culture site were within 12 to 20 km of it (McQuaid and Phillips 2000).

## Potential for reproductive establishment of escaped aquaculture species in Canadian aquatic ecosystems

### Atlantic salmon

The potential for escaped farmed fish to successfully reproduce and become reproductively established (i.e., reproduce within an ecosystem over successive generations) in Canadian waters depends on numerous factors (e.g., generation time in captivity, life stage of release, environmental conditions), although it is generally considered lower than wild fish. The majority of work examining reproductive potential of escaped fish has been regarding Atlantic salmon in semi-natural or laboratory conditions (see below). These studies have shown reproductive potential of escaped salmon can be influenced by sex, length of time or generation time in captivity, life-stage of release, and whether released in native or non-native habitat. In European studies in semi-natural stream environments (circular stream environments using gravel and water current to simulate natural breeding environments), farmed salmon, particularly male salmon, had overall lower reproductive success than wild conspecifics. Male farmed Atlantic salmon had decreased aggressive and courting behaviour, decreased mate acquisition, participated in fewer spawning events, and showed lower fertilization success, which resulted in reproductive success as low as 1-3% of wild conspecifics in semi-natural environments (Fleming et al. 1996). Farmed males also had lower ability to form the dominance hierarchies that influence spawning success in wild males, and while they may court a higher number of female salmon relative to wild males, they often fail to release sperm (Weir et al. 2004). Farmed females also have low reproductive success relative to wild salmon, although generally perform better than farmed males. Female farmed Atlantic salmon have altered breeding behaviour, decreased number of nests, increased number of unfertilized nests, increased egg retention, decreased nest covering, increased nest destruction, increased egg mortality, and spawn for shorter periods relative to wild conspecifics, resulting in reproductive success of approximately one third of wild salmon in semi-natural environments (Fleming et al. 1996). Poor reproductive success is due in part to the culture environment, and in part to genetic effects of domestication. For example, wild male salmon raised in hatcheries and released as smolts had 51% the reproductive success of genetically equal salmon reared in natural conditions when reproductive success was examined in a simulated stream environment, although there was no effect of hatchery rearing on female reproductive success (Fleming 1995; Fleming et al. 1997). Despite poor reproductive success, the large number of salmon escapes in some areas in Canada has resulted in a report of significant numbers of these salmon reproducing (20% of redds in the Magaguadavic River, New Brunswick were thought to be of maternal farm origin in the 1992/1993 spawning period, Carr et al. 1997a). As well, extensive reproduction of escaped Atlantic salmon has been noted in Europe (e.g., 14 of 16 rivers examined in Scotland had fry with maternal farm origin, ranging from 0-17.8% of the population, Webb et al. 1993b). While the lifetime reproductive success of first generation escaped Atlantic salmon is low, little work has examined whether lifetime and reproductive success changes over several generations in natural ecosystems. Lifetime success may increase over several generations, as natural selection would likely result in those fish most suited genetically to natural conditions surviving and reproducing (e.g., suboptimal traits from culture would likely be weaned out). As well, epigenetic effects in response to environmental conditions may also increase success of escaped farmed individuals.

In non-native habitat, farmed Atlantic salmon in a simulated stream (gravel channel in a rearing pond with water flow from a local river) in British Columbia demonstrated low proportion of spawning (<30%), high egg retention, poor redd construction, limited egg viability, and subdued male breeding behaviour (Volpe et al. 2001b). As well, intentional stocking of Atlantic salmon worldwide initiated in the late 1800's and early 1900's resulted in only a few isolated locations of establishment (MacCrimmon and Gots 1979), and Atlantic salmon are considered to have poor establishment success relative to successful introductions of other salmonids (e.g., Rainbow trout, Chinook salmon). This suggests that Atlantic salmon may have limited reproductive success outside their native territory. However, feral juvenile Atlantic salmon have been identified in 3 British Columbia rivers, including 2 year classes in one river (Volpe 2000; Volpe et al. 2000), indicating successful reproduction of escaped Atlantic salmon is possible in British Columbia waters. While poor survival, disrupted migration patterns, and low reproductive success of farmed Atlantic salmon may limit their ability to become reproductively established, the large numbers of escaped fish in both Atlantic and Pacific Canada have resulted in successful reproduction of some individuals on both coasts (see above), although the extent of reproductive establishment is not known.

### Other Salmonids

The potential for other escaped farmed species to become reproductively established has not been directly examined in Canadian waters. However, reproductive success in artificial stream channels artificial (water flow and gravel conditions designed to simulate natural spawning grounds) of Coho salmon reared in culture conditions throughout their lifespan was approximately half of Coho salmon of common genetic background that were released to natural environments as smolts (Bessey et al. 2004). As well, stocking of Rainbow trout, Brook trout, Chinook salmon, and Coho salmon for recreational fishing has resulted in establishment of these species in some non-native Canadian water systems. In contrast, there is also a high failure rate of intentionally stocked hatchery fish to attain self-sustaining populations (reviewed by Fleming and Petersson 2001), suggesting escaped farmed salmonids may not become established in many circumstances. While secondary effects of domestication from aquaculture may decrease establishment potential relative to stocked finfish as outlined for Atlantic salmon above (e.g., poor survival and reproduction in natural conditions relative to wild conspecifics), the successful reproduction of some escaped farmed Atlantic salmon in Canadian waters indicates other salmonid species may also have potential for reproduction.

### Marine Finfish

The potential for non-salmonid escaped farmed finfish to become reproductively established has not been examined. For pelagic spawners such as Atlantic cod, lack of reliance on complex migration patterns for reproduction, and ability to spawn while enclosed in net-pens or land-based systems with direct connection to suitable water, indicates they would have greater potential for establishment than salmonid species (e.g., spawning of Atlantic cod within net-pens, and subsequent release of pelagic larvae has been noted in Norway, Jørstad et al. 2008). However, farmed Atlantic cod have lower reproductive success than wild cod in laboratory conditions (summarized by Trippel et al. 2009), and may have other poor fitness traits in natural environments due to genetic, epigenetic, and some environmental effects of culture. To our knowledge, the potential for farmed Sablefish to reproduce within the net-pen, or in natural environments post-escape, has not been addressed.

### Bivalves

For farmed bivalve species for which seed is taken directly from local wild stock, determining the spread or establishment of these organisms would be challenging, and may be moot unless farmed away from areas in which they are already present (e.g., farmed in areas beyond larval dispersal distance of wild stock). Historic efforts to predict the ability of non-native bivalves to establish and spread have proved to be very difficult (see Landry et al. 2006; McKindsey et al. 2007), although non-native oysters, mussels and clams have become established in British Columbia, indicating a high likelihood for such occurrences in some circumstances. Selective breeding may increase the ability to spread, as properties that can influence the spread of bivalves (e.g., rapid growth under a wide variety of conditions, tolerance to a range of stressors, reproductive outputs) are often traits sought for aquaculture (reviewed by McKindsey et al. 2007). For example, the spread of Pacific oysters in Brazil was greater than expected given high water temperatures present, but hatchery breeding may have selected for those with warm water resistance (Melo et al. 2009). In contrast, although Mediterranean mussels were predicted to spread over approximately 150 km in South Africa based on a wind-driven hydrodynamic model, mussel beds themselves that result from dispersal from a single aquaculture source were observed to spread along the coast at a rate closer to 5 km per year (McQuaid and Phillips 2000). Studies outside Canada have found the spread of exotic bivalves can be influenced by numerous factors such as degree of site exposure, temperature, etc. (Nehls et al. 2006; Branch et al. 2008). The majority of farmed non-native bivalves established in Canada are located in BC and have been present for multiple decades. On the east coast, the only non-native bivalve species that is known to have become established outside of its native range is the European oyster (*Ostrea edulis*) which has become established in various locations in the area after its initial introduction for aquaculture trials (Vercaemer et al. 2006; Burke et al. 2008). The spread of such non-native bivalves may increase should culture of these species expand into new marine areas, artificial selection increase establishment potential of farmed populations, and/or climate change increase the suitable range of these species within Canadian waters. Such an effect has been observed with respect to the Pacific oyster in Europe. Originally, water temperature was thought to be too cold to allow Pacific oysters to reproduce and establish in Sweden. However, due possibly to climate change, Pacific oysters are now well established in Scandinavia with established naturalized populations in Denmark, Sweden, and as far north as 60° N in Norway (Wrange et al. 2009). At times, these populations can be directly related to adjacent current or past culture operations but there is also evident that some established populations distant from these sites are due to longer-distance dispersal.

## Strength of evidence, knowledge gaps and recommended research

In Canada, there is clear evidence for occasional large magnitude escapes and potential for frequent low magnitude trickle escapes from net-pens and hatcheries of various salmonid species used in aquaculture, as well as reproductive escapes of farmed non-native bivalves. As such, sensitive ecosystem components may have long-term exposure to escaped farmed fish through repeat escape events and/or reproductive establishment of escaped finfish and bivalves. There are abundant, consistent field, semi-natural, and laboratory data that demonstrate escaped farmed finfish have decreased survival relative to wild conspecifics in almost all circumstances. As well, there is abundant field data that demonstrate newly escaped farmed finfish have aberrant migratory patterns, although culture rearing and/or domestication among other things differentially influence migration.

Simulated- or semi-natural and field studies have consistently reported greatly decreased reproductive success of farmed salmon, although these studies are primarily based on cultured (farmed or hatchery) finfish that are new to the simulated-natural or natural environment. It is not known whether this poor reproductive performance will translate to conditions where finfish have had time to acclimate to natural conditions (i.e., released as juveniles, or second generation escaped finfish). While the underlying factors influencing alteration in survival, dispersal and reproductive potential of farmed fish relative to wild conspecifics are not always identified, genetic, environmental, and possibly epigenetic effects of culture likely play varying roles. Despite expected relatively poor performance of escaped farmed finfish, there is evidence of survival, dispersal and reproduction of escaped farmed Atlantic salmon in both Atlantic and Pacific Canada. As well, there is evidence for continued presence of farmed salmon in some systems known to contain sensitive wild salmon populations (e.g., Magaguadavic River). However, there are limited data on the extent of release, survival, dispersal and reproduction of farmed species in Canadian waters. As such, the current extent of release is not known, and predicting the survival and reproduction of escaped fish is difficult. The first step in assessing the effects of escaped fish on ecosystem function in Canada is determining the extent that susceptible Canadian ecosystems may be exposed to escaped fish. To do this, the following knowledge gaps must be addressed to determine the extent of escape events and the potential for escaped fish to survival in, dispersal through, and reproduction in

Canadian waters.

- While most Provincial Regulations require reporting of known escape events from marine net-pens, there is minimal knowledge of the extent of "trickle" escapes from net-pens and hatcheries, or of the indirect escape of reproductive material from contained bivalves and Atlantic cod. As such, the full magnitude of aquaculture escapes in Canada is not known. To address this, experiments should be designed to estimate trickle escapes in a variety of relevant circumstances, as well as to determine the total reproductive output of farmed bivalves (particularly non-native species) and Atlantic cod prior to harvest.
- The potential fate of escaped farmed fish in Canada, and the numerous factors affecting this potential are poorly understood. This may be addressed by expanding current monitoring programs to include freshwater salmonids, Atlantic cod and Sablefish, or with simulated release experiments to determine the fate of escaped farmed fish in various ecosystems (marine Atlantic and Pacific, as well as freshwater rivers and lakes) in large and small magnitudes. Of interest is how feeding behaviour, survival, dispersal, and reproduction change over time, and how these are affected by life-stage, time of release, local biotic and abiotic factors, whether in native or non-native habitat, etc. in Canadian waters. For example, field data could be gathered to develop models to predict the survival, dispersal, and reproductive patterns of escaped fish, including population dynamics of potential feral populations over several generations considering relevant levels of continued influx of escaped fish.
- Genetic, environmental, and epigenetic bases for decreased natural performance of escaped farmed fish should be more fully defined (Tymchuk et al. 2006b). In particular, how fitness is influenced by life-stage of release (i.e., time spent in nature), and whether altered fitness relative to wild species will persist in second and further generations, should escaped populations become reproductively established in natural environments (i.e., will natural selection influence reproductive and lifetime success of escaped aquaculture species over several generations in natural environments? More specifically, will natural selection restore fitness over time and if so to what extent and over what time scale?).
- The majority of studies examining the fate of aquaculture fish have examined Atlantic salmon escapes. Experiments should be designed to determine the appropriateness of Atlantic salmon data to determine the survival, dispersal and reproductive success of other escaped farmed finfish species.
- More information is needed on the freshwater dispersal of escaped hatchery finfish, and survival, dispersal, and reproduction of escaped freshwater salmonids. Determining the validity of extrapolating findings of intentional hatchery release studies to unintentional hatchery or freshwater escapes should be explored to fill this information gap.
- The extent that feral populations of non-native bivalves (e.g., Pacific oysters, Manila clams, Mediterranean and Blue mussels in Pacific Canada, European oysters in Atlantic Canada) have become established should be identified. As well, factors could be identified that may effect establishment potential, including aquaculture density, local currents, dispersal rates, length of larvae life-stage, and climate change, that may help predict potential of future naturalized expansion from aquaculture escapes.
- The potential for other currently and potentially farmed exotic species or stocks (e.g., Japanese oysters, *Patinopecten yessoensis* and *P. caurinus* in BC, Bay scallops, *Argopecten irradians*, in eastern Canada) to establish and spread outside of farm sites should be determined.

## SENSITIVITY OF CANADIAN ECOSYSTEMS TO STRESSOR

The probability for and magnitude of effects of escaped farmed fish to components of Canadian ecosystems will be dictated in part by the sensitivity of such ecosystem components to effects caused by the presence of escaped fish. Sensitivity can also be described as ecosystem health – i.e., the resilience of the ecosystem component to effects. An ecosystem that has been perturbed by numerous factors (e.g., habitat degradation through human use, over-fishing, etc.) may have poor resilience to further perturbation by escaped farmed fish, while a relatively pristine ecosystem may have higher resilience to perturbation by escaped fish. The sensitivities of ecosystems are expected to range widely across Canada on local and regional scales. However, our understanding of factors influencing the vulnerability or resilience of ecosystem components is limited. The main factor identified as influencing the sensitivity to escaped farmed fish is the relative numbers of wild and escaped fish. For example, numerous populations of Atlantic salmon, Pacific salmon and Atlantic cod are listed as at-risk by COSEWIC due to declining numbers brought on by over-fishing, habitat alterations and climate change. As such, these populations may be particularly sensitive to effects of escaped farmed fish, particularly if escapees are present in high numbers. The most extreme example of this is Atlantic salmon in the Bay of Fundy. Atlantic salmon stocks in this region are endangered, with many runs totally less than 100 fish per year. This region is also the site of high-intensity Atlantic salmon net-pen aquaculture (see Figure 1) such that annual numbers of farmed salmon contained in the net-pens outnumber wild salmon at ratios greater than 600:1 (Fraser, personal communication). The very low numbers of wild Atlantic salmon combined with the very high potential for repeat intrusions of escaped salmon in this region result in high potential of this ecosystem to effects from escaped farmed salmon. For other at-risk wild populations such as Atlantic cod and some Pacific salmon, the relative numbers of farmed versus wild fish are far less than for Atlantic salmon. As such, while these populations may be sensitive to escaped farmed organisms, the potential for and magnitude of effects will likely be less than for wild Atlantic salmon in the Bay of Fundy.

The sensitivity of ecosystem components to escaped farmed fish may also be influenced by the naïveté of the component to the effects of aquaculture escapes. For example, if fish escape to a community without a top-level piscivore predator, this may have a larger impact on prey populations than in communities where salmonids or other top-level predators are already present (see Podemski and Blanchfield 2006). Other factors that may influence ecosystem sensitivity are not known, but may include human-induced perturbations to ecosystem components.

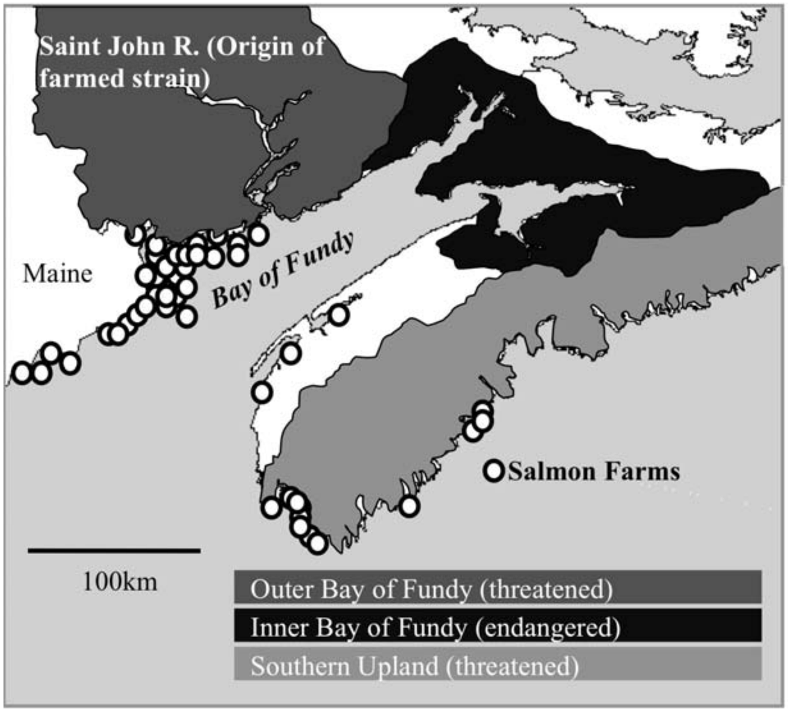

*Figure 1. Location of Atlantic salmon fish farms, and status of wild Atlantic stocks in and around the Bay of Fundy. Adapted from Fraser et al. (2008). Approximately 12-20 million salmon are farmed annually, while salmon returns number less than 20 000 annually across approximately 85 rivers.*

## EFFECTS: CHANGE IN WILD FISH HEALTH

### Finfish

There is concern that the escape of farmed organisms could result in the transfer of disease to wild populations. However, the potential for aquaculture fish – either when contained in net-pens or escaped from land-based aquaculture facilities – to cause significant negative effects to wild populations through transfer of disease has been widely debated with no clear conclusions drawn (see Olivier 2002; McVicar et al. 2006). The potential for wild fish to be impacted by release of pathogens from finfish contained in net-pens is discussed in another POE document (Grant and Jones in press). Escaped Atlantic salmon are thought to have brought furunculosis to numerous rivers in Norway (Johnsen and Jensen 1994), although there are no other known cases where escaped farmed fish have been directly implicated in disease transfer to wild fish. The transfer of pathogens between wild and farmed salmon can be bidirectional. In Canada, the Fish Health Protection Regulations and standard vaccination procedures limit the potential for farmed fish to introduce new diseases. However, wild fish could transfer some disease agents to penned finfish, where high densities of farmed finfish may result in a disease outbreak within the fish farm (see McVicar et al. 2006). This may result in higher vector capabilities of such finfish should they escape from culture facilities. McVicar et al. (2006) suggested the initial risk of disease transfer from escaped salmon to wild finfish would depend on the length of time of escapee's survival, the behaviour of escaped fish, and the decreased disease transfer potential through decreased fish density. Escape of infected farmed finfish could potentially increase the range of a pathogen through dispersion of escapees, but may also decrease transmission potential through a dilution effect relative to those in a net-pen. It is expected that only the fittest escaped finfish would survive, and the most seriously affected finfish would have selectively higher mortality (McVicar et al. 2006), possibly minimizing survival of escaped finfish with high vector capabilities. Morton and Volpe (2002) reported 25.8% of escaped Atlantic salmon caught in British Columbia fisheries had sea lice infections, and escaped salmon may have more sea lice than wild finfish because of behavioural and size differences (see McVicar et al. 2006). However, the effects of transfer of sea lice from farmed Atlantic salmon to wild Pacific salmon has been contested within the scientific literature (e.g., Brooks and Jones 2008). The virus causing ISA has been isolated in a few escaped Atlantic salmon in Atlantic Canada (see Olivier 2002), indicating some diseased or carrier finfish may survive in some circumstances. Escaped Atlantic salmon and cod have been identified in areas where wild conspecifics aggregate (i.e., spawning grounds, Morris et al. 2008; Uglem et al. 2008), and anecdotal evidence suggests escaped Atlantic salmon in British Columbia can be associated with wild Steelhead salmon (Morton and Volpe 2002). While the expected poor survival of infected escaped finfish may reduce vector potential, the identification of infected escaped finfish in the wild, the very large number of escaped finfish in some instances (hundreds of thousands of individuals), and potential for dispersal of escaped finfish to areas of high wild finfish aggregation suggests disease transfer from escaped farmed organisms to wild fish cannot be ruled out (see Figure 2 for steps necessary for infected farmed escapees to infect wild populations). Where disease agents are native species and strains (i.e., equivalent strains to those observed in local wild populations), overall effects to the wild populations may be minimal, relative to non-native species or strains of disease agents, unless the escape of infected finfish results in increased occurrence of the disease in the wild population. However, there is currently limited evidence to either support or challenge the potential for escaped aquaculture fish to negatively affect wild fish health. Determining such potential will be problematic due to difficulties determining the cause, or even the presence, of disease outbreaks in wild populations.

### Bivalves

The potential for escaped bivalves to alter wild bivalve health through disease transfer has been poorly addressed. In diseases where direct horizontal transmission is possible, infected bivalves that have fallen off culture apparatuses or migrated away from site of culture (i.e., clam species) could theoretically infect local wild populations with the disease agent. As well, in diseases with vertical transmission (e.g., some herpes viruses in oysters, Barbosa-Solomieu et al. 2005; da Silva et al. 2008), infected larvae released from an infected farmed population could theoretically disperse the disease agent to new wild populations. However, to our knowledge the potential for either of these scenarios has not been addressed in Canadian systems. As with escaped finfish, transfer of disease from escaped bivalves to wild bivalve populations may only affect wild populations where the disease agent is non-native or non-local, or native but results in increased occurrence or magnitude of disease in the wild population.

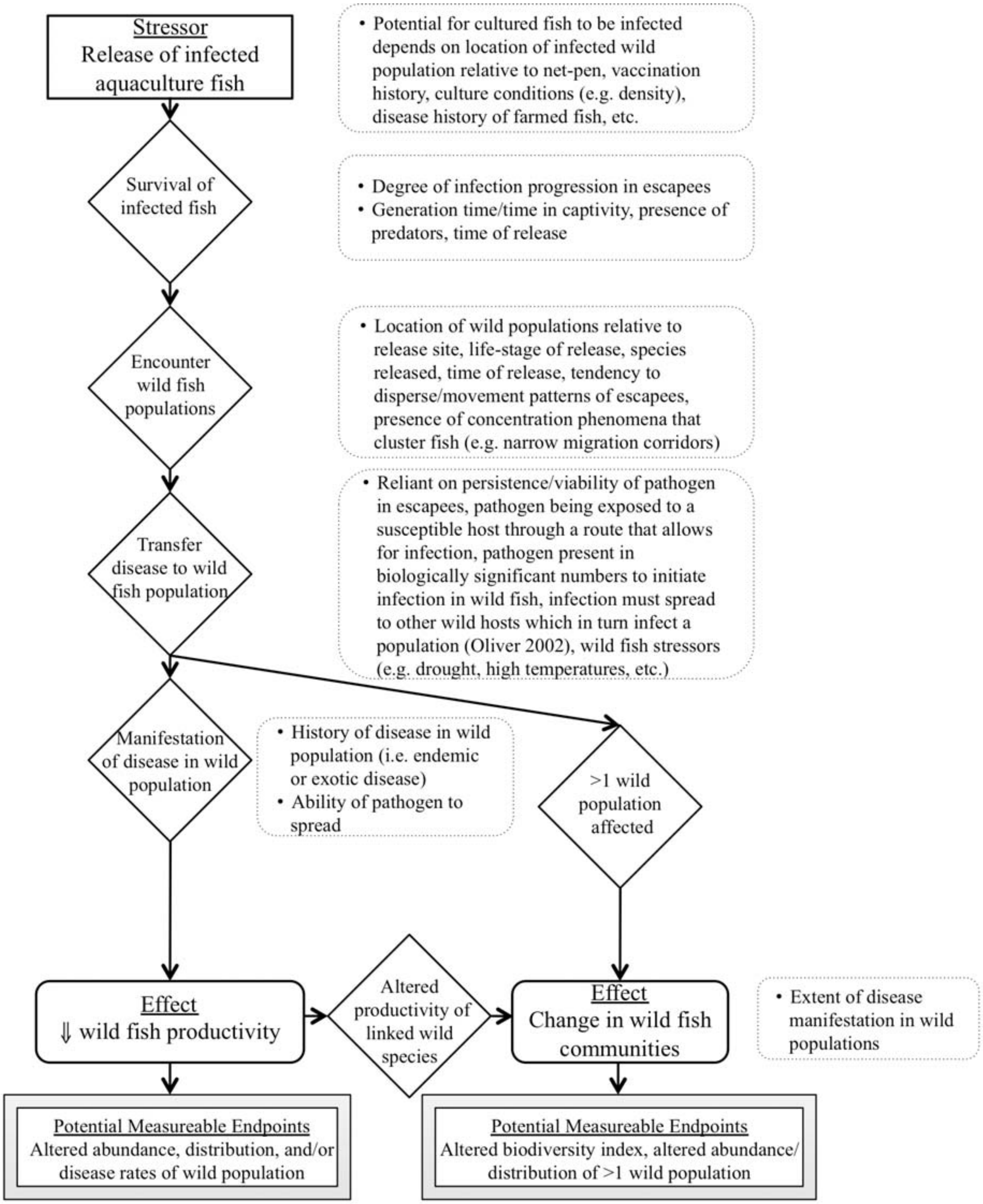

*Figure 2. Effects of released aquaculture organisms on wild fish health. Text in diamonds indicate steps required in order for stressor (rectangle) to result in effects (rounded rectangle) and measurable endpoints (double rectangle). Comments in dashed bubbles indicate factors shown to affect potential for each step in stressor-effect scenario.*

### Genetic Health

Repeated hybridization of escaped farmed finfish or hatchery-reared bivalves with wild populations may result in reduction in population genetic variation and diminishment of local adaptation of wild populations. This can result in overall lower genetic and phenotypic health of the wild population. In some regions, the risk of this occurring may result in restricting introductions and transfers for aquaculture (e.g., Sea scallops in Quebec). This will be discussed below.

## EFFECTS: CHANGE IN WILD FISH POPULATIONS/COMMUNITIES

### Competition with, predation on, and providing prey for wild fish populations

The primary mechanisms of effects of escaped fish on wild fish populations is thought to be through competition for limited resources (e.g., food and optimal habitat) and predation (see Johannes 2006; Podemski and Blanchfield 2006). This could result in displacement of wild fish, decreased productivity of wild fish populations, and/or altered community dynamics (through food availability, predator-prey interactions, etc.). In areas where wild fish or other sensitive populations are at risk, this could potentially result in local extirpation of wild populations should farmed fish escape in large quantities or become established.

### Atlantic salmon

Escaped Atlantic salmon on either coast could impact wild salmon populations and other organisms occupying similar niches through competition for food and optimal habitat. This could take place in the marine environment as post-smolts and adults and in the freshwater environment as juveniles.

### Predation and competition in the marine environment

Escaped Atlantic salmon may impact various fish and invertebrate populations in the marine environment through predation. Escaped Atlantic salmon have been found in wild Atlantic salmon feeding grounds, and are thought to consume similar prey to Atlantic salmon after an acclimation period to the natural environment (reviewed in Johannes 2006; Thorstad et al. 2008). Stomach contents of wild Atlantic salmon include species listed by COSEWIC as at-risk (e.g., juvenile Atlantic cod, various rockfish and wolfish species, Jacobsen and Hansen 2000). Assuming escaped Atlantic salmon consume similar prey to wild salmon, predation on the above species could threaten survival of these populations should farmed salmon escaped in sufficient quantities and migrate to areas containing at-risk populations of fish. However, the potential for such predation by escaped Atlantic salmon has not been examined in Atlantic Canada (see Figure 3 for steps required for aquaculture escapees to impact wild populations through predation). In contrast, only 3.4% of escaped Atlantic salmon caught in the Pacific Ocean had wild prey in their stomachs (Morton and Volpe 2002), indicating escaped Atlantic salmon in this ecosystem would have limited potential to impact wild fish populations through predation or competition. Morton and Volpe (2002) also found the percent of escaped salmon with stomach contents increased with time in the natural environment, indicating escaped Atlantic salmon in the Pacific may have increased ability to impact prey species over time.

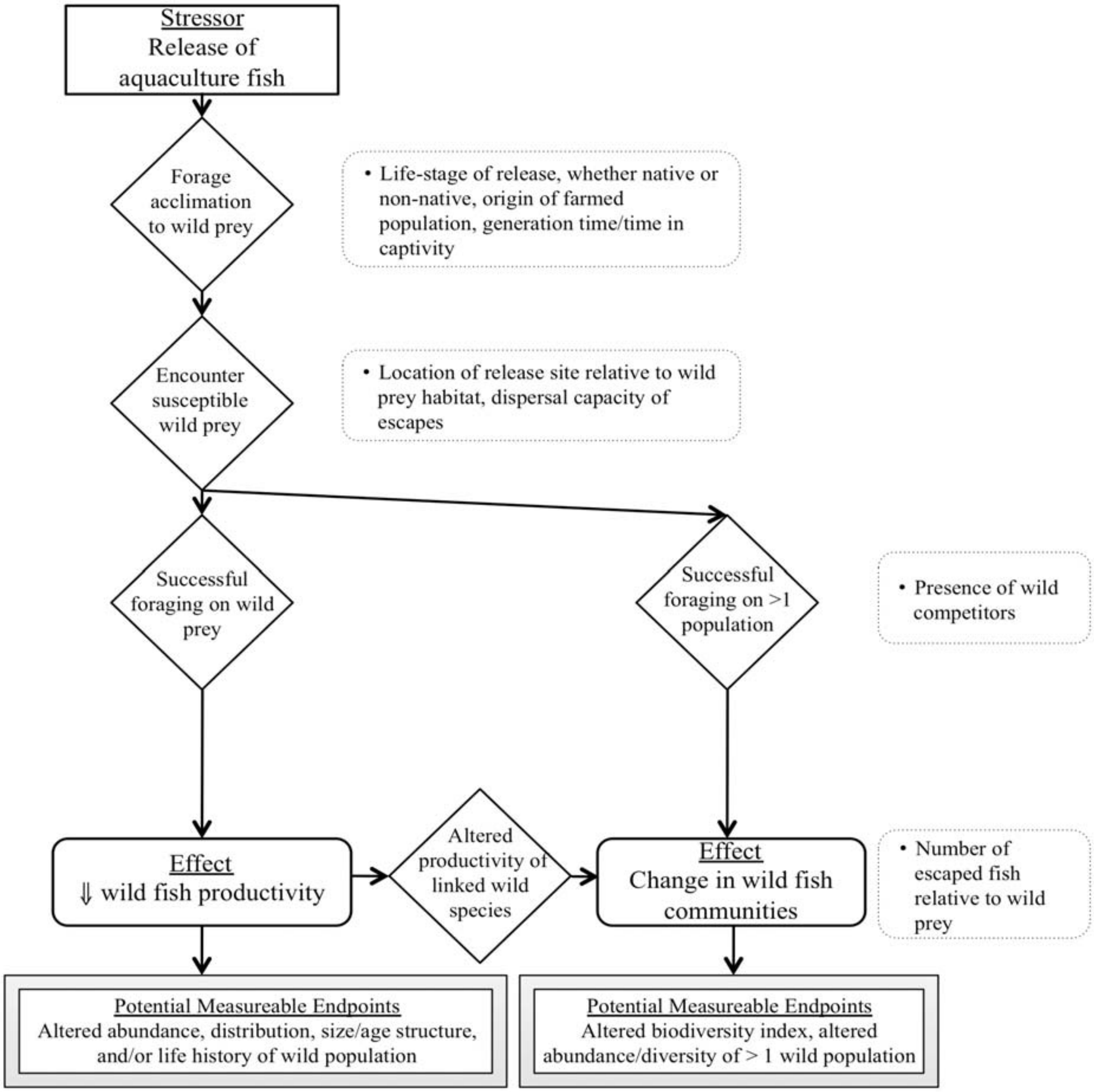

*Figure 3: Effects of released aquaculture salmon on wild fish communities through predation. Text in diamonds indicates steps required in order for stressor (rectangle) to result in effects (rounded rectangle) and measurable endpoints (double rectangle). Comments in dashed bubbles indicate factors shown to affect potential for each step in stressor-effect scenario.*

However, of the 775 salmon examined, the stomachs of one salmon had a salmon smolt, one salmon had a herring, and 5 salmon had sand lance (other wild prey included shrimp, unidentified finfish, and unidentified invertebrates), indicating the potential for negative impacts on these populations of fish through predation from escaped Atlantic salmon is low. Escaped Atlantic salmon also have poor acclimation to wild forage in non-native environments outside of Canada (e.g., Chile), especially compared to other salmonids in non-native habitat (e.g., salmon and Rainbow trout, Soto et al. 2001).

Competition between escaped Atlantic salmon and wild species in the marine environment has not been directly examined, and as such the potential for escaped salmon to impact wild finfish in this ecosystem is not known (DFO 1999). However, ocean survival of wild Atlantic salmon in Norway is density-independent, and is thought to be density-independent for most Pacific salmon in North America (Jonsson and Jonsson 2004; Wertheimer et al. 2004), although Pink Salmon may influence survival of other Pacific salmon in the North Pacific Ocean (reviewed in Ruggerone and Nielsen 2004). However, several studies show marine body size of wild and hatchery released Pacific salmon in North America are density-dependent (reviewed in Holt et al. 2008). Inter- and intraspecies competition for a limited marine prey-pool may be limiting body size in these salmon (reviewed in Holt et al. 2008) with unknown consequences to wild populations. Consequently, increasing marine density of salmonids through escape of farmed salmonids may further impact body size of fish in this region (see Figure 4 for steps necessary for escaped farmed fish to impact wild populations through marine competition for resources). However, poor forage acclimation of escaped Atlantic salmon in the Pacific may limit any effects of escaped fish to body size of wild fish. In the western Atlantic Ocean, food supply does not appear to limit post-smolt growth or survival of wild Atlantic salmon in the Bay of Fundy and the Gulf of Maine (Lacroix and Knox 2005). In Atlantic Canada, growth of post-smolt Atlantic salmon appears to be constrained by intraspecific competition in the Miramichi River, Gulf of St. Lawrence, in the first 1-2 months of marine inhabitation, but not at later stages (Friedland et al. 2009). Consequently, competition from escaped salmon or their offspring in the Atlantic marine environment is expected to have little or transient impact on productivity of wild populations.

### Juvenile competition in freshwater

Escaped Atlantic salmon are most likely to impact wild salmonid populations through competition at the juvenile freshwater stage, either as escaped hatchery fish or feral offspring of escaped adults. For example, McGinnity et al. (2003) found farmed Atlantic salmon parr in a natural stream displaced wild parr downstream, yet had lower marine survival than wild fish, indicating greater potential for impacts to wild populations at the juvenile stage. Figure 5 details the steps required for escaped farmed salmonids to affect wild salmonid populations through freshwater resource competition. In native North American rivers, wild Atlantic salmon parr display density-dependent growth (e.g., Grant and Imre 2005), and stocked juveniles display density-dependent mortality that may be reversed by the presence of predators (e.g., Whalen and Labar 1994; Ward et al. 2008). As such, growth or survival of wild juveniles may be affected by increasing density through introduction of escaped juveniles. The ability of escaped Atlantic salmon to successfully compete with wild populations for food or optimal habitat varies and may be influenced by numerous factors including length of time in the natural environment, water currents, number of escaped fish relative to wild fish, prior residency, presence of predators, generation time in captivity, size differences, genotype, strain of wild fish, and whether endemic or exotic. In general, survival of escaped Atlantic salmon is lower than wild conspecifics, suggesting poor capacity of farmed salmon to acclimate to natural environments,

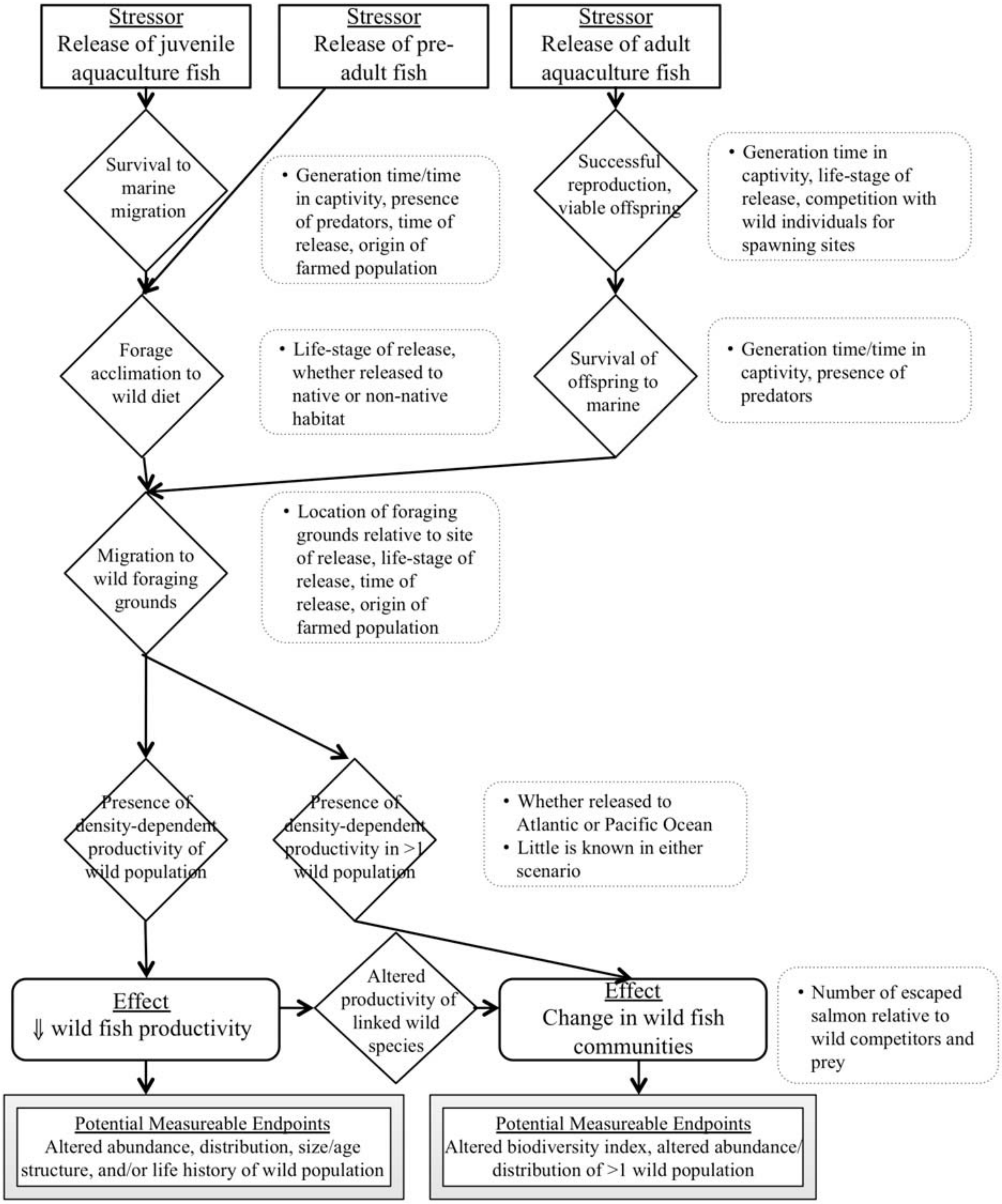

*Figure 4. Effects of released aquaculture salmon on wild fish communities through marine competition. Text in diamonds indicates steps required in order for stressor (rectangle) to result in effects (rounded rectangle) and measurable endpoints (double rectangle). Comments in dashed bubbles indicate factors shown to affect potential for each step in stressor-effect scenario.*

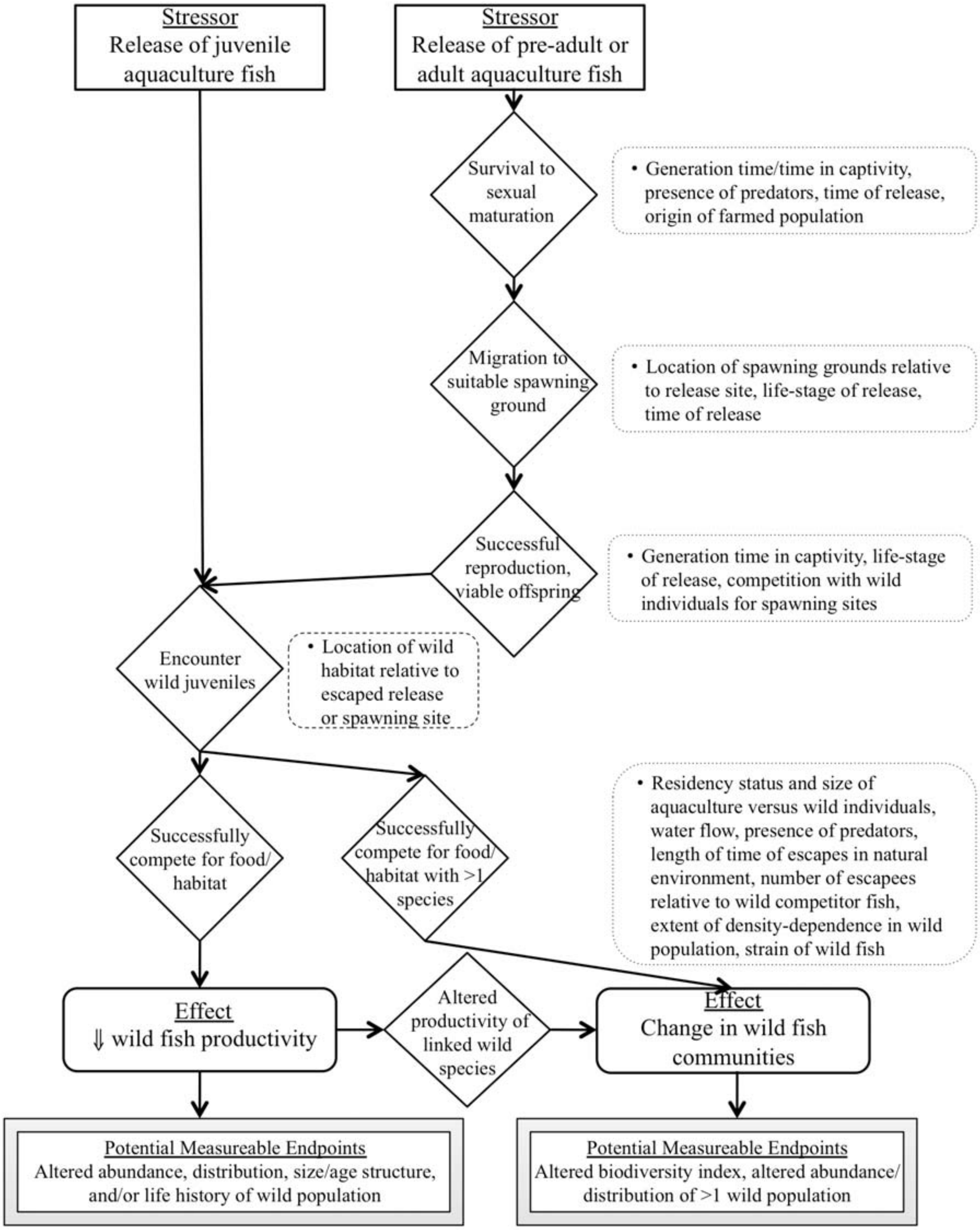

*Figure 5. Effects of released aquaculture salmon on wild fish communities through freshwater juvenile competition. Text in diamonds indicate steps required in order for stressor (rectangle) to result in effects (rounded rectangle) and measurable endpoints (double rectangle). Comments in dashed bubbles indicate factors shown to affect potential for each step in stressor-effect scenario.*

although the majority of studies have focused on marine rather than freshwater survival. Orlov et al. (2006) reported hatchery Atlantic salmon juveniles in Russia ate more poor quality food, had more false feeding attempts, ate less, and chose sub-optimal habitat for foraging relative to wild conspecifics in natural conditions. However, Einum and Fleming (1997) found habitat use and diet of wild and farmed juveniles in a natural environment suggested potential habitat and food competition. The discrepancies between studies may be due to differing acclimation time of escaped parr to wild forage, although factors affecting timeframe of acclimation to wild prey have not been well examined.

Natural and laboratory studies suggest farmed parr can competitively displace smaller wild parr (McGinnity et al. 1997), are generally larger and more aggressive, and can dominate wild parr, although wild parr may dominate in fast water currents or if they have residency advantage (reviewed by Jonsson and Jonsson 2006). A study in Atlantic Canada found St. John strain farmed Atlantic salmon were more competitive in laboratory conditions than Stewiacke wild strain, but equally competitive as Tusket wild strain – indicating relative competition of escaped fish will depend on the strains in contest (Houde et al. 2009a). In semi-natural studies, Stewiacke wild parr had decreased mortality when hybrid Stewiacke x farmed parr to wild parr ratios were 30:70 and 50:50, but not at 15:85 hybrid:wild, while Tusket wild parr had decreased mortality only when hybrid:wild ratios were 30:70 (Houde et al. 2009a). Consequently the impacts of competition from escaped farmed parr or their hybrids on wild parr may be influenced by ratio of farmed:wild fish, as well as the strain of wild salmon considered. Studies in a Norway river found feral farmed Atlantic salmon juveniles emerge earlier and initiated feeding earlier than wild salmon (Lura and Sægrov 1993), suggesting farmed salmon offspring may obtain a residency advantage in optimum feeding areas relative to wild salmon in some circumstances.

Farmed and hatchery salmon are greater risk takers in both natural and laboratory studies (Einum and Fleming 1997; Dieperink et al. 2001), indicating they have higher mortality in areas of high predation pressure. As such, they may have greater impacts on wild juveniles in areas of low predation pressure. Success of escaped juveniles increases with length of time spent in nature (reviewed in Jonsson and Jonsson 2006), and potential for competitive impacts are expected to increase with generation time in nature. For example, Carr and Whoriskey (2006) found first generation escaped hatchery Atlantic salmon parr in New Brunswick primarily in sites near the hatcheries, and wild salmon in sites away from hatcheries, indicating that in areas where habitat is not limiting, escaped juveniles may not encroach on wild juvenile habitat. In contrast, natural studies in Europe have found farmed juveniles overlapped in habitat with wild juveniles when farmed and wild eggs were implanted simultaneously in an experimental stream, and farmed offspring were thought to have competitively displaced smaller wild salmon downstream (McGinnity et al. 1997; McGinnity et al. 2003). Fleming et al. (2000) found natural wild Atlantic salmon smolt productivity was 30% less than the expected level based on stock-recruitment relationships in the presence of farmed and hybrid Atlantic salmon offspring, suggesting resource competition and competitive displacement of wild Atlantic salmon by bigger farmed and hybrid salmon. High densities of hatchery salmon have been negatively associated with abundance and diversity of wild salmon (e.g., Berg and Jorgensen 1991), although lower densities of escaped salmon have inconclusive effects on wild species (reviewed in Johannes 2006).

On the Pacific coast, laboratory studies show Atlantic salmon are generally inferior competitors to wild Steelhead salmon, Coho salmon and Cutthroat trout when size matched or given equal residency time, but may be equal or greater competitors if given greater residency time or if they have a size advantage over the wild salmonids (Volpe et al. 2001a; Blann and Healey 2006). Atlantic salmon fry hatch 2 months ahead of Steelhead salmon, and as such feral populations of

Atlantic salmon may gain residency advantage over native Steelhead (Volpe et al. 2001a), potentially resulting in competitive displacement and decreased productivity of wild fish. Such interactions could potentially take place between feral Atlantic salmon and populations of Coho and Sockeye salmon listed as at-risk by COSEWIC. However, coexisting farmed Atlantic and wild Pacific salmon have not been directly observed in nature, and further research is required.

### Predation in freshwater

Escaped farmed Atlantic salmon entering the Magaguadavic River, New Brunswick show abnormal behaviour that may affect their predation impacts on prey species in this river. The majority of these salmon enter the river immature (Carr et al. 1997a), lack gonadal steroid changes associated with sexual maturation (Lacroix et al. 1997), have limited in-stream migration, do not migrate to spawning grounds, and do not return to the ocean after the spawning period (Carr et al. 1997b). The cause of this unusual migration is not known, but it is clearly not a spawning migration. This behaviour has not been noted in escaped salmonids in other parts of Canada or worldwide. Whether these non-mature salmon stop feeding as mature salmonids do while in the river system is not known (Carr et al. 1997b). However, as they do not have other behavioural or physiological changes associated with mature salmon, the potential for them to continue to feed while in the river environment cannot be ruled out. Should these non-mature escaped salmon feed in the river environment, they could potentially pose unique hazards to wild prey, potentially including predation on migration wild salmon smolts, and competition with species occupying similar niches as the escaped salmon. However, these effects would be isolated to the Magaguadavic River as non-maturing escaped salmonids have not been noted in other rivers.

### Other Salmonids

The potential for trophic interactions between wild finfish populations and escaped farmed salmonids other than Atlantic salmon have been poorly studied. As marine survival of wild Pacific salmon is thought to be density-independent (Jonsson and Jonsson 2004; Wertheimer et al. 2004), escaped Pacific salmon may have little impact on production of wild salmon populations in the marine environment, but may influence body size of wild salmon (Wertheimer et al. 2004; Holt et al. 2008). Laboratory studies report farmed Coho salmon juveniles are equal competitors relative to two strains of wild Coho salmon (Blann and Healey 2006), and maintain their high growth rate when reared in semi-natural conditions (stream troughs enriched with creek water, gravel, branches and rocks) with wild counterparts (Tymchuk et al. 2006a). As such, farmed Coho juveniles may decrease productivity of wild conspecifics through food and habitat competition at this life stage. However, the estimated number of escaped Pacific salmon per year is less than 0.01% of total wild Pacific salmon population numbers (see Johannes 2006), and as such they may only have significant impacts where large numbers of escaped salmon compete with at-risk wild populations. It is worth noting that escaped salmon are likely to concentrate in areas of high aquaculture intensity. While escaped Pacific salmon may number much less than wild populations, wild populations located close to areas of high fish farming activity may be exposed to relatively high numbers of escaped salmon. We are unaware of any other work that has examined trophic impacts of escaped farmed Pacific salmon, although impacts may be similar to those reported in Atlantic salmon.

The trophic impacts of farmed escaped freshwater salmonids in Canada have been poorly studied. Historically, intentional or accidental introduction of Rainbow trout worldwide have repeatedly resulted in loss of native salmonid and non-salmonid species through competition and/or predation pressure, particularly in ecosystems with no existing top-level piscivores (reviewed in Podemski and Blanchfield 2006). However, historic and current stocking efforts in Canada have resulted in Rainbow trout populations being established in some areas with current potential for high magnitude escape of farmed Rainbow trout (i.e., culture in freshwater net-pens). In these areas, the impact of escaped farmed salmonids may be difficult to separate from effects of established or stocked Rainbow trout (Podemski and Blanchfield 2006), particularly where stocked fish greatly outnumber potential annual escape numbers, and stocked and farmed fish are of the same strain (e.g., Rainbow trout in Lake Huron). Potential for inter- and intra-specific juvenile competition for food and habitat among escaped freshwater and wild salmonids is likely similar to that observed for escaped juvenile Atlantic salmon. However, the impacts of pre-adult or adult escaped salmonids in freshwater oligotrophic lakes that house most freshwater net-pens is just beginning to be examined (Podemski and Blanchfield 2006). By nature, these lakes are not considered productive. Historic escapes of up to several hundred thousand Rainbow trout have occurred, and such high magnitude escapes may have significant negative impacts on wild populations inhabiting similar niches of oligotrophic lakes. In semi-natural conditions with competition, the survival of domestic Rainbow trout was greater than wild trout (Tymchuk et al. 2007), indicating farmed salmonids may outcompete wild salmonids in limiting environments. However, domestic trout had lower survival than wild trout in the presence of predation (Tymchuk et al. 2007), and as such effects of competition may be limited by the presence of predation. The life-stage of escape may influence the trophic impact of escaped Rainbow trout. Rikardsen and Sandring (2005) found Rainbow trout escaped as post-smolts fed primarily on wild prey, had similar foraging ratios to wild trout, and increased weight one month post-escape. In contrast, Rainbow trout escaped as adults fed primarily on indigestible items, had decreasing condition factor over time, and had low foraging ratios over a 15-month period. As such, trout escaped as adults may have limited impacts on wild populations, regardless of resource limitations. Rainbow trout released from an experimental farm maintained growth rates comparable to in-pen rearing, likely due to reliance upon waste feed (Blanchfield et al. 2009). However, some escaped trout exhibited wide dispersal, a varied diet and lack of reliance on the cage site, suggesting the potential to influence the receiving ecosystem (Blanchfield et al. 2009).

### Marine Finfish

There has been little work examining the potential for trophic interactions between other aquaculture species and wild fish populations. Brooking et al. (2006) suggested escaped Atlantic cod may have potential to prey on migrating populations of endangered Atlantic salmon smolts, based on migratory patterns of wild cod. Other potential effects are not known, but both Atlantic cod and Sablefish are piscivorous to some extent and have potential to impact various prey species. As well, escaped finfish have potential to competitively interfere with wild finfish inhabiting similar niches. Any juvenile escaped farmed fish also have potential to be prey for numerous wild piscivores, although this is generally expected to have positive impacts on wild populations.

### Bivalves

Larvae and adults of bivalves listed in Table 2 are planktivorous, feeding primarily on phytoplankton and microzooplankton. As such, feral populations of farmed bivalves could potentially impact species utilizing similar resources. Wild-caught native farmed bivalves that escape are not expected to significantly impact wild populations through trophic interactions. However, non-native bivalves established beyond the culture site could competitively exclude native species in some circumstances. This has not been noted in Canadian systems. However, several non-native farmed bivalves established in Canada (e.g., Pacific oysters and

Mediterranean mussels) have been implicated in restricted occurrence of numerous native shellfish species worldwide (e.g., Pacific oysters preventing re-establishment of *Ostrea lurida* in Washington, USA, Trimble et al. 2009; Pacific oysters restricting Blue mussels in the Wadden Sea, Europe, Diederich 2006; Mediterranean mussel replacing *Aulocomya ater* and restricting *Perna perna* and *Scutellastra argenvillei* in South Africa, Steffani and Branch 2005; Bownes and McQuaid 2006; see Ruesink et al. 2005; McKindsey et al. 2007 for reviews). Introduced bivalve species may have faster growth, greater survival, higher desiccation and temperature tolerance, as well as faster rate of establishment in a disturbed area relative to native species, potentially pushing native species out of some niches (Erlandsson et al. 2006; Ruesink et al. 2006; McKindsey et al. 2007; Nicastro et al. 2008). Suspension feeding of feral farmed bivalves could also theoretically decrease the food supply of other filter feeders occupying the same tidal body of water (Dankers and Zuidema 1995; Cranford et al. 2003; Anderson et al. 2006; McKindsey et al. 2006; GESAMP 2008), as well as decrease larval abundance through passive predation (Troost et al. 2009). Direct field evidence and ecosystem modeling show farmed Blue mussels control the overall phytoplankton biomass in a Prince Edward Island bay where mussel culture accounts for >50% of the bay surface area (Grant et al. 2007; Grant et al. 2008). In restricted environments, competition between mussels can result in decreased growth rate of individuals in some areas, due to decreased food availability (e.g., Karayücel and Karayücel 2000, among others). Feral populations of farmed bivalves grown in off-bottom and suspended culture are expected to be in lower density than those contained in culture facilities, and may have lesser potential for negative impacts with respect to food depletion. However, bivalves that grow infaunally or on-bottom, such as Manila clams and oysters may grow at densities that are similar to or even greater than those in culture situations. Manila clams may dominate infaunal communities in BC, both within and outside of culture sites, at times accounting for a greater biomass than endemic species and may be more abundant in naturalized populations than in farmed ones (Whiteley and Bendell-Young 2007). Similarly, naturalized oysters may grow at greater densities than ones farmed in on-bottom sites, given their propensity for growing in complex 3-D structures. Large densities of bivalves in shallow waters, specifically exotic species, have been shown to be able to control plankton communities in coastal areas (Cloern 1982; Officer et al. 1982). The increased abundance of these species in coastal areas may impact plankton communities in near-shore environments with unknown cascading effects on the greater ecosystem. Such effects have not been examined directly and require research. In contrast, farmed bivalves may indirectly increase primary production by increasing nitrogen turnover in the water column or increasing clarity of the water (Dankers and Zuidema 1995; McKindsey et al. 2006), thereby increasing food supply for competitor species. However, this potential for positive trophic impacts, particularly for feral aquaculture populations, remains theoretical and requires examination.

## Hybridization with wild populations

### Atlantic salmon

One of the greatest concerns regarding escaped farmed Atlantic salmon in the North Atlantic is the potential for interbreeding with wild populations. Genetically distinct populations of wild salmon can be present in different rivers, or even within the same river (e.g., Danielsdottir et al. 1997; Fraser et al. 2008), and there is considerable indirect evidence of local adaptation among distinct Atlantic salmon populations (reviewed in Garcia de Leaniz et al. 2007). In contrast, worldwide aquaculture production of Atlantic salmon is largely based on a few strains (see Thorstad et al. 2008), and some farmed and hatchery salmon are reported to have decreased allelic diversity and decreased heterozygosity (Cross and King 1983; Verspoor 1988; Mjølnerød et al. 1997; Norris et al. 1999), as well as a change in the frequency and types of alleles present (reviewed in Thorstad et al. 2008). Should escaped farmed fish successfully hybridize with wild populations to a significant extent, this could result in 1) a shift in phenotype towards farmed – and presumably less fit – traits, 2) loss of local adaptation, and/or 3) loss of genetic variation that allows for phenotypic plasticity in wild populations.

The extent that hybridization occurs is expected to be context specific. In general, farmed salmon have decreased reproductive potential relative to wild salmon (see pg. 13), and may be temporarily or spatially isolated from spawning wild salmon (Gausen and Moen 1991; Lura and Sægrov 1993; Fleming et al. 1997). Despite this, escaped Atlantic salmon in Europe have been found at spawning grounds concurrently with wild salmon (Thorstad et al. 1998), and evidence of interbreeding with wild salmon has been reported (e.g., Crozier 1993; Webb et al. 1993a; Webb et al. 1993b; Sœgrov et al. 1997; Clifford et al. 1998b; 1998a). In semi-natural competition experiments with wild salmon, farmed male salmon can have low reproductive success (e.g., 1-3% of wild salmon, Fleming et al. 1996). In contrast, farmed females performed better than farmed males when in reproductive competition with wild salmon (e.g., 30% of wild salmon, Fleming et al. 1996). As well, farmed male mature parr have been reported to have higher reproductive success than wild male mature parr (Garant et al. 2003). As such, the primary mechanism of gene flow from farmed to wild populations is through adult female or mature male parr farmed salmon (Fleming et al. 2000; Weir and Fleming 2006). In particular, the poor reproductive success of newly transplanted male farmed salmon in Norway resulted in greater numbers of hybrid offspring (farmed maternal parentage) than pure farmed offspring when similar numbers of wild and farmed salmon were present at spawning (Fleming et al. 2000). In a review of 31 papers on introgression of intentionally stocked salmonids to wild populations, Fleming and Petersson (2001) found 45% of these papers reported little or no introgression from large scale and/or long-term stocking. Escaped farmed salmonids are expected to have even lower introgression rates due to the low numbers of escaped relative to stocked salmonid numbers. However, in areas where small, endangered wild populations are exposed to repeated intrusion by escaped fish (i.e., within the Bay of Fundy, see Figure 1), introgression is probable.

Cultured finfish generally perform poorly in natural conditions relative to wild finfish due to a combination of phenotypic effects of culture rearing and genetic effects of direct and indirect selection for culture and/or founder effects. Those traits with genetic bases could potentially be transferred to hybrid offspring, resulting in decreased fitness of the wild population. The genetic effects of hybridization with escaped farmed fish on wild fish populations have not been well studied in natural environments (see Figure 6 for steps required for escaped farmed fish to impact wild populations through hybridization). A study of farmed, wild, and $F_1$, $F_2$, and backcross ($BC_1$) Atlantic salmon transplanted as eyed-eggs to an Irish river found lifetime success (from eyed-egg to adult), and length of hybrid salmon were intermediate between farmed and wild salmon, depending on the proportion of genetic material obtained from wild or farmed origin (McGinnity et al. 2003). Hybrid offspring of wild and farmed Atlantic salmon in Norway had intermediate length at some life-stages, and hybrid smolts migrated to sea after farmed offspring, but before wild offspring (Fleming et al. 2000). Numerous laboratory and semi-natural studies in various salmonid species have shown partial transfer of a number of

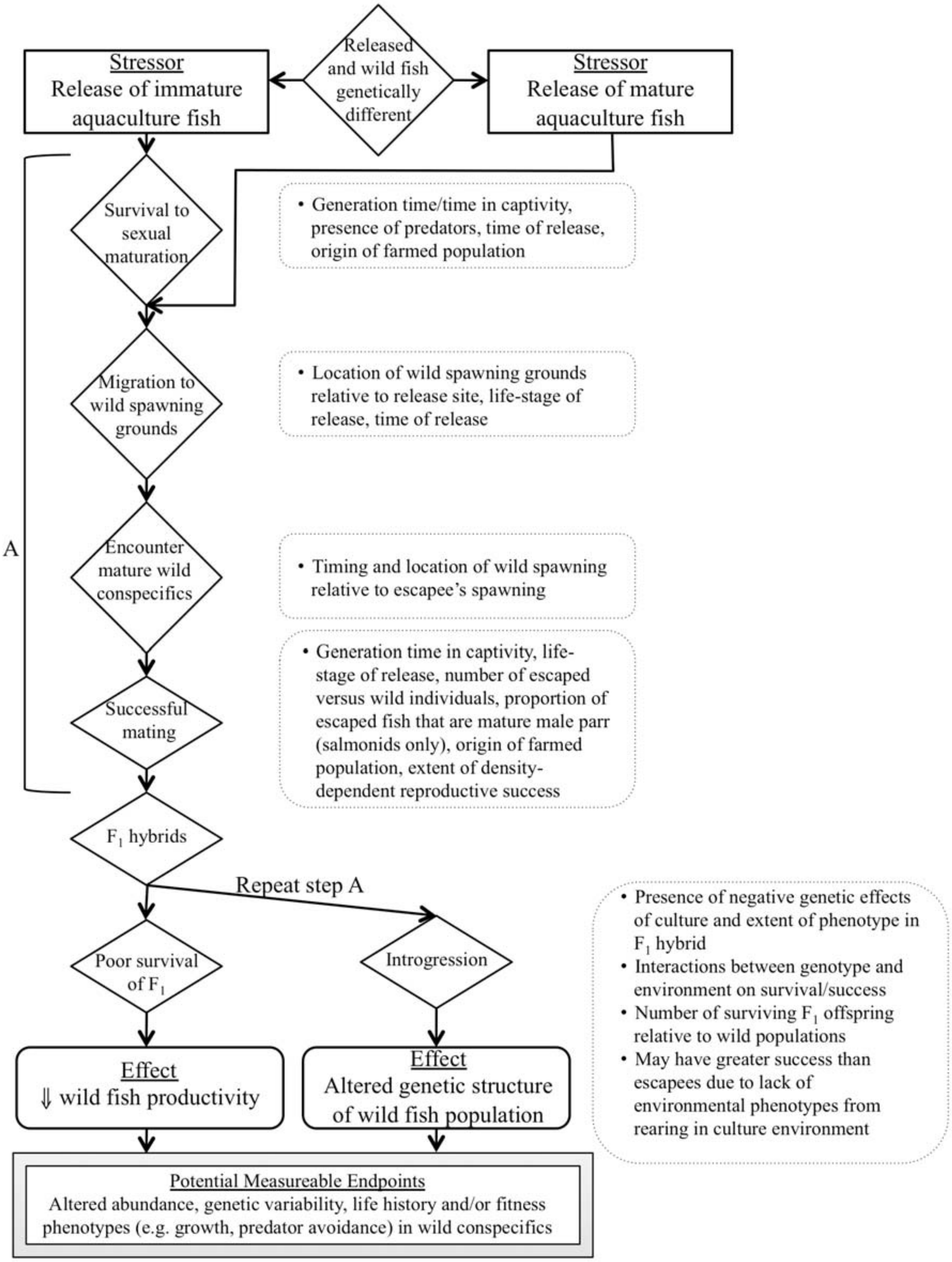

*Figure 6: Effects of released aquaculture salmon on wild fish communities through intraspecific hybridization. Text in diamonds indicates steps required in order for stressor (rectangle) to result in effects (rounded rectangle) and measurable endpoints (double rectangle). Comments in dashed bubbles indicate factors shown to affect potential for each step in stressor-effect scenario. Modified from Kapuscinski et al. (2007).*

cultured phenotypes to hybrid offspring. Studies in farmed x wild hybrids ($F_1$ and $F_2$) and backcrosses of salmon and trout have found apparent additive (i.e., hybrids have intermediate expression of phenotype/genotype between the two parent strains depending on proportion of farmed or wild genotype) and non-additive genetic effects in a number of characteristics including growth rate, general survival or survival in the presence of competition or predation, life-history and morphological traits, pathogen resistance, acid tolerance, metabolic traits, competitive ability, predator avoidance, seawater acclimation, and fecundity (Ayles and Baker 1983; Bryden et al. 2004; McClelland et al. 2005; Tymchuk and Devlin 2005; Tymchuk et al. 2006a; Tymchuk et al. 2007; Houde et al. 2009b; 2009a; Lawlor et al. 2009; Normandeau et al. 2009; Fraser et al. in press). There is also minor, inconsistent evidence for outbreeding depression (i.e., hybrid fish have lower fitness traits than either parent strain) over several generations of hybridization (e.g., hybrid Rainbow trout backcrossed with two generations of wild trout had the lowest survival in semi-natural conditions with predation, Tymchuk et al. 2007). Limited reports of outbreeding depression may be due to limited studies of multiple generations of hybridization, as outbreeding depression may not manifest itself until the second or later generations of hybridization (reviewed by Hutchings and Fraser 2008).

Hybridization with wild populations may also destroy local adaptation of wild fish, and decrease the genetic diversity necessary for genetic adaptability of wild populations to fluctuating environments. For example, Fraser et al. (2008) found wild salmon locally adapted to an acidified river were more resistant to acidified water in laboratory conditions than farmed salmon or $F_1$ farmed-wild hybrids, although wild salmon had similar resistance to $F_2$ farmed-wild hybrids. Comparisons of wild Atlantic salmon from the Tusket River (Southern Upland) and Stewiake River (Inner Bay of Fundy, see Figure 1) found numerous trait differences between these populations (Houde et al. 2009b; 2009a; Fraser et al. in press). As well, the effects of hybridization with farmed St. John strain (origin from Outer Bay of Fundy) differed between Tusket and Stewiake strains, despite them being equidistant from the farmed strain in terms of genetic differentiation (Fraser et al. 2008; Houde et al. 2009b; 2009a; Normandeau et al. 2009; Fraser et al. in press). Consequently, the effects of hybridization with farmed fish are expected to differ among different wild populations of fish. As well, significant genotype x environment interactions have been identified for numerous phenotypes (Ayles and Baker 1983; Tymchuk et al. 2007; reviewed by Garcia de Leaniz et al. 2007). Consequently, the impact of wild x farmed introgression is largely unpredictable (Normandeau et al. 2009), and detailed hybridization data may be necessary to determine changes in fitness from farmed introgression within divergent populations of wild fish (Fraser et al. in press).

Genetic variation of wild fish is thought to cushion, or hide the effects of deleterious recessive genes (see Tymchuk et al. 2006b). Interbreeding of escaped salmon with wild salmon could also result in decreased genetic variability of wild salmon, depending on the circumstances, potentially decreasing genetic and phenotypic fitness of the wild population. For example, modeling data based on a 37 year study of wild and sea-ranched Atlantic salmon spawning in the wild suggested introgression could decrease recruitment and disrupt the capacity of wild populations to adapt to changing waters temperatures associated with climate variability (McGinnity et al. 2009). Genetic diversity of wild salmon populations in Maine (Lage and Kornfield 2006) and Norway (Skaala et al. 2006) have been reported to decrease over time. The cause of this is postulated to be due to hybridization with escaped farmed salmon, but may also be due to bottleneck effects as these populations also decreased in size over time. The above studies demonstrate the potential for negative effects to wild populations through hybridization with escaped farmed fish, although further field work is needed to determine the long-term consequences to wild populations. As well, results from laboratory studies suggests hybridization with farmed salmon could substantially modify the genetic control of gene transcription in wild populations, resulting in unpredictable and possibly detrimental effects to the survival of wild populations (Roberge et al. 2008).

There are some reports of heterosis, or hybrid vigour, in phenotypic effects when two strains of low genetic variability are crossed, particularly if they are not highly genetically divergent (reviewed in Tymchuk et al. 2006b). However, most crosses of farmed and wild finfish result in additive-type effects of phenotypes (see above), and repeated hybridization with escaped farmed finfish would likely remove any heterosis effects of a single hybridization event. In circumstances where wild populations have decreased to the extent that inbreeding occurs, introgression could conceivably improve overall population health by generating hybrids with improved fitness (Fraser et al. in press). Hybridization with farmed fish could also impart a fitness advantage to wild populations in certain circumstances, such as where farmed fish have been selected for improved pathogen resistance, although this has not been examined in fishes (reviewed by Hutchings and Fraser 2008).

Extensive laboratory studies and limited field studies show introgression with farmed fish can cause significant fitness reduction in wild fish. However, the probability of that occurring in natural populations, and the long-term effects to the wild populations, has not been well addressed, and are likely very context dependent. For example, Fraser et al. (in press) suggested Stewiake River Atlantic salmon were more at risk than Tusket River salmon, and have been exposed to greater proportions of escaped salmon (Morris et al. 2008). Consequently, Stewiake salmon are more likely to undergo changes of higher magnitude than Tusket River salmon. Hindar et al. (2006) modeled effects of introgression of farmed salmon into wild using lifetime success rates of escaped salmon in the wild and varying introgression rates. This revealed substantial changes in wild populations (i.e., the percent that was wild) in 10 generations when intrusion rates of farmed salmon were 20%, although low invasion rates resulted in low potential for farmed salmon to become established (Hindar et al. 2006). Once the modeled populations had become mixes of hybrid and farmed salmon, recovery to an all wild-population was unlikely even after many decades of no intrusion (Hindar et al. 2006). Laboratory data have also found restoration to wild phenotype would likely take greater than three generations of wild x hybrid backcrosses (Fraser et al. in press). This would also rely on an absence of further farmed fish intrusion, which would be unlikely in areas of high fish farming intensity. Another modeling study showed that the extinction probability of a wild population was greatest when small wild salmon were exposed to large numbers of frequently intruding farmed salmon (Hutchings 1991), and as such the greatest risk of invading escapees is to small populations of wild salmon. In Eastern North America, estimated numbers of escaped farmed salmon per year average approximately 10% of known wild salmon runs (Johannes 2006), and documented escapes in 1997 approximately equalled the number of wild salmon returns to Nova Scotia and the Bay of Fundy (DFO 2006). Farmed adult salmon have been identified in 22 Eastern North American rivers containing wild salmon populations, 11 of which are endangered (Morris et al. 2008). Of these rivers, 54% had >10% farmed salmon, 41% had >20% farmed salmon, 23% had >80% farmed salmon, and 14% had 100% farmed salmon in at least one year measured (Morris et al. 2008). The rate of intrusions or introgressions in such populations has not been examined, although poor reproductive success of farmed salmon suggests introgression success with wild salmon will be less than 100%. However, Fleming et al. (2000) found when approximately equal numbers of mature farmed and wild Atlantic salmon were transplanted to a river in Norway, hybrids made up at least 25% of the resulting fry, indicating significant introgression is possible between farmed and wild salmon. In areas where wild populations are small and are outnumbered by escaped farmed salmon, the above modeling scenarios suggests there is high potential for extensive introgression or extinction of some wild Atlantic salmon populations due to interbreeding with escaped farmed salmon.

### Other Salmonids

While little work has examined the impact of hybridization of other escaped farmed salmonids with wild conspecifics in natural conditions, laboratory studies in Coho salmon and Rainbow trout (Tymchuk and Devlin 2005; Tymchuk et al. 2006a; Tymchuk et al. 2007) indicate hybridization and introgression with farmed fish will have similar effects to wild populations as Atlantic salmon. However, relative numbers of farmed versus wild conspecifics is expected to be lower for other salmon species than for Atlantic salmon. Consequently, the probability for negative impacts of hybridization with escaped farmed salmonids on wild salmonids is expected to be lower than for Atlantic salmon. For example, the estimated number of Pacific salmon escapes per year is <0.01% of total Pacific North American salmon populations (Johannes 2006). COSEWIC lists one Coho salmon population as endangered in British Columbia (Interior Fraser watershed population), and Steelhead and Chinook as high priority candidates. However, the last reported escaped of farmed Coho salmon and Steelhead in the Pacific Ocean were 1995 and 1987, respectively (BCMAL 2006), indicating there may be limited occurrence of large numbers of escaped Coho and Steelhead salmon hybridizing with wild conspecifics in Canada. Reported Chinook escapes have also greatly declined in recent years, although increasing Chinook salmon aquaculture production may increase potential for escape and effects of hybridization in this species. While low escape numbers and high overall wild numbers may limit effects of escaped Pacific salmon in many circumstances, escaped salmon may cause impacts where at-risk wild populations of Pacific salmon are exposed to large numbers or repeated escapes. For Rainbow trout, the majority of net-pen culture takes place in Ontario (Podemski and Blanchfield 2006), outside its native range, and as such introgression with native wild populations is not a concern in this province. While some freshwater salmonid farming takes place within its native range (e.g., Rainbow trout farmed in British Columbia, Brook trout in Quebec, Arctic charr through much of its farmed range) the impact of potential escaped salmonids on wild populations of conspecifics has not been addressed. Studies examining introgression of various stocked and wild salmonids species suggest freshwater salmonids are more susceptible to introgression than anadromous salmonids (reviewed in Utter 2001). Consequently, wild freshwater salmonid populations such as Rainbow trout may be more susceptible to introgression relative to Atlantic salmon. However, as historic and current stocking of such salmonids often occurs in potential areas of release, often using the same strain, the genetic impact of escaped salmonids may be difficult to separate from impacts of stocked fish on wild populations.

### Marine Finfish

Farmed Atlantic cod escaped from Norway have been found in spawning grounds of wild conspecifics during spawning season (Uglem et al. 2008), indicating potential for hybridization between wild and escaped farmed Atlantic cod. Laboratory studies report poor reproductive success of farmed male cod in competition with wild males, and acoustic studies in the wild found farmed males were prevented from entering spawning areas where wild males existed (summarized by Trippel et al. 2009). In contrast, farmed female cod interacted with wild males at a greater rate than was expected by chance, suggesting significant potential for hybridization of farmed females with wild males (summarized by Trippel et al. 2009). As well, Atlantic cod are capable of spawning within net-pens, and suppressing maturation of cod through light alterations in net-pens has proved unsuccessful (Trippel et al. 2008). Jørstad et al. (2008) reported Atlantic cod in Norway spawned while contained in their net-pens, and the resulting larvae made up 20% of the local wild population after spawning. These offspring would presumably not have environmental disadvantages associated with culture rearing, but would contain genetic changes associated with direct and indirect selection as well as non-genetic maternal effects (e.g., egg size) associated with the culture environment. Should they successfully mature and mate with wild populations, this could result in introgression of farmed traits within the wild populations. The effects of such introgression on wild Atlantic cod have been poorly examined. Atlantic cod have less population structure than Atlantic salmon (summarized by Trippel et al. 2009), and potentially less local adaptation than salmon. As such, impacts of hybridization with escaped farmed cod may not be as great as for salmonids in terms of disruption of local adaptation. However, genetic variability and different genetically-based responses exist among cod populations, and cod populations differ on a smaller spatial scale that previously thought (Hutchings and Fraser 2009; Trippel et al. 2009). Consequently, disruption of local adaptation of wild cod through introgression with escaped cod cannot be ruled out. Several populations of Atlantic cod in Canada are listed as endangered, threatened or of special concern by COSEWIC, and introgression with farmed strains may further threaten these populations. Currently, wild stocks of Atlantic cod greatly outnumber aquaculture production of cod in Canada, and as such, impacts of hybridization may not be as great as for Atlantic salmon where aquaculture production far exceeds wild population numbers. However, should cod culture continue to expand and wild cod populations continue to decline in Canada, the probability and magnitude of effects to wild cod populations through hybridization with escaped cod will increase. The potential for hybridization of escaped Sablefish with wild conspecifics has not been examined.

Bivalves

As bivalves are broadcast spawners, farmed bivalves have potential to hybridize with local wild conspecifics while contained within aquaculture apparatus or as feral populations established outside aquaculture apparatus. On the West Coast, the majority of farmed species are non-indigenous (McKindsey et al. 2006), and do not have associated risks of intraspecific hybridization with native wild conspecifics. Hatchery-reared native bivalves may have similar introgression effects observed in finfish (see above). Genetic selection in bivalves has resulted in genetic drift, loss of rare alleles, and decreased genetic variability, although it has had inconsistent effects on heterozygosity (Dillon and Manzi 1987; Vrijenhoek et al. 1990; Durand et al. 1993; Sakai et al. 2000; Carlsson et al. 2006), and has resulted in altered phenotypes such as larval survival and metamorphosis success (Taris et al. 2007). While the effects of introgression between hatchery-reared and wild bivalves have not been well addressed, finfish models suggest it would be detrimental, particularly where farmed bivalves greatly outnumber wild bivalves. Currently, there is only minor use of hatchery-produced native bivalves in Canada, and the above pathway is likely not of great relevance in Canada. However, use of hatchery-raised bivalves is greatly increasing worldwide, and this trend may also affect native bivalve culture in Canada, with resulting increased potential of introgression impacts to wild populations in the future.

The majority of farmed bivalve operations on the East Coast use seed collected from wild populations and grown in or near the area of collection (McKindsey et al. 2006). However, there may be some circumstances where hybridization of these wild-caught bivalves with wild populations may be detrimental to the wild populations, i.e., when farmed bivalves are transplanted to an area that contains genetically distinct wild populations, or where the culture environment results in a shift in genotype of the farmed populations. Translocation and consequent hybridization between previously isolated stocks can result in similar effects as hybridization between wild and domesticated individuals (reviewed by Cook et al. 2008). For example, translocation of Pearl oysters (*Pinctada margaritifera cumingii*) in French Polynesia resulted in homogenization of previously genetically distinct wild populations in seven atolls

(Arnaud-Haond et al. 2004). In some areas of Atlantic Canada, Blue mussels are transplanted over several kilometres to areas that do not have local designated collection sites, from areas that have desirable populations of mussels (e.g., from areas that have pure *M. edulis*, rather than mixed populations of *M. edulis*, *M. trossolus* and their hybrids, see Penney et al. 2006, or from areas that have preferred genetic traits, Tremblay et al. 1998b). However, whether farmed populations are transferred to areas containing genetically distinct wild populations is not always known. Wild populations of bivalves may be genetically isolated on a small spatial scale (e.g., embayments with circulating gyres may result in self-recruiting populations), or may recruit from tens to hundreds of kilometres away (see Beaumont 2000). Information on the genetic differences between farmed and local wild populations is necessary to determine the potential for genetic impacts to wild populations from hybridization with farmed individuals (Beaumont 2000). Because of this issue, movement of the Sea scallop for aquaculture purpose is restricted in Quebec. The culture environment has also been reported to influence the genetic make-up of wild caught bivalves. Farmed Blue mussels in one area of Eastern Canada are reported to have decreased heterozygosity relative to the wild population they were collected from, possibly due to more heterozygous individuals having increased mobility with consequent increased risk to fall-offs from turbulence and/or self-thinning (Tremblay et al. 1998a; Myrand et al. 2009). Whether this decreased heterozygosity could be transferred to hybrid offspring of wild and farmed bivalves has not been addressed, and would depend on whether the more heterozygous farmed individuals were truly lost to the system, or persisted outside the culture apparatus.

## Reproductive interference with wild populations

Other than intraspecific hybridization (discussed above), escaped finfish have the potential to reproductively interfere with wild populations through nest destruction, disruption of mating patterns, and interspecific hybridization, resulting in decreased reproductive productivity of the wild population. Potential for such interactions are most obvious between escaped farmed finfish and different species of wild fish utilizing similar spawning areas, but may also take place between conspecifics of farmed and wild salmon (see Figure 7 for steps necessary for farmed escapees to effect wild populations through reproductive interference).

### Atlantic Salmon

While reproductive interference from escaped fish has not been directly studied in the wild, indirect evidence and studies with non-farmed salmonids suggests it may occur in some circumstances. While relative spawning time has not been well studied, several studies have reported adult escaped farmed Atlantic salmon ascend rivers later than wild populations (Gausen and Moen 1991; Carr et al. 1997a; Fleming et al. 1997), suggesting they may spawn later in some circumstances and potentially superimpose nests on prior deposited wild nests. In contrast, Lura and Sægrov (1993) found escaped farmed Atlantic salmon spawned earlier than wild salmon, and Carr et al. (1997b) found net-pen escaped Atlantic salmon did not migrate to wild spawning grounds. In these circumstances escaped salmon would not have associated nest-destruction risks. However, depending on the relative timing between early and late spawners, earlier spawners may prevent access to the highest quality spawning sites and mates, which could reduce or delay reproduction of slightly later spawners. The timing and

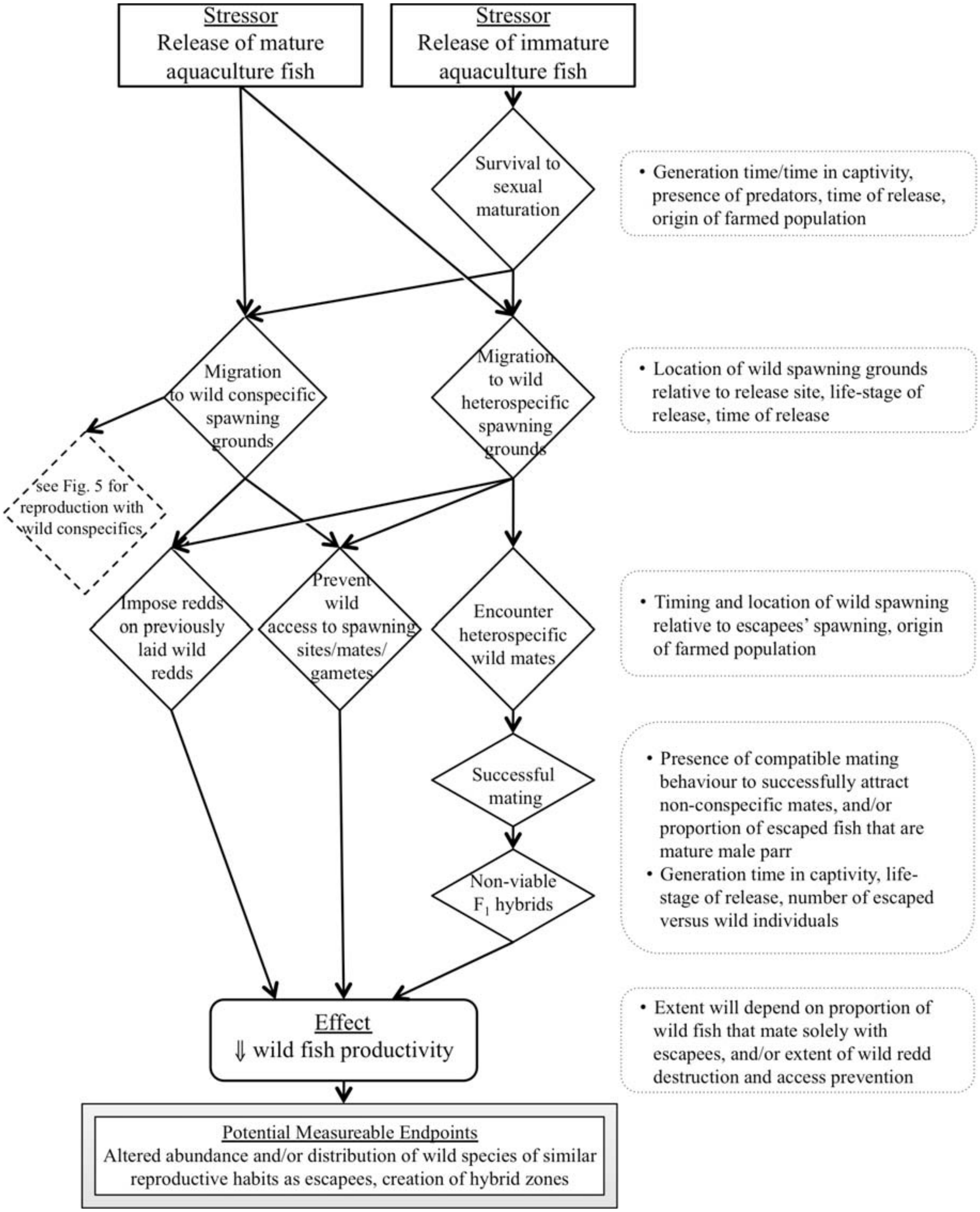

*Figure 7. Effects of released aquaculture salmon on wild fish communities through reproductive interference. Effects of viable $F_1$ hybrids are discussed in Figure. 6. Text in diamonds indicate steps required in order for stressor (rectangle) to result in effects (rounded rectangle) and measurable endpoints (double rectangle). Comments in dashed bubbles indicate factors shown to affect potential for each step in stressor-effect scenario.*

location of hatchery-escaped spawners is not well studied, and may be more similar to wild salmon (Lacroix and Stokesbury 2004). Consequently, the potential for intraspecific reproductive interference in Atlantic salmon may vary depending on the release time, and spawning time and migration of escaped salmon.

There is concern over potential for interspecific reproductive interference between escaped Atlantic salmon and wild Pacific salmon in British Columbia. While escaped Atlantic salmon are expected to have low reproductive potential in British Columbia (Volpe et al. 2001b), adult Atlantic salmon have been reported in >80 rivers in British Columbia, and feral juveniles have been reported in 3 rivers (Volpe 2000; Volpe et al. 2000; Thorstad et al. 2008). As such, the presence of reproductively mature Atlantic salmon in some British Columbia streams should be expected. Field and laboratory data suggest little potential for hybridization between Atlantic and Pacific salmon species. There are no known reports of natural hybridization between Atlantic salmon and Pacific salmonid species, either where Atlantic salmon are introduced to Pacific areas, or where Pacific salmon are introduced to Atlantic areas (reviewed in Waknitz et al. 2003). Laboratory crosses between Atlantic and Pacific salmonids are generally non-viable, with the exception of low numbers of viable offspring in one Pink x Atlantic salmon cross, and one Steelhead x Atlantic salmon cross (reviewed in Waknitz et al. 2003). Escaped Atlantic salmon are expected to spawn after fall-spawning Pacific salmon species, and before spring-spawning Steelhead runs (Volpe et al. 2001a), and as such offset spawning time should further minimize hybridization potential. Should spawning between Atlantic salmon and Pacific salmon take place at similar times, studies in a Lake Ontario tributary between established non-native Pacific salmon and hatchery-raised Atlantic salmon suggest Chinook and Atlantic salmon may not attempt to hybridize when suitable conspecifics mates are available (Scott et al. 2003), but Chinook salmon may attempt to hybridize with Atlantic salmon in the absence of suitable conspecifics mates (Scott et al. 2005). As such, any attempted reproductive hybridization between Atlantic and Pacific salmon may not impact the main population of breeding Pacific salmon. However, more research is needed, particularly in natural situations within native habitat of Pacific salmon. As well, the role mature male parr may have on hybridization between non-conspecific escaped and wild fish has not been examined. Youngson et al. (1993) found when examining hybridization between wild or farmed Atlantic salmon and brown trout, farmed female Atlantic salmon were almost nine times more likely to hybridize with brown trout than wild female Atlantic salmon. While this particular cross is not relevant to native Canadian systems as brown trout are non-native, it suggests escaped salmonids may reproductively interfere with similar wild salmonid populations by drawing male attention away from wild females. As well, escaped farmed Atlantic salmon may hybridize with established non-native brown trout populations that may be of interest to the recreational fishing industry. Farmed Atlantic salmon in a controlled stream in British Columbia were found to spawn in habitats typical of Pacific salmon, although at slightly different times than Coho or Steelhead salmon (Volpe et al. 2001b). As such, they may superimpose redds on nests of Pacific salmon that spawn at an earlier time, although suitable spawning sites are likely not limiting in British Columbia (Volpe et al. 2001a). The capacity for reproductive interference by escaped Atlantic salmon on Pacific salmon appears limited, but should not be discounted, particularly if large numbers of Atlantic salmon migrate to spawning areas of low numbers of Pacific salmon.

### Other Finfish

The potential for reproductive interference between other aquaculture finfish species listed in Table 2 and native populations of finfish has not been examined, although widespread extirpation of cutthroat trout by hybridization with stocked Rainbow trout has been noted (reviewed in Waknitz et al. 2003).

Bivalves

As bivalve species of interest in Canada are broadcast spawners, there is no expected risk of escaped farmed species disrupting mating patterns of wild bivalve populations. However, there is some risk of interspecies hybridization between farmed and native mussels on both coasts. In British Columbia, introduced *Mytilus edulis* and *M. galloprovincialis* have been shown to hybridize with native *M. trossolus*, although the hybrid abundance is unstable and is likely only maintained by repeated introductions from aquaculture (Shields et al. 2008). In this case there is no apparent hybrid vigour (Matson et al. 2003) and *M. trossolus* appears to maintain a pure population (Shields et al. 2008), although hybridization with introduced species may decrease reproductive productivity of *M. trossolus*. In Atlantic Canada, the main mussel farmed is *M. edulis*. However, there are wild native populations of *M. edulis*, *M. trossolus*, and their hybrids, and the proportion of pure and hybrid forms in natural populations varies from site to site (Penney et al. 2006). *M. trossolus* tends to have slower growth than *M. edulis* in culture. To maintain consistent growth of farmed mussels, some provinces tend to collect mussel spat from pure *M. edulis* areas for culture grow-out in areas where the natural set is mixed *M. edulis*, *M. trossolus*, and their hybrids (Penney et al. 2006). Reproduction of these pure *M. edulis* farmed populations with mixed *M. trossolus*/*M. edulis* populations may increase the proportion of hybrids present in the wild population. The potential for and consequences of this has not been addressed to our knowledge, but may decrease the health of the wild population if local conditions favour the growth of *M. trossolus* over *M. edulis* or their hybrids.

There is minor interest in Canada in inducing triploidy in hatchery-produced bivalves to prevent decreased growth and meat quality during sexual maturation (see Leggatt 2009). While most triploid bivalve species are functionally sterile, some species are sexually mature and release aneuploid gametes (e.g., Manila clams, Pacific oysters, Guo and Allen 1994; Utting et al. 1996). There is concern that release of large quantities of aneuploid gametes from triploid bivalves in areas of wild conspecific populations may result in non-viable hybrid offspring, and decreased productivity of the wild populations. However, poor performance of triploid bivalves has restricted current use of these organisms for aquaculture in Canada to research phases only (see Leggatt 2009). As well, of the triploid bivalves that are known to reproductively mature (e.g., Manila clams and Pacific oysters), none are native to Canada. Consequently, there is little current potential for triploid bivalves to affect wild populations in Canada.

## Strength of evidence, knowledge gaps and recommended research

There are substantial laboratory and semi-natural studies, as well as limited natural and modeling studies that demonstrate escaped Atlantic salmon can impact wild populations of Atlantic salmon through juvenile competition as well as hybridization pathways. However, other POEs of Atlantic salmon escaped species (i.e., marine competition and predation, reproductive interference), as well as POEs of other escape species are less well studied.

There is substantial evidence that feral Atlantic salmon parr can outcompete wild parr for resources in some circumstances. Limited natural studies demonstrate that this can result in displacement and decreased productivity of wild parr, and these studies support semi-natural studies demonstrating decreased productivity of wild parr from the presence of escaped juveniles or hybrids. However, these studies also demonstrate the potential for and magnitude of effects is very context dependent, and is influenced by residency status, size differences between wild and escaped fish, presence of predators, and ratio of wild to escaped fish, among others. The potential for competition or predation effects of escaped Atlantic salmon in the marine environment has not been directly studied. Studies in the Pacific, and limited studies in the Atlantic, suggest the presence of density-dependent body size, but not survival, in wild salmon populations. Whether increasing density of wild populations with escaped farmed salmon may decrease body size of wild salmon has not been directly studied. There are relatively few studies of trophic effects of other escaped farmed species on wild fish populations. Limited studies suggest other species of escaped salmonids may impact wild populations through juvenile freshwater competition as observed with Atlantic salmon. However, there is a paucity of data regarding trophic effects of escaped non-Atlantic salmon in the marine environment, and further research is required to determine the potential for such effects.

Numerous laboratory and semi-natural studies, and limited natural and modeling studies demonstrate that hybridization between wild and escaped Atlantic salmon is possible, and can result in transfer of farm genotype to hybrid offspring, decreased productivity of wild populations, and may result in extirpation or extinction of wild populations in some circumstances. As with trophic effects the potential for and magnitude of hybridization effects are very context specific, and can be influenced by the health of the wild population, strain differences, wild-to-escaped fish ratios, among others. However, the long-term effects of repeat intrusion of escaped salmon (as likely occurs in areas of high aquaculture intensity such as the Bay of Fundy) are not known, although limited semi-natural studies and modeling data suggest recovery to an all-wild genotype would take several generations, if at all, once escape intrusions ceases. The effects of hybridization between other escaped farmed species and wild conspecifics have received less attention than Atlantic salmon. However, limited semi-natural studies in Rainbow trout and Coho salmon indicate hybridization and introgression effects would be similar to those of escaped Atlantic salmon. However, further research is required, particularly in marine species such as Atlantic cod, to determine if Atlantic salmon hybridization effects can be generalized to other species of escaped finfish. Escaped salmonids may also affect wild populations through reproductive interference (e.g., nest destruction, intraspecific hybridization, etc.). This potential has been poorly studied, and is likely context-dependent (e.g., dependent on relative spawning time and location of wild and escaped fish, species of wild and escaped fish, etc.), although further research is required. The potential for reproductive interference effects of marine species such as Atlantic cod have not been identified.

Negative effects of escaped bivalves or their reproductive material on wild shellfish populations have received limited direct attention in Canada, and such studies are limited to hybridization studies of exotic mussels. However, extensive studies outside Canada have found non-native bivalve species used in Canadian aquaculture can outcompete native shellfish utilizing similar habitat under some circumstances. Whether such effects have occurred or are possible in Canadian systems is not known. The effects of wild-caught escaped bivalves used in local habitat are not expected to differ from those of local wild populations. There is potential for wild-caught farmed escaped bivalves that are transferred to non-local habitat to impact wild populations in the recipient environment through hybridization effects. However, the potential for such has not been addressed. There is evidence that non-native mussels in British Columbia form unstable hybrid zones with native species in BC. However, the potential for other reproductive interference effects (e.g., effects of hybridization with sterile triploids) of escaped bivalves or their reproductive material has not been examined.

The current data on the effects of escaped farmed fish on wild fish populations indicate effects are possible, but factors influencing the type, probability, extent, and magnitude of effects require further identification and characterization. The potential to generalize between species of escaped fish, as well as to extrapolate effects from laboratory or semi-natural to natural populations, or even between field-to-field studies, requires examination. As well, there is a paucity of data examining effects of escaped farmed fish on wild fish communities – i.e., whether and to what extent the effects to one wild fish population will affect other community members that are reliant on or influenced by the affected population. Overall, the effect of escaped farmed fish on wild fish at the population and community levels requires further examination. The following recommended research should be addressed to better predict the consequences of escaped farmed fish on wild fish populations and communities.

- All relevant data indicates that effects of escaped fish are very context-dependent. In particular, the probability and magnitude of effects will be influenced greatly by the health of the population being affected. Research is needed to improve our understanding of factors influencing the vulnerability and resilience of wild populations to escaped farmed fish, particularly in areas containing high densities of net-pens or shellfish culture (e.g., Bay of Fundy, Broughton Archipelago, and Northern Lake Huron).
- More work is needed to examine the consequences (e.g., lifetime success) to wild populations in terms of competition and hybridization with, and predation on wild fish, given relevant varying factors (i.e., escaped versus wild species/strain, life stage, time and location of release, wild and escaped fish ratios, etc.). These could be addressed with targeted in-depth investigations in well-defined ecological systems where escapes are known to occur and reproduce (e.g., through continuing and expanding studies in the Bay of Fundy, initiating studies of Atlantic salmon and Pacific oysters in BC, and Rainbow trout in Newfoundland).
- Whether direct effects of competition with or predation on wild populations indirectly affect overall community dynamics could be addressed through modeling (i.e., through use of Ecopath with Ecosim). For example, Harvey and Kareiva (2005) modeled how removal of non-native finfish predators from a reservoir would affect juvenile salmonid prey species. They found removal of non-native predators had little effect on native prey population size due to indirect food-web effects that resulted in increased populations of native predators of juvenile salmonids. Applying this model in reverse, if introduction of escaped farmed fish resulted in decreased productivity of native competitor species without affecting prey species productivity, these effects would only be observed by examining effects on multiple species within the local food-web.
- The long-term effects of frequently intruding aquaculture fish brought about by multiple POEs (e.g., juvenile competition, hybridization) have not been well addressed. The probability for and range of such effects could be examined through modeling scenarios given relevant experimental information (e.g., introgression and competition rates), or potentially through long-term examination of a well-defined ecological system where escapes and effects are known to be occurring (e.g., continuation and expansion of Magaguadavic River studies in New Brunswick).
- Some studies report similar effects of other escaped finfish species (e.g., Coho salmon and Rainbow trout) through juvenile competition and hybridization pathways, suggesting generalizations among salmonid species can be made in some circumstances. However, a wider variety of research is needed to determine the extent to which generalizations can be made between species (i.e., between Atlantic salmon studies and studies with other salmonids, Atlantic cod, and Sablefish) and ecosystems, and what factors may influence the suitability of such generalizations.
- The majority of studies examining POEs of escaped finfish to wild fish populations have used laboratory or semi-natural experiments. These have shown that effects may be influenced by environmental and strain differences. Research is needed to identify critical variables that influence laboratory/semi natural-to-field – as well as field-to-field –

extrapolations. This could determine the extent that extrapolations can be made, and could incorporate uncertainty into the POE process.

- Whether feral populations of escaped fish have competitive, predation, or reproductive effects associated with culture should be addressed. In particular, the interactions between genotype and environment on fitness traits of farmed fish affecting competition, predation, and reproductive effects needs to be explored to better understand the range of effects escaped farmed fish may have on wild populations over one or many generations. For example, models with varying relationships between genotype, phenotype, and fitness could be developed to help predict the consequences of introgression (Tymchuk et al. 2006b).
- Transfer of wild bivalve stocks between locations for purposes of aquaculture could theoretically affect genetic structure or proportion of hybrids of wild populations in the recipient location. The potential for such could be determined by examining genetic differences between local and transferred stocks, and whether transferred stocks significantly introgress with the local wild populations.
- Determining effects of feral populations of non-native bivalves is expected to be problematic as the main non-native farmed bivalves (Pacific oysters, Manila clams) have been established in Canadian waters since the early 1900's, and some ecosystem effects have likely stabilized to a new equilibrium. However, the abundance of Pacific oysters is, at times, increased in foreshore areas adjacent to suspended oyster culture sites relative to distant, otherwise similar, foreshore areas, suggesting that such farm sites increase recruitment of the species locally. Similarly, McQuaid and Phillips (2000) suggest that most recruitment of the Mediterranean mussel occurred in areas immediately surrounding the culture site from which larvae were dispersing, although modelling suggested that larvae would be transported a great distance from the farm site. Thus, impacts may be limited to local effects and should be evaluated. Localized effects due to increased abundances of oysters in intertidal zones due to the introduction of the Pacific oyster for aquaculture purposes have been observed in Argentina (Escapa et al. 2004). Similar studies should be done in Canada.
- Should hatchery-reared native stock or triploidy use increase in bivalve aquaculture, or exotic bivalve use expand in Canada, the potential effects of these on wild shellfish populations should be examined prior to increased or expanded use.
- The success rates of escaped female, male, and mature male salmonid parr to compete for wild mates needs to be addressed considering: ratios of wild to escaped individuals, life-stage of release (length of time in natural environment), location or time of year of release relative to wild spawning location/time, etc. In particular, the spawning success rates of escaped farmed salmon in East Coast rivers should be more thoroughly examined.
- The relative spawning time, duration, and habitat use of escaped farmed versus wild species utilizing similar spawning habitat needs to be examined to determine the potential for nest destruction of wild species and other spawning interference.
- Whether escaped salmon in either Atlantic or Pacific regions cause increased density of wild populations, resulting in negative density-dependent effects (e.g., decreased body size) on wild populations could be addressed.

## EFFECTS: CHANGES IN FISH HABITAT

### Salmonids

Nest digging of wild salmonids and mass spawning mortality of wild Pacific salmon species could potentially alter the stream habitat of some aquatic invertebrates. Redd construction of Pacific salmon is reported to decrease stream insect and algal biomass by 75-85% (Moore and Schindler 2008), decrease macrophytes, algae and mosses, modify pool-riffle character (Field-Dodgson 1987), decrease insect density, and alter insect community structure (Minakawa and Gara 2003). Such effects are likely due to alteration in habitat of invertebrates and algae through redd digging. Escaped salmonids from aquaculture could potentially influence redd-induced alteration in invertebrate and algae habitat by 1) increasing number/density or distribution of salmonids constructing redds, or 2) decreasing wild salmonid abundance thereby decreasing the number of adults constructing redds. However, the potential for escaped farmed salmonids to influence redd-induced habitat alterations has not been investigated either directly or indirectly, and cannot be assessed at this point.

Mass spawning mortality of wild Pacific salmon species may increase the abundance of some macroinvertebrates by providing temporary habitat and food resources. For example, Minakawa et al. (2002) found insect community biomass and individual caddis fly larvae biomass increased in the presence of salmon carcasses. However, these benefits may be restricted to rivers with sediment particles greater than 32 mm, while those with particles less than 32 mm may be negatively affected by salmon carcass loads on benthic macroinvertebrates (reviewed in Janetski et al. 2009). The carcasses of escaped salmonids could alter bottom habitat for macroinvertebrates by 1) increasing density or distribution of fish carcasses (predominately in escaped Pacific salmon), or 2) decreasing wild Pacific salmonid abundance (through mechanisms listed above) and reducing the total biomass of carcasses added to the river. The potential for escaped farmed salmonids to affect carcass-induced alterations in habitat has not been investigated either directly or indirectly, and cannot be assessed at this point. However, such effects, if they occur, would be restricted to the Pacific region. In contrast, Atlantic salmon do not die after spawning and therefore do not introduce a significant source of nutrients in the form of carcasses to spawning rivers and streams.

### Marine Finfish

Escaped farmed Atlantic cod and Sablefish are not expected to alter fish habitat to an appreciable extent since they are repeat spawners that spawn in the marine environment.

### Bivalves

The physical presence of bivalves in culture can greatly affect fish habitat, primarily through enhancement by providing three-dimensional structure as habitat (see McKindsey in press). Farmed populations can be established beyond the original culture site when larvae are released and provide similar structure, and result in far-field effects to fish habitat. The main bivalves farmed in Canada (oysters and mussels) are considered foundation species, i.e., species that are dominant in abundance and/or biomass and have positive effects on community inhabitants due to their physical presence (McKindsey et al. 2007). Farmed bivalves obtained from local stocks (e.g., as in Atlantic Canada) are not expected to alter fish habitat. However, non-native bivalves (e.g., most bivalve culture in Pacific Canada) can alter fish habitat by either creating new or modifying existing habitat structure where no native foundation species exists or by partially or completely replacing native foundation species. Non-native farmed bivalves (e.g., Pacific oyster, Mediterranean mussel, Manila clam) have become established in Pacific Canada, but the effects of these feral populations on native fish habitat have been poorly examined in Canada. Pacific oysters can inhibit growth of eelgrass (defined by DFO as sensitive habitat important for fish and invertebrates, Vandermeulen et al. 2006) in British Columbia (Kelly and Volpe 2007). The exclusion of eelgrass by feral populations of Pacific oysters could result in loss of species that depend on eelgrass for cover, settlement, and critical habitat. Research is needed to confirm this and evaluate other potential effects of feral populations of non-native farmed bivalves in Canada. However, effects of the main non-native species farmed in Canada, Pacific oysters and Mediterranean mussels, have been noted in other areas where these species have become established. Oyster and mussel beds can influence benthic finfish, invertebrates, and macroalgae by creating three-dimensional habitat, shelter, enhancing settlement and recruitment, causing sediment accumulation and influencing sediment porosity, and influencing food supply and biogeocycling pathways (reviewed by McKindsey et al. 2007; Cook et al. 2008). In areas where there are no foundations species, creation of mussel or oyster beds can greatly increase species abundance and diversity (reviewed by McKindsey et al. 2007). The partial or complete replacement of native foundation species with feral non-native bivalves is reported to have little or no effect on community structure (e.g., Robinson et al. 2007; Hanekom 2008), cause a shift in community structure (e.g., Kochmann et al. 2008), or increase species richness, abundance, biomass and/or diversity (e.g., Robinson et al. 2007; Markert et al. 2010). The potential effects of feral non-native bivalves on fish habitat are influenced by tidal zone (Robinson et al. 2007), species, location, age, and type of habitat (reviewed by Cook et al. 2008). Whether feral populations of non-native farmed bivalves can cause similar effects in Canada is not known, but worldwide studies indicate some effects may be likely in some circumstances.

Established feral populations of farmed bivalves may also impact fish habitat by altering organic cycling. Benthic filter feeders, including species listed in Table 2, are important in cycling organic matter from the water column to the sediments. For example, oyster reefs and mussel beds are sites of intensive organic matter decomposition and inorganic nutrient supply. They catalyze the flux of nutrients from the water column to the sediments, by consuming phytoplankton and depositing organic matter to the benthos through biodeposition. They retain organic matter in estuary systems that may otherwise be lost to the water column, potentially increasing the diversity and abundance of benthic organisms (Kautsky and Evans 1987; Dankers and Zuidema 1995; Cranford et al. 2003; NAS 2004). However, the potential for feral populations of farmed bivalves to impact suspended sediment concentrations in Canadian waters has not been examined. Where native species of bivalves are used, negative or positive effects are not expected to differ greatly from those of wild populations. Where non-native bivalves are farmed, long histories of establishment make determining the effects of feral populations difficult. However, potential changes in fish habitat should be addressed if new exotic species are introduced to culture, or current use of non-native bivalves expands to new areas or sites in Canada. These knowledge gaps may be addressed by comparing areas where exotic bivalves have established to areas where they have not.

## EFFECTS: CHANGES IN WATER QUALITY

### Salmonids

Escaped finfish and shellfish have the potential to alter food availability and supply. Escaped Pacific salmon species may cause large nutrient fluxes in stream ecosystems through mass mortality following spawning resulting in both beneficial and adverse effects, For example, Chinook carcasses can increase total phosphorous, soluble reactive phosphorous, inconsistently increase periphytoplankton biomass, increase litter mass loss rate (Yoder et al. 2006), increase biofilms of bacteria and eukarya that in turn result in increased insect and finfish populations (Schuldt 1998), food resources, and productivity of juvenile salmon (Shaff and Compton 2009). A literature review found Pacific salmon carcasses had positive, but very inconsistent effects on dissolved nutrients, sediment biofilm, macroinvertebrate and resident finfish communities, and isotopic enrichment (reviewed in Janetski et al. 2009). In contrast, Zhang et al. (2003) found pulsed marine-derived nutrients from spawned salmon indirectly decreased detrital processing in streams, while Foggin and McClelland (1983) found spawned Kokanee carcasses had no effect on stream or nitrate-nitrogen concentrations, but did increase total phosphorous concentrations. As well, salmon carcasses may release bioaccumulated contaminants to the spawning streams. For example, O'Toole et al. (2006) found spawning Chinook salmon in Lake Ontario increased total PCB's, DDT's and other organochlorine compounds downstream of spawning site.

Escaped farmed salmonids may alter the magnitude – and hence the scale of effects – of this mortality by increasing the number of spawning salmon present, or by negatively affecting wild salmon population numbers resulting in lower numbers of salmon present in spawning grounds. For example, large scale escapes of farmed Chinook or Coho salmon may result in increased river carcass loads, should escaped salmon survive and migrate to spawning grounds. However, the potential for escaped salmon to affect carcass-induced alterations food and water quality has not been investigated either directly or indirectly, and cannot be assessed at this point.

### Marine Finfish

Other than potentially decreasing food availability, escaped farmed Atlantic cod and Sablefish are not expected to alter water quality to an appreciable extent.

### Bivalves

Farmed bivalves have potential to impact various components of water quality, both negatively and positively (see Chamberlain and Page in press, for relevant POEs). Feral populations established beyond the original culture site via the release of gametes may have similar but far-field impacts. Bivalve culture can affect food webs by increasing or decreasing phytoplankton and primary production in the water column and potentially increase primary production by increasing nitrogen and/or silicate availability, and/or decreasing turbidity (Kasper et al. 1985; Dankers and Zuidema 1995; Bastien-Daigle et al. 2007). In contrast, bivalve culture may decrease primary production by decreasing algal biomass through filter feeding (Dankers and Zuidema 1995). This can result in stabilizing phytoplankton blooms in the ecosystem (Anderson et al. 2006), or may contribute to more frequent algal blooms (Cranford et al. 2003), which may indirectly effect on oxygen levels in the water column. Whether these impacts are positive or negative will vary depending on environmental conditions. The potential for feral populations of farmed bivalves to affect water quality has not been investigated in Canada. As with habitat alterations, farmed species in their native habitat are not expected to cause effects beyond those observed from wild conspecifics. In contrast, feral populations of non-native farmed bivalves may cause changes in water quality far-field from the culture site. However, in bivalve culture, the scale or intensity of operations appears to be the main driving force for negative effects (Bastien-Daigle et al. 2007). As the intensity of feral populations established on the benthos beyond the local culture site is expected to be lower than farmed water column populations, the potential for negative effects on water quality from feral farmed bivalves is likely low.

## INTERACTIONS WITH OTHER STRESSORS ASSOCIATED WITH AQUACULTURE

There are few expected interactions between the escape (release) of farmed organisms and other stressors identified in other Pathways of Effects associated with aquaculture (i.e., alteration in light; release of chemicals and litter; release of pathogens; release or removal of nutrients, non-cultured organisms, and other organic material; physical alteration of habitat structure; noise), and any impacts would be anticipated to be minor. Should future aquaculture use genetically modified organisms, such as transgenic fish containing bioactive compounds, the escape of these organisms would constitute a release of chemicals into the natural environment and their effects should be considered. Such "toxic" effects are currently regulated under the Canadian Environmental Protection Act (CEPA) 1999. If escaped farmed organisms are infected with pathogens, this would be considered a release of pathogens to the environment. The potential for escaped organisms to transfer pathogens to wild populations relative to those contained in net-pens is not known. Escaped organisms may have greater potential to transfer disease to distant wild populations, or may have lower potential to transfer disease due to dilution effects of fewer fish in a larger body of water. Escaped or feral populations of farmed organisms can result in the removal of food and oxygen and the release of excretory waste in areas beyond the site of culture. The potential for removal of food is discussed in the sections 'Competition with, predation on, and providing prey for wild fish populations' and 'Effects: changes in water quality'. Any effects of oxygen removal or release of excretory wastes are expected to be lower than at the aquaculture site due to the dilution effect of fewer organisms in a larger body of water.

## CONCLUSIONS AND RECOMMENDATIONS

### PATHWAY OF EFFECTS DIAGRAM

Aquaculture is an extensive business in Canada, representing >150,000 tonnes of product to market per year. While the extent of aquaculture escapes in Canada is unknown, there is clear evidence for frequent low magnitude escapes and occasional large magnitude escapes of various salmonid species, as well as reproductive escape of non-native bivalves farmed in Canada. The POEs through which escaped farmed organisms may cause negative effects to natural components of Canadian ecosystems are outlined in Figure 8.

### SUMMARY OF EFFECTS OF AQUACULTURE ESCAPES

Field, semi-natural, and laboratory studies show that the potential and severity for escaped farmed organisms to persist in and negatively affect components of Canadian aquatic environments are very context-dependent. They are also influenced by numerous factors including aquaculture species released relative to exposed wild populations, numbers and frequency of release, whether released in native or non-native habitat, generation time in captivity, life-stage and time of release, strain of wild population affected, biotic (i.e., competitors or predators) conditions at site of release, time in natural environment, location of sensitive habitats/populations relative to site of release, genotype-by-environment interactions, etc. The evaluation of effects may often require examination at a local population scale. The temporal and spatial potential and severity of effects is dictated in part by the frequency and magnitude of escapes, as well as the ability of escaped fish to survive, disperse and reproduce in natural environments. Escaped farmed finfish have reported lower survival, aberrant dispersal patterns, lower reproductive success, and overall lower lifetime success relative to wild conspecifics. However, due to the persistent release of significant numbers of farmed Atlantic salmon, survival, dispersal and reproduction of these salmon has been reported in both Atlantic and Pacific Canada. Poor survival, forage acclimation, dispersal, and reproduction may limit the effects of farmed organisms in some circumstances, but it cannot be assumed to limit effects in all circumstances. Canadian aquatic ecosystems may have long-term exposure to escaped fish through repeated escape events (typical in areas of high-intensity aquaculture operations such as Atlantic salmon culture in the Bay of Fundy), and/or through reproductive establishment of escaped farmed organisms (e.g., Pacific oysters and other exotic bivalves in Pacific Canada). Each exposure scenario may pose different risks to aquatic ecosystem components. As well, the health of the ecosystem component exposed, combined with the magnitude of escape exposure, will influence the potential for escaped fish to cause an effect. For example, at-risk wild fish populations exposed to high numbers of frequently intruding escaped farmed fish (e.g., wild Atlantic salmon in the Bay of Fundy) are expected to be highly susceptible to the effects of escaped fish. Wild populations with strong numbers exposed to few escaped fish (e.g., some Pacific salmon populations) would not be expected to be as susceptible to the effects of escaped fish.

The following summary focuses on potential effects of escaped Atlantic salmon, as fish with the greatest potential for escape, and the effects of which have been most studied. Information from other species is noted where known, and the potential for extrapolation from Atlantic salmon studies to different species of escaped fish is discussed. Table 3 provides a summary of the availability of knowledge regarding the different POEs of escaped finfish and bivalves, and highlights which POEs and species are supported by substantial studies, and which are supported by few or no studies.

One of the pathways escaped farmed salmonids are most likely to affect wild populations is through competition for food and habitat at the juvenile freshwater stage. Studies that examine this ability indicate this is context dependent. In general, escaped or feral juvenile salmon are most likely to be superior competitors to wild salmon where escaped salmon are larger, have residency status, or where low predation pressure results in increased advantage of the greater foraging risks taken by farmed juveniles. A European study found feral farmed Atlantic salmon hatched earlier than wild salmon (Lura and Sægrov 1993), and feral Atlantic salmon could potentially hatch before Steelhead salmon populations in Western Canada (Volpe et al. 2001a), suggesting feral escaped salmon may gain residency status over wild juveniles in some circumstances. Studies in Europe found the presence of feral aquaculture and hybrid competitors caused displacement of small wild fry downstream (McGinnity et al. 2003), and decreased expected juvenile productivity of Atlantic salmon by 30% (expected productivity based on stock-recruitment relationships, Fleming et al. 2000). Semi-natural studies also demonstrate competition with escaped fish or hybrids can decrease wild juveniles' survival, although such effects depend on the presences of predators, ratio of wild to hybrid fish, and

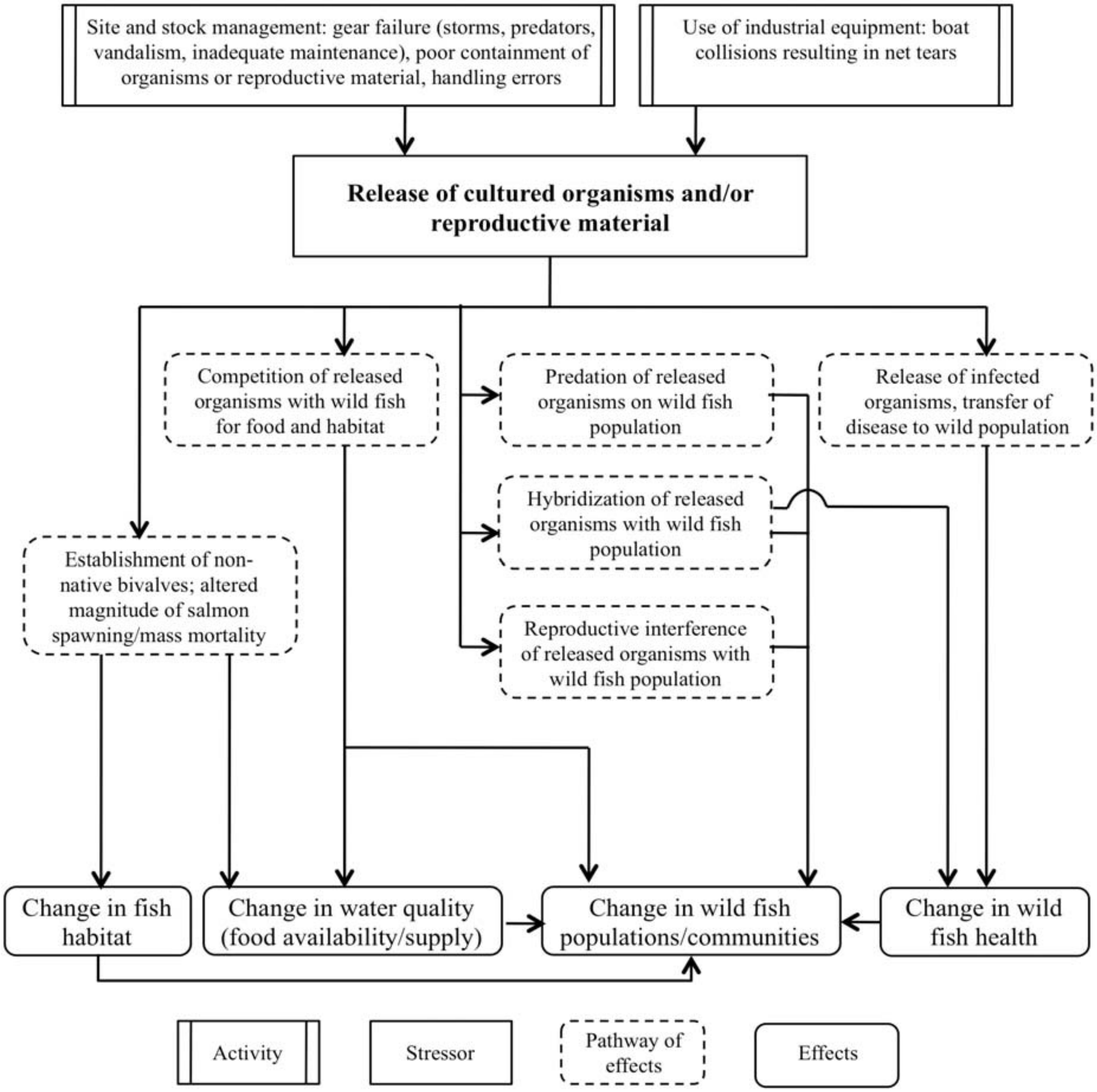

*Figure 8: The potential pathways of effects of released (escaped) farmed organisms on components of Canadian aquatic ecosystems.*

*Table 3. Availability of evidence from peer-reviewed sources supporting the existence of pathways of effects of escaped aquaculture fish to components of aquatic ecosystems. Note that this table does not recognize the direction or magnitude of stressor-effect linkages, or what factors influence the probability, direction, and magnitude of effects. This information is available in the text of the document.*

| Ecosystem components | Release of Atlantic salmon | Release of Pacific salmon | Release of freshwater salmonids | Release of marine finfish | Release of bivalves |
|---|---|---|---|---|---|
| **Fish Health** | | | | | |
| Wild/farmed fish health | Limited evidence | Not supported in the literature | | | |
| **Wild fish populations and communities** | | | | | |
| Competition pathways | M: Limited evidence; FW: Substantial evidence | M: Limited evidence; FW: Some evidence | Some evidence | Limited evidence | Substantial evidence |
| Predation pathways | M and FW: Limited evidence | M and FW: Not supported in the literature | Limited indirect evidence | Limited evidence | Limited indirect evidence |
| Hybridization pathways | Substantial evidence | Some evidence | Limited evidence | Some evidence | Limited evidence |
| Reproductive interference pathways | Some evidence | Limited indirect evidence | Limited indirect evidence | Not supported in the literature | Limited evidence |
| **Fish Habitat** | | | | | |
| Habitat structure | Not supported in the literature | Some indirect evidence | Not supported in the literature | | Substantial evidence |
| Substrate composition | | Substantial indirect evidence | | | Substantial evidence |
| **Water Quality** | | | | | |
| Food availability/food supply[1] | | Substantial indirect evidence | | | Substantial indirect evidence |
| Primary productivity | | | | | Substantial indirect evidence |
| | | | | | |

[1]Other than through competition and predation pathways
M = Marine environment; FW = Freshwater environment

**Key to table**

- Substantial evidence – this area has been studied in detail through peer-reviewed processes
- Some evidence – this area has been the subject of a number of studies
- Limited evidence – this area has received only minor attention
- Not supported in literature – the area was not identified as having been effectively studied
- Indirect evidence – evidence of effects has been reported in another group (e.g., intentionally released finfish or bivalves) that may apply to escaped farmed fish
- Blank cell – indicates specific pathway of effect has not been identified at this time.

strain of wild fish (Tymchuk et al. 2007; Houde et al. 2009a). While it is clear that escaped or feral salmonid juveniles can affect wild fish productivity through juvenile competition, the potential and magnitude for such effects given a range of factors relevant to Canadian ecosystems requires further examination.

Escaped Atlantic salmon may also impact wild populations through competition and decreased food supply in the marine environment. In the Pacific, survival of wild salmon is not density-dependent, but body size is (Holt et al. 2008). However, escaped Atlantic salmon in this region have poor acclimation to wild forage, although foraging success may increase with time (Morton and Volpe 2002). Escaped Atlantic salmon in this area will likely not impact wild salmon body size through density-dependent mechanisms, unless conditions are sufficient for escaped salmon to survive long enough to acclimate to wild forage. In Atlantic Canada, early marine survival and growth of wild post-smolts are not limited by food supply in the Bay of Fundy and the Gulf of Maine (Lacroix and Knox 2005). However, growth may be density-dependent in the Gulf of St. Lawrence in early post-smolt stages, but survival and growth at later stages may not be (Friedland et al. 2009). The potential for escaped salmon to impact wild populations through competition or decreasing food supply in the Atlantic Ocean may be limited to specific areas. In marine environments, Atlantic salmon escapes in the Atlantic Ocean have been found in wild fish feeding grounds and consume similar prey to wild conspecifics. As such, they have the potential to affect various prey species through predation. These could include at-risk populations of Atlantic cod, wolfish, and Atlantic salmon smolts, further jeopardizing the recovery of these populations. However, the potential for escaped Atlantic salmon to significantly impact populations of marine prey has not been examined. In the Pacific, escaped Atlantic salmon have been reported to consume little in the way of natural prey species, and are not expected to significantly impact wild prey populations.

One of the greatest concerns regarding escaped fish is the potential for interbreeding with wild populations resulting in possible decreased genetic variability and local adaptation of wild populations (reviewed in Tymchuk et al. 2006b; Weir and Fleming 2006). Occurrences of wild x farmed hybrids have been reported in European and Canadian rivers. Laboratory studies show farmed salmonids generally have decreased genetic variability, and decreased fitness traits with genetic basis. As well, partial transfer of farm phenotypes to hybrid offspring of wild and farmed salmonids has been observed in numerous laboratory, semi-natural, and natural studies, indicating potential genetic and phenotypic effects to wild populations are likely, should escaped salmonids successfully mate with wild conspecifics. While reproductive success of escaped salmonids is reduced, significant hybridization has been noted in natural environments. As such, there is potential for hybridization between escaped and wild finfish, resulting in altered genotype of wild populations. Modeling studies indicate extensive hybridization can result in extirpation of wild genotypes, particularly where small wild populations are exposed to repeat intrusions of escaped salmon (Hindar et al. 2006), as is observed in some Bay of Fundy rivers (Morris et al. 2008). As well, backcross experiments and modeling studies indicate recovery to an all-wild genotype will take several generations – if at all – after intrusion of escaped fish ceases (Hindar et al. 2006; Fraser et al. in press). Escaped Atlantic salmon may also reproductively interfere with wild salmonid species by superimposing redds on previously laid wild redds, or by blocking wild fish access to optimal spawning grounds. However, this has not been directly observed in natural spawning grounds, and further research regarding the relative spatial and temporal spawning times of escaped and wild salmon is needed to address this issue.

Limited known occurrences suggest escaped farmed organisms infected with pathogens could transfer these pathogens to wild hosts, potentially resulting in increased disease occurrence in one or more wild fish populations, and decreased productivity of these populations. The potential for this to occur is difficult to determine due to in part to the difficulty in determining cause, or even presence, of disease outbreaks in wild fish populations. Infected finfish escaped from net-pens may have lower potential to infect wild fish relative to contained finfish due to dilution of fewer fish in a larger area, or may have greater potential to infect fish over a larger geographical area by transferring disease to wild populations within dispersal distance from the site of release. While limited studies have examined this, poor survival of infected finfish in natural environments is expected to limit disease transfer in most circumstances.

The potential for other escaped salmonid species to affect natural populations has received less attention than escaped Atlantic salmon. However, a few semi-natural studies in Rainbow trout and Pacific salmon found these fish could impact wild populations through juvenile competition and hybridization pathways (Bessey et al. 2004; Tymchuk and Devlin 2005; Blann and Healey 2006; Tymchuk et al. 2006a; Tymchuk et al. 2007) similarly to Atlantic salmon, although the probability and magnitude of such effects likely differs between species. The potential for other POEs of escaped non-Atlantic salmon has received little attention, and the legitimacy of generalizing POEs of Atlantic salmon to other salmonid species requires further examination. Escape of Pacific salmon could theoretically alter freshwater fish habitat and water quality through alteration of mass-spawning mortality-induced changes, although the potential has not been examined. The effects of escaped marine finfish have received limited (Atlantic cod) or no (Sablefish) attention. These fish would not have juvenile freshwater competition effects associated with salmonids, but whether they may impact wild populations through marine competition is not known. The lack of spatially and temporally restrained reproductive pathways observed in salmonids may decrease the magnitude of hybridization effects of escaped marine finfish. However, Atlantic cod have a greater propensity for direct and indirect escapes than salmonids (Jørstad et al. 2008; Uglem et al. 2008), and recent studies indicate wild populations differ genetically on a smaller spatial scale than previously thought (Hutchings and Fraser 2009; Trippel et al. 2009). As such, the potential for hybridization effects of escaped Atlantic cod may exist, although the legitimacy of generalizing between Atlantic salmon and Atlantic cod requires further examination. The potential effects of escaped Sablefish require examination, particularly if use of this species in net-pens expands in Canada. While escape of other finfish may have similar effects as escape of Atlantic salmon, the scale of escapes relative to wild population numbers in Canada is substantially lower for other finfish than for Atlantic salmon. Therefore, Atlantic salmon have a higher overall potential for and magnitude of effects to wild populations, particularly conspecifics, although this does not exclude the potential for other finfish to affect components of Canadian aquatic ecosystems.

The potential for escaped farmed bivalves to affect components of Canadian ecosystems has been poorly studied. In general, bivalves have low potential for direct escape and dispersal from sites of entry, but have high potential for indirect escape through broadcast spawning resulting in release of viable larvae or hybridization with wild populations. In Atlantic Canada farmed bivalve seed is generally obtained from local or nearby wild populations and consequently feral populations of farmed bivalves are not expected to affect natural ecosystems beyond those effects of local wild conspecifics. Transfer of wild-caught aquaculture populations to areas containing genetically distinct wild populations could theoretically influence the genetic health of the recipient wild population should hybridization occur. However the potential for the presence of genetically distinct recipient wild populations combined with significant hybridization has not been examined in Canada. In Pacific Canada, bivalve farming relies primarily on hatchery-raised non-native populations, and feral populations of the main non-native farmed bivalves have existed since the 1920-1930's. Effects of these populations in Canada have not been noted, other than the presence of unstable hybrid zones of escaped non-native mussels with wild native mussels. However, studies of these organisms in other non-native habitat have reported decreased distribution, extirpation, and extinction of native shellfish occupying similar niches to feral non-native bivalves, as well as alterations in fish habitat resulting in little effects to great increases in community abundance and diversity. Whether these effects may apply to Canadian systems requires examination, particularly if non-native bivalve use expands in Canada, although it should be noted that previous efforts have found predicting the spread and effects of non-native bivalves to be difficult (reviewed by Landry et al. 2006; McKindsey et al. 2007). Bivalves contained in culture apparatuses are reported to effect water and sediment quality – both negatively and positively – through filter feeding and biodeposition. Feral populations of bivalves may have similar far-field effects, although negative effects may be limited as they are associated with high density of farmed bivalves, while feral populations are expected to be in lower density than those bivalves grown in suspended or off-bottom culture. In contrast, naturalized and farmed populations of Manila clams will likely be in similar densities whereas naturalized Pacific oysters may have similar or even greater densities – relative to on-bottom culture sites.

## MEASURABLE ENDPOINTS

The most likely pathways through which escaped farmed fish will affect components of Canadian ecosystems are through juvenile competition with wild populations where escaped salmonids have size or residency advantage over wild salmonids and through hybridization with wild populations resulting in altered genotype of the wild populations. However, there are few to no studies examining the biological implications of these and other POEs of escaped farmed fish on wild fish populations, community structure, and overall ecosystem function. This paucity of data may be due partially to lack of defined, quantifiable endpoints of effects of escaped farmed fish on wild fish populations and communities, as well as difficulty measuring such endpoints in contexts relevant to the presence of escaped farmed fish in Canadian ecosystems. Potential measurable endpoints include altered abundance, distribution, life history, size/age structure, genetic variability, or fitness phenotypes of one or more wild fish populations, as well as altered biodiversity index of exposed ecosystems. The most likely communities to be affected by escaped farmed fish consist of those containing wild finfish species similar to the escaped species (e.g., conspecifics). In particular, small wild populations exposed to large or repeated populations of escaped fish (e.g., many wild Atlantic salmon stocks in Eastern Canada) are likely most vulnerable to direct negative effects from escaped farmed fish. Alteration in abundance, distribution, etc. of one wild species may have indirect effects on other populations reliant on that species, potentially resulting in altered food-web dynamics and local community biodiversity.

Anadromous salmon, particularly Pacific salmon, are thought to be ecosystem engineers, where digging of redds and decomposition of spawned carcasses can have large implications on ecosystem function and dynamics. As well, bivalves are foundation species, where their physical presence can greatly influence the surrounding community structure and dynamics. Any effects of or to such species may likewise affect ecosystem function and biodiversity of local environments. The potential for catastrophic effects (e.g., extirpation of wild species or altered biodiversity index) from repeated exposure of sensitive ecosystems to escaped farmed fish has been poorly addressed. In some cases, such effects would likely be on a local scale. However, in the case of Atlantic salmon in the Bay of Fundy, the presence of multiple at-risk populations in an area of high-intensity net-pen farming could result in extirpation on a larger spatial scale. As well, given the great distance over which bivalves may disperse, far-scale effects due to escapes from bivalve aquaculture may also occur.

A major difficulty in examining effects of escaped farmed fish on Canadian ecosystems is the design of experiments that accurately predict the effects of escaped fish in contexts relevant to Canadian ecosystems. In the natural environment where wild populations have been exposed to escaped fish, immeasurable uncontrolled factors result in great difficulty in determining causation of ecological effects, although it is these uncontrolled factors that make translation of laboratory studies to a natural context difficult. Controlled stream environment experiments could give more relevant results, although this may be restricted to examination of single generation effects, particularly in anadromous salmon. Examination of juvenile competition in semi-natural and natural environments reported similar negative effects to wild juveniles, indicating some extrapolation from semi-natural to field studies may be appropriate. However, these studies have also demonstrated that effects are very context specific, and can be influenced by factors such as presence of predators, ratio of wild to escaped juveniles, and strain of wild finfish exposed. Consequently, the context surrounding wild and escaped fish interactions must be considered when predicting effects. Modeling of population events over several generations given different relevant circumstances may be an alternative method for determining long-term effects of escaped fish on wild fish populations. Future studies should also consider that escaped fish could effect wild populations through more than one pathway (i.e., escaped juveniles may compete with wild juveniles for food and habitat, and then for mates at a later life-stage).

## SUMMARY OF STRENGTH OF EVIDENCE, KNOWLEDGE GAPS AND RECOMMENDED RESEARCH

While escape, survival, dispersal and reproduction of aquaculture organisms have been documented in Canadian water systems, the extent of escape, and the fate of escapees given biotic and abiotic conditions at release site are not well known. There is substantial evidence that escaped finfish can effect wild populations through juvenile competition and hybridization pathways, although the probability and magnitude for such are very context specific (see Table 3 for a summary of strength of evidence). However, limited or no work has directly examined the potential for escaped organisms to cause effects to ecosystems through disease transfer, predation, marine competition, and reproductive interference pathways. As well, the effects of escaped farmed fish on single populations over several generations of interaction, or on wild fish communities (i.e., through food-web interactions) have not been examined. The following broad recommended research goals could decrease uncertainty and knowledge gaps regarding effects of escaped farmed organisms, and possibly allow for accurate predictions of effects of future escapes on natural ecosystem components in Canada. For knowledge gaps and recommended research specific to each stressor-effect pathway, see relevant sections above.

- Quantifiable endpoints related to effects of escaped farmed fish that are relevant to Canadian wild fish populations and aquatic ecosystems should be defined, and methods for measuring such endpoints established.
- Further data should be gathered regarding the foraging success, survival, dispersal, and reproductive success of escaped wild fish over time in Canadian waters, with emphasis on influence of life-stage, and time of release, local biotic and abiotic factors, and whether released to native or non-native waters. Such data could be used to develop models to predict survival, dispersal and reproductive patterns of escaped fish given specific variables.
- Relative success of escaped finfish to compete with wild finfish for food, habitat, and mates should be determined given relevant variables including time and generation time of escaped finfish in natural environments and number of escaped versus wild finfish. The range of effects of such competition on wild finfish productivity, or genetic and

phenotypic fitness over several generations of repeat intrusion should be addressed.

- Further research is needed to determine how to best utilize laboratory and semi-natural studies to predict effects of escaped fish in the natural environment. Factors that influence the ability to extrapolate from laboratory to field scenarios should be better identified to incorporate uncertainty into such extrapolations.
- Research is needed in Canadian ecosystems on escapes from a wider variety of farmed species such as bivalves, marine finfish and salmonids other than Atlantic salmon. These studies would examine the interactions with conspecifics, other species, and ecosystem components to assess whether generalizations can be made between species/ecosystems.
- Greater advantage should be taken of “natural experiments”, where escaped farmed species have successfully reproduced in the wild (i.e., Atlantic salmon and Pacific oysters in British Columbia, Rainbow trout in Newfoundland), to determine the long-term fate of these organisms and their effects on the natural environment where they have reproduced. The creation of in-place research funding sources that could be rapidly initiated at the discovery of such populations could provide the necessary support for determining long-term effects of escaped farmed fish on natural ecosystems in Canada.
- Further information on the factors that influence the resilience of natural populations or other ecosystem components to escaped fish is needed (e.g., wild population size and juvenile growth rate, ratio of wild to escaped fish, genetic variability of wild fish, etc.).
- As aquaculture practices expand and change over time, the potential for and magnitude of effects from escaped farmed fish will also change, and should be addressed accordingly – ideally before such changes take place. Increased or expanded use of Rainbow trout, Atlantic cod, Sablefish, non-native bivalves, triploid bivalves, and hatchery-reared native bivalves for aquaculture may result in unique or increased effects to Canadian aquatic ecosystems and should be addressed when relevant.
- The above knowledge gaps may be addressed through a number of mechanisms. These include observations on escaped fish or purposeful releases (e.g., migration, pathogen loads, stomach contents, presence in spawning grounds, presence of feral or hybrid offspring, productivity of encountered wild fish populations, etc.). Targeted in-depth investigations need to be initiated or expanded in well-defined ecological systems where escapes and interactions are known to be occurring (e.g., Magaguadavic River, New Brunswick). Studies must be of sufficient temporal and spatial scale to reduce uncertainty and provide clear outcomes useful for management decisions. Laboratory or semi-natural studies may give further insight to phenotypic fitness and effects of farmed fish (e.g., competition success, spawning ability, disease resistance, pathogen load, etc.), although such studies should ideally address potential genotype x environmental interactions. Such data could be used to model higher trophic interactions and/or genetic effects of introgression over several generations. This may give insight into the effects of escaped farmed fish on overall wild fish community dynamics, as well as long-term effects of several generations of interactions. These studies should be initiated in areas of high escape potential and susceptible wild populations (e.g., Atlantic salmon in the Bay of Fundy, and the Broughton Archipelago), and continue with areas of lesser culture intensity but large gaps in knowledge (i.e., Rainbow trout culture in the Great Lakes, Atlantic cod culture in Atlantic Canada).

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