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

Volume IV

The Role of Genotype and Environment in Phenotypic Differentiation Among Wild and Cultured Salmonids

(Wendy E. Tymchuk, Robert H. Devlin and Ruth E. Withler)

Cultured and Wild Fish Disease Interactions in the Canadian Marine Environment

(A.H. McVicar, G. Olivier, G.S. Traxler, S. Jones, D. Kieser and A.-M. MacKinnon)

Trophic Interactions Between Finfish Aquaculture and Wild Marine Fish

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FOREWORD

Context

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

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

Goal and Scope

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

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

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

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

State-of-Knowledge Series

DFO plans to publish 12 review papers as part of the SOK Initiative, with each paper reviewing one aspect of the environmental effects of aquaculture. This Volume contains 3 papers: The Role of Genotype and Environment in Phenotypic Differentiation Among Wild and Cultured Salmonids; Cultured and Wild Fish Disease Interactions in the Canadian Marine Environment; and Trophic Interactions Between Finfish Aquaculture and Wild Marine Fish.

Further Information

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THE ROLE OF GENOTYPE AND ENVIRONMENT IN PHENOTYPIC DIFFERENTIATION AMONG WILD AND CULTURED SALMONIDS

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EXECUTIVE SUMMARY

This paper reviews the existing literature examining genetic influences on and consequences of the interaction between cultured and wild salmonids. The paper identifies major phenotypic changes that have occurred in domestic strains (e.g. morphology, physiology, and behavior), and examines whether these changes have effects on fitness in laboratory and natural environments. Long-term effects of interactions between domestic and wild strains will primarily arise from genetic effects, but the phenotype of domestic strains relative to wild strains arises from both genetic and environmental forces. Separating these causal components of phenotype is required to understand the potential effects of introgression events, yet achieving this goal remains a difficult task. Studies in the wild are required to fully determine the fitness of domestic and wild strains and thus examine potential long-term consequences arising from their interaction.

Genotype, in addition to environment, determines the adaptive phenotypic characteristics (i.e. reproductive capabilities and ongoing survival) of salmonids, and, as such, it is likely that disruption of this genetic structure may have short-term and long-term effects on individual fitness as well as the future resilience of populations to natural and anthropogenic pressures. Domestication has been noted to have a significant effect on life history traits in salmonids (Thorpe 2004). Domestication may select for many different traits, including improved growth rates, earlier age at maturity and spawning, greater survival, increased tolerance to high temperature and resistance to disease (Hynes et al. 1981). Differences between wild and cultured fish represent a phenotypic continuum, ranging from differences among natural strains, to differences between wild and sea-ranched fish, to differences between wild and highly selected domestic cultured fish (Figure 1). Alterations in fitness-related traits in hatchery fish should be typical of differences expected in aquacultured salmon, although the latter may show a greater magnitude of change due to an increased length of time under intentional and indirect selection, which is usually conducted in isolation from wild genetic pools. Accumulated evidence now indicates that some fitness-related traits affected by domestication, such as growth, competitive ability, and anti-predator behavior, are in part genetically controlled. Transgenic fish, which can be viewed as an extreme form of domestication, are not considered in the present discussion except when examined as a model system for assessment of genotype/phenotype relationships (Devlin et al. 2001).

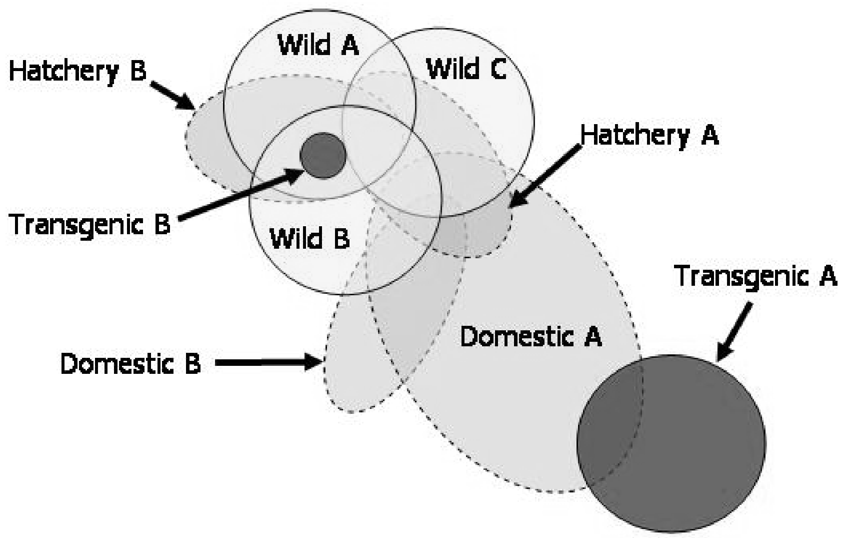

Figure 1. Representation of the relationships among phenotypic states for one hypothetical set of wild, hatchery, domestic, and transgenic strains. The ranges of phenotype observed among different wild populations are anticipated to overlap considerably with each other and with hatchery strains derived from them. Domestic strains that have undergone directed and unintentional selection are expected to possess phenotypes different from wild and hatchery populations, often in a common direction away from the wild phenotype, and in some cases to an extent seen for transgenic strains. Transgenic strains can possess a wide range of phenotypic transformations for novel traits, and for existing traits previously possessed by the host strain, or may have no change in phenotype from the host strain.

- ***Phenotypic differences between cultured and wild fish***

Rearing fish in a culture environment can lead to environmentally determined differences in morphology relative to those reared in the wild. The extent of these differences depends on the type and the length of time spent within the artificial environment, and the intensity of the culture conditions such as crowding, food supply, etc. Multiple generations of strains kept within the culture environment may lead to genetically based morphological differences arising from selection for traits affording fitness benefits in culture.

Domestication has also been shown to alter the physiology of fish. Environmental factors such as availability of food resources and temperature will of course have an effect on growth of fish. However, there can also be large differences in growth between cultured and wild strains as a result of genetic differences between the strains. The magnitude of the growth differences caused by genotype will be dependent on the *purpose and history of the cultured strain. Aquacultured strains that have been intensely selected for enhanced growth show a larger shift in growth phenotype from the founding line compared with those strains that have not experienced directed selection. It is important to note that it is often not clear whether physiological differences are a cause or consequence of other phenotypic differences between the strains (such as growth or behavior differences). It is therefore difficult to clarify whether physiological differences have a genetic basis per se, or if they are a product of the environment.*

Behavioral differences commonly arise during domestication. Cultured and wild fish do show differences in the level of aggression displayed towards conspecifics, although there has not been a consistent trend as to whether aggression increases or decreases under culture. A common assertion is that aggression will decrease under culture when fish are reared in crowded conditions and do not have to fight for limited food resources. A genetically determined reduced response to predators seems to be a consistent trend in domestic strains across several species. In contrast, little research has been conducted to reveal genetic control of foraging strategy, habitat selection, and dispersal. A genetic basis for altered foraging strategy could arise from phenotypic expression of other genetically influenced traits such as growth or morphology, which would drive foraging behavior characteristics.

Expression of physiological and behavioral phenotypes will ultimately determine survival. Survival is influenced by most other phenotypic traits, and the environment in which they are expressed. Cultured fish, either through a plastic response to their environment or through an adaptive response to altered selection pressures, tend to express phenotypic characteristics best suited for the culture environment. Consequently, they tend to have a lower survival than wild fish in a natural environment. However, few studies have examined whether cultured fish that experience a natural environment throughout their life history will still show decreased survival relative to the wild fish. Furthermore, the strength of the genetic basis of survival is not known, nor is it clear whether cultured fish still have the ability to show a phenotypically plastic response to the environment that will maximize their ability to survive.

Reproductive capabilities of domesticated fish are often affected. The literature consistently observes that cultured fish often have the physiological ability to spawn, but that altered spawning behavior limits their success. While the reproductive success of farmed fish may be low, the potential for significant gene flow still exists because the population of farmed fish often outnumbers the population of resident wild fish (at least in the case for Atlantic salmon), at times by as much as 3:1 (Lund et al. 1994; Lura and Økland 1994). There are no data comparing the ability of farmed and wild Pacific salmon to spawn in nature, but comparisons between hatchery and wild coho salmon, and studies examining cultured wild strains indicate that trends observed for Atlantic salmon may be typical of the phenotypic changes expected during domestication.

Genetic effects of farmed fish on wild populations would depend in part on the reproductive behavior of farmed fish in the wild. Evidence suggests that farmed fish have the ability to breed successfully in the wild, although contradicting results exist. There are generally significant differences in breeding potential between cultured and wild fish (Fleming and Gross 1992, 1993; Fleming et al. 1996; Berejikian et al. 1997; Bessey et al. 2004), although other studies have found similar reproductive success for hatchery and native fish in the wild (Dannewitz et al. 2004; Palm et al. 2003). Morphology and life *history traits related to reproductive behavior respond evolutionarily to altered selection regime in the hatchery environment (Fleming 1994; Fleming and Gross 1989). The genetic effect of aquacultured salmon on wild populations will depend not only on the size of the wild population, but also on variation in breeding success (Fleming and Petersson 2001).*

- ***Cause of phenotypic differentiation between cultured and wild strains***

Phenotypic differences between farmed and wild salmonids may arise from a combination of genetic and environmental effects, but in most cases, the origin of the difference is not well defined. Environmentally based phenotypic differences would not be passed to offspring as they do not have a genetic basis, and are thus anticipated to have single generation effects arising directly from escaped fish. In contrast, genetic differences have the potential to affect the wild populations of a species over a longer time frame. Thus, it is therefore critical to separate the influence of genotype and environment.

To assess genetic effects, experiments must be performed by rearing fish of different origins in a common environment (i.e. common-garden experiments.). Such experiments can help determine whether cultured fish have an altered genotype that has arisen in response to selection pressures from an artificial environment. Environmental effects (i.e. phenotypic plasticity) can be tested by rearing fish of a common genetic background in different environments, revealing whether phenotypic plasticity (Hutchings 2004) may have altered phenotype in response to the environmental conditions.

Currently, there is still limited knowledge on how the environment will act on inherent genetic differences among strains (i.e. will environmental conditions affect different genotypes in distinct ways through genotype x environment interactions). For example, fast-growing domestic fish may have a greater growth advantage relative to wild fish under culture conditions than they do in nature. An understanding of genotype by environment interactions remains one of the most critical components influencing phenotype and fitness. Research in this area is required to improve prediction of genetic effects arising from interaction between wild and cultured fish.

- ***Mechanism of genetic interaction***

Genetic effects of domestic fish may be direct or indirect. Direct genetic effects include the alteration of the wild genome (introgression) as a result of interbreeding between wild and domesticated fish, or the production of sterile hybrids. Indirect effects include the effect of reduced effective population size or altered selection pressure arising from competition or the introduction of pathogens (Krueger and May 1991; Skaala et al. 1990; Waples 1991). Genetic effects of hybridization between farmed and wild salmon are somewhat unpredictable and may differ between populations, but most interactions have been generally found to be disadvantageous when the genetic effects alter fitness-related traits (Hindar et al. 1991). Most studies have focused on the fitness of the F_1 *generation when exploring the effects of interbreeding between domestic and wild strains. While such hybrids may have enhanced fitness due to hybrid vigor, the negative effects of outbreeding depression are not manifested until* F_2 *and later generations, and thus simple first-generation hybrid studies have limited predictive value.*

The genetic effect of escaped cultured fish on wild populations will also depend on the demographic of the wild population, the magnitude and frequency of the escape, and the extent of introgression of aquacultured genotypes into the wild population (Hutchings 1991). The phenotype of wild and farmed hybrids may vary depending on the source and genetic structure of the wild population (e.g., see Einum and Fleming 1997). Anadromous populations of salmonids may be somewhat resistant to introgression due to aspects of their complex life histories such as overlapping maturation age classes and straying among distinct populations (Utter and Epifanio 2002). Furthermore, genetic distance between the two populations does not seem to be a reliable indicator of the potential effects of introgression (Utter and Epifanio 2002).

KNOWLEDGE GAPS AND RECOMMENDATIONS

- ***More fully define the genetic basis of domestic traits and the mechanisms by which they alter phenotype.***

It is clear that phenotypic differences (particularly growth) between cultured and wild fish are due in part to altered genotype. However, the specific genetic changes that have occurred to cause these phenotypic differences are not yet understood. For example, traits that are controlled by many alleles of small effect will present different risks to wild populations and will require different management strategies relative to traits that are caused by a small number of alleles of large effect. A better understanding of the genetic changes underlying desired traits will also aid in the development of custom aquaculture strains through the use of marker-assisted selection. Such genetic information may be obtained from: 1) additional breeding studies (e.g. assessing heteritabilities for critical traits in wild and cultured populations under culture and natural conditions, and the scale to which outbreeding depression and/or heterosis are at play among populations); 2) experiments mapping and identifying genes and alleles responsible for specific phenotypes; and, 3) gene expression studies identifying candidate genes involved in fitness-related processes.

- ***Determine whether conserved genetic and physiological pathways are employed among domestic strains to achieve alteration of specific trait.***

Further to the above, it will be crucial to assess whether genetic changes arising through the process of domestication are a conservative process. There has been little comparison among strains and species of cultured fish to determine if the genetic alterations leading to phenotypic differences occur in predictable patterns, or if each strain is developed through a unique set of alleles. This information will determine whether a general risk management strategy could be generalized, or if plans must be developed on a case-by-case basis.

- ***Extensive research is required to determine which environmental variables play controlling roles in influencing the magnitudes of phenotypic differences among***

wild and between wild and domestic strains (i.e. improve our knowledge of phenotypic plasticity and genotype x environment interactions).

Because of the difficulty of making observations in natural environments, there are few studies that test whether differences among strains observed in an artificial environment are an accurate predictor of the characteristics that will be displayed in the natural environment. Thus, there is a need for more rigorous assessments of the plasticity of cultured and wild strains to assess whether domestic genotypes have response to environmental conditions which differ from wild type in non-parallel ways (i.e. genotype x environment interactions). This area of research is critical.

- ***Undertake experiments to evaluate the contribution of phenotypic differences between domestic and wild strains to survival and reproductive fitness.***

Altering the expression of a phenotypic trait can alter overall fitness. Different phenotypic traits will interact in a complex manner to determine the fitness of an individual. While there is much literature on discrete phenotypic differences among cultured and wild strains, there is a need for more complex analyses of how these differences interact during the life history of the fish and consequently influence their ability to survive and reproduce.

- ***Fitness evaluations must be undertaken in nature to provide information to reliably predict net fitness and consequences of domestic genotypes introgressed into wild populations. Without data from nature, laboratory experiments may reveal forces causing phenotypic and fitness differences, but their true magnitudes cannot be known with certainty.***

It is critical to extend laboratory studies and assess identified genetic differences such that true determinations of their influence on fitness in nature can be determined. It will also be important to examine the ability and the rate that populations may be able to revert to naturally selected genotypes and phenotypes following introgression events.

- ***Given current uncertainty in our ability to a priori predict consequences of introgression, research directed to monitoring and minimizing interactions should be supported.***

The outcome of genetic interaction between farmed and wild populations is difficult to predict as our understanding of genetic dynamics is poorly developed for age-structured populations with overlapping generations such as those shown by salmonid populations. Consequently, conservative approaches have been recommended when assessing genetic effect risks (Ryman 1997; Waples 1991). Clearly, an important first step is to minimize escape of cultured fish into the wild (Altukhov and Salmenkhova 1990; Krueger and May 1991). Effort should also be directed at developing molecular techniques to better identify and monitor introgression of cultured strains into wild populations, particularly for reproductively mature stages and consequent early stages of their progeny. The use of triploid fish or other containment techniques in aquaculture may eliminate genetic effects, and reduce the ecological consequences of escaped farmed fish on wild stocks (Cotter et al. 2000; Devlin and Donaldson 1992).

- ***Develop models that make use of the emerging understanding of the relationship between genotype, phenotype and fitness to allow prediction of the consequences of introgression of domestic and wild strain.***

Recent research has revealed that many phenotypic traits that differ between wild and domestic strains are controlled by additive genetic variation (Tymchuk et al. 2006, McGinnity et al. 1997, 2003, Fleming et al. 2000). These observations could now allow estimation of the effects of introgression on the genotype of wild populations, assuming neutral fitness. Further, modeling exercises can allow sensitivity analysis to estimate risk arising from different genotypes under various introgression scenarios, and, coupled with studies of natural fitness among genotypes, may be used in the future to predict consequences in the wild.

CULTURED AND WILD FISH DISEASE INTERACTIONS IN THE CANADIAN MARINE ENVIRONMENT

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EXECUTIVE SUMMARY

Intensive mariculture of fish is a recent industry in Canada relative to farming of land animals. This newness alone raises a unique set of questions and potential problems. Whenever there is a new use of the natural resources of an area, there is an inevitable alteration to that part of the environment being used. In the case of marine cage culture of fish, this is most obvious in the scenic sense and in the reduction of previously held rights to access by other users. However, other less apparent changes such as disease can also occur. In this context, the question frequently and justifiably asked is whether the changes due to the occurrence of infectious diseases in aquaculture introduce a significant or acceptable risk of detrimental effects to the environment and, in particular, to wild fish populations.

Over the last 20 years, several reviews have already comprehensively assessed the available scientific literature on the potential for disease interchange between wild and farmed fish (Hastein and Lindstad 1991; Brackett 1991; McVicar et al. 1993; McVicar 1997a, b; Hedrick 1998; Reno 1998; Amos et al. 2000; Amos and Thomas 2002; Olivier 2002). Notably, none of these reviews has found irrevocable evidence that fish farming has contributed to detectable adverse changes in wild fish populations, yet the topic remains one of the most controversial in the media and scientific community. The objective of this review is to focus on the main areas of potential risk using both the conclusions of individual authors who have reviewed the relevant literature and the outcomes of the different special workshops and conferences on the topic.

Disease in wild populations is rarely documented and therefore demonstrating changes in the patterns of disease in wild populations is challenging. As in any wild animal population, large numbers of different potential disease-causing agents can occur in any one species of fish. When epizootics do occur, clinically diseased specimens with high levels of infectious agents are usually easy to find, as was the case with the pilchard die-off in BC (Traxler et al. 1999). However, in comparison with farmed fish stocks, there are relatively few records of epizootics in wild fish. This cannot be interpreted as evidence of their absence or of a low level of risk of their occurrence. Highly pathogenic infectious agents that rapidly kill fish typically occur at low levels in non-epizootic situations.

Furthermore, carriers of infection without evidence of clinical disease are difficult to detect due to the size and inaccessibility of the environment. Finally, sick animals are rapidly removed by selectively high predation (McVicar 1997b).

Much more is known regarding disease interactions among the host, pathogen and the environment of cultured fish than wild fish populations because cultured fish are more easily observed. A dependence on unreliable data on the relationship between diseases in farmed and wild fish populations has often led to widely different interpretations of the same information, which in turn has further fueled the considerable controversy in this area. It is well established in Canada and elsewhere that there is not a unidirectional transfer of infection from either farmed fish to wild or vice versa, but that interchange of infection between the different environments is normal. There is a tendency for those with interests in aquaculture and with wild fish to focus on the route of transmission from one direction only. A major constraint to reaching robust conclusions on possible changes and effects of disease is a widespread lack of adequate information on the disease status of wild stocks prior to the establishment of aquaculture. The inability to compare fish disease patterns before and after the establishment of fish farming is a problem not only within Canada, but also internationally. Information on the extent of variation in naturally occurring disease is required before an assessment can be made on any effects that may be superimposed by infections in aquaculture. It is also difficult to prove a negative effect on wild fish populations since fluctuations in fish populations are normal, but the causes are multifactorial and complex. Unfortunately, the background information on natural variations is usually sparse from areas where fish farming is now being conducted. Information from areas with no fish farms can provide a general perspective of the natural levels of infection that can occur but should be treated with caution in the absence of sequential information on temporal and spatial variations.

Reports have indicated that a variety of pathogens are present in numerous marine fish species, which may then act as reservoirs for pathogens of farmed fish (Kent et al. 1998). The finding of infectious hematopoietic necrosis (IHN) virus in migrating sockeye salmon in seawater raises the possibility of a marine source or reservoir of the virus (Traxler et al. 1997), although there have been no reports of losses in wild salmonids in the marine environment due to viruses (Bakke and Harris 1998). The low density of salmonids in the marine environment reduces the potential for disease to affect populations. An understanding of the dynamics of infection and of the persistence of disease is necessary before conclusions can be drawn on the extent of any new risk being posed by the occurrence of disease in farms to local wild fish populations. Different host species that are capable of becoming infected may show a natural range of susceptibility to the same infection. Under high stress conditions (e.g., elevated temperatures, spawning), even the same host may show higher susceptibility to infection (Bernoth et al. 1997). These complexities in the interaction between the occurrence of infection in fish and the development of disease and the insufficiency of basic research have contributed in a major way to the uncertainties in the evaluation of the level of impact of diseases in fish farms on wild fish populations. In this context, the role of sea lice on farms has been extensively debated internationally, but a conclusion has not been reached in any country (McVicar 2004). Similarly, the impact of IHN virus on wild stocks of fish is an area that *is poorly understood and requires more research. As new aquaculture species are developed for culture in Canada, there will be a new opportunity to study disease interactions between wild and cultured species.*

The introduction of new infectious agents into an area previously free of that infection could lead to serious outbreaks of disease (Olivier 2002; Kent 1994; Noakes et al. 2000). This can be due to the lack of an evolved resistance in the indigenous populations that may act as susceptible hosts. However, little can be done to prevent or restrict the natural spread of diseases associated with the normal movements of fish populations between areas or natural changes in distribution associated for example with climatic change. The focus must therefore be on human activities such as the transfer of live fish and eggs between aquaculture sites or where trade activities increase the risk of transferring infection significant to fish.

When wild fish are exposed to pathogens shed from farmed fish, neither infection nor disease is inevitable in the wild fish population. The following factors are critical: the occurrence and persistence of the infection in the source population; the availability of susceptible potential new hosts; the viability and concentration of the infectious organism in the environment; and the ability of the infection to affect the recipient population from individual fish infections (Olivier 2002). These complexities in the interaction between the occurrence of infection in fish and the development of disease and the insufficiency of basic research have contributed in a major way to the uncertainties in the evaluation of the level of impact of diseases in fish farms on wild fish populations.

The initial risk level of infection in wild fish associated with escaped farmed fish depends on the length of survival, behavior of the escaped fish after leaving the farm, and the reduced disease transmission opportunity in the lower fish densities outside the farm. Farmed fish in general are recognized to be maladapted to survival in the wild (Fleming et al. 2000) and the additional liability of fish carrying disease when they escape is likely to result in the early disappearance of the most seriously affected fish. The significance of the risk associated with diseased fish escaping from farms is therefore likely to be rapidly reduced towards levels equivalent to those for wild fish.

The introduction of new infectious agents into an area previously free of that infection can lead to serious outbreaks of disease (Kent 1994; Noakes et al. 2000; Olivier, 2002). Trade of live fish or eggs between areas carries risk of disease transfer as do other human activities such as processing where substantial concentrations of viable pathogens may be present. However, regulatory management steps taken by Canada has controlled this risk and the effectiveness of these actions is reflected in the fact that there are no recorded examples in Canada of any non-native fish diseases of concern being introduced either into farms or the natural environment.

Locally occurring diseases could get into farms principally through water, food or equipment. With the exception of treated or ground sources of seawater, fish farms are vulnerable to naturally occurring infections that are transmitted through water. It is more probable that the initiation of infections in marine fish farm is related to the level of *infection in the surrounding environment, such as that in wild fish, and the proximity of wild fish to fish farms. Diseases may be transmitted in water typically for short distances or through the escape of infected animals or through direct contact with infection sources (infected animal or other contaminated material). However, as the level of risk will vary considerably with different infectious agents and because of the complexity of factors influencing the initiation of infection and thereafter the development of disease, the simplistic view of risk being directly related to the level of exposure is not tenable.*

During the early stages of marine salmonid farming in Europe, disease outbreaks due to bacterial infections (e.g., Vibrio *species) and parasites (e.g.,* Ichthyophonus*) were directly attributed to the use of fresh fish as a main source of food. The processing of manufactured feeds, which is used exclusively in current Canadian mariculture, destroys known infections of concern and is no longer as a source of disease.*

Although farm gear, including nets, graders, harvesting equipment, and even staff boots and clothing, can potentially transfer bacterial and viral infection between farms, the level of infection present on farms is usually sufficiently low that this is considered a relatively low-risk area compared with that associated with the transfer of live stocks. In epizootic disease situations particular caution has to be taken. Even in such circumstances, good farm management practices in relation to biosecurity measures can be effective in further reducing the level of risk and in helping to mitigate the possibility of future disease incidents.

The conditions such as crowding, which are typically found within a fish farm, are such that once infection is present there is risk of it spreading and causing a disease outbreak within the farm stocks. In this respect, fish farming is no different from intensive or semi-intensive farming on land. The development of effective vaccines in the fish farming industry has significantly reduced the problems associated with some of the serious diseases (Youngson et al. 1998). Where vaccines are not available, alternative disease management approaches have proved to be successful in reducing disease incidents on farms (McVicar 2004). Such approaches include, removing all fish from a farm facility to break disease cycles, area or bay management, and use of single generations and targeted administration of chemotherapeutants at critical times in the disease development cycle (e.g., of lice).

RECOMMENDED RESEARCH

- *Gaps in knowledge on potential disease hazards should be identified early and addressed through directed research based on the principles of risk assessment to provide options for their management in a structured manner.*
- *Baseline information on the disease status of wild stocks or a newly cultured species <u>prior</u> to the development of aquaculture in an area with emphasis on temporal and spatial variation would facilitate understanding of any effects that may be attributed to aquaculture.*

- *When a new species susceptible to a disease enzootic in native stocks is cultured, baseline information on pathogenicity and on wild-farmed fish disease interactions is desirable. An example would be nodaviruses in the family* Betanoviridae.
- *More information is needed on the cause–effect relationship in the transmission of disease between wild and cultured fish.*
- *Further studies are needed to objectively evaluate whether sea lice transfer between wild and cultured fish has any direct negative effect on the overall health of wild populations, particularly on the epizootiology of sea lice among Pacific salmon and its transmission to juveniles in inshore waters.*
- *Rapid diagnostic tests for IHN are needed. Studies on the factors involved in virus transmission and the susceptibility of other fish species should be conducted.*
- *Studies on waterborne disease agents or infective stages are needed to determine pathogen dispersion rates, since pathogens are frequently shed with feces.*

Trophic Interactions between Finfish Aquaculture AND WILD MARINE FISH

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EXECUTIVE SUMMARY

This review examines the literature on trophic interactions between marine finfish aquaculture and wild fish populations to determine the state of existing knowledge and identify research gaps for future study. Three questions are central to this discussion: What is the predation effect of caged finfish on wild fish and available prey? Do finfish farm sites attract wild fish and affect their productivity? What are the competition and predation effects of escaped finfish on local and regional wild fish populations?

Recent aquaculture reviews have highlighted ecosystem effects and provided general discussion on farm site attraction and the predation and competition effects of caged and escaped finfish. However, no comprehensive reviews exist. The majority of studies on these topics have focused on behavioural and genetic interactions between escaped finfish and wild fish, or on the attraction of wild fish to farm sites. Little direct empirical or experimental work has been conducted to address these questions and a knowledge gap exists in northern temperate marine systems, including Canada.

The published literature does indicate that cultured finfish can have measurable effects through predation of, attraction to, and competition with wild fish or available wild prey. These effects can occur at the level of local farm sites and ecosystems, and can occur potentially at regional scales. While these effects vary with respect to the three questions above, they are generally linked by the nature and productivity of the local ecosystem around farm sites (i.e. warm oligotrophic to eutrophic; cool oligotrophic to eutrophic), the number and species of cultured finfish, and the number and proximity of farm sites in relation to concentrations of wild fish. Available literature on these subjects is limited and therefore it is difficult to quantify the relevance and risk of effects resulting from trophic level interactions between farmed finfish and wild fish populations.

Only a few studies have examined the predation effects of caged finfish on wild fish, and those completed to date have been conducted in marine systems in British Columbia. Results indicate that caged salmon feed at low rates on wild fish and plankton prey and that this interaction is dependent on the salmon species cultured, season, and farm location. Farmed fish consumed low numbers of wild fish and plankton but showed trends in behaviour and prey selection similar to those of wild salmon. The studies were observational in nature and did not fully test the effects of caged salmon feeding on wild

prey. Future Canadian studies should incorporate an experimental design to evaluate the predation effects of caged finfish on wild fish and prey, and determine the variation in potential effects among caged finfish species, season, and spatial proximity of farm sites to wild fish populations.

A few studies have been conducted in northern temperate marine systems to examine the attraction of wild fish to farm sites. Results indicate that wild fish use farm sites as artificial reefs or shelter, as well as enhanced sources of food from surplus pellet feed, farm and fish waste, and from the abundance of local macrofauna on or near these sites. Results also indicate that wild fish densities increase by 1- to 10-fold near cool northern temperate farm sites as a result of local attraction, but show little response in overall wild fish community biodiversity. Increases in density, population size and age structure, and overall community biodiversity near warmer nutrient-poor farm sites indicates higher levels of attraction response by wild fish. Further study is needed in Canada to examine the wild fish population and community level attraction to farm sites and determine what level of interaction exists. These studies should consider use of appropriate indicator species to determine levels of interactions.

Limited data exist on the number, local distribution, and feeding behaviour of escaped farmed fish and their potential interactions with wild fish. New study is needed to quantify potential interactions and effects of escaped farm fish on wild fish populations. The existing literature shows three patterns of interaction. High densities of escaped fish are negatively associated with the abundance and diversity of wild fish, and escaped fish are principally competitors and secondarily predators. Lower densities of locally escaped farmed fish have inconclusive effects on wild fish; although escaped fish do revert to wild-type feeding behaviour. Finally, exotic, as compared with endemic, farmed species show differences in feeding behaviour. There is a knowledge gap in available research linking escaped fish density, survival and feeding to wild fish populations in proximity to farm sites.

This state of knowledge should be integrated into an overall appraisal of the risks of farmed finfish on wild fish populations from other reviews to prioritize research and develop novel management approaches.

GAPS IN KNOWLEDGE

1. *New studies are required to determine whether caged marine finfish (salmon and other cultured fish species like sablefish, cod, halibut) feed on local wild populations of plankton and fish. These studies should examine local and regional scales of influence between farmed finfish and wild fish populations to determine the relevance of this interaction.*
2. *New studies are required to determine the level and type of attraction by wild fish to marine finfish farm sites in Canada.*

3. *Studies of farmed finfish escaped into natural environments are required to link cause and consequences for wild fish and their ecosystems at both local and regional scales.*
4. *Comprehensive monitoring and incident reporting are required to clearly establish the timing, quantities, species and condition of escaped farmed fish into the wild.*
5. *Most study results to date have incorporated little experimental design and have been empirical or observational in nature. Experimental or adaptive approaches should be considered to provide a range of risk exposure of finfish aquaculture to wild fish populations to reflect growing experience and understanding.*
6. *New study is required to compare and contrast the diet and consumption patterns of caged, escaped and wild salmon with the distribution of available food organisms and environmental conditions in marine environments.*
7. *The selection of research priorities for study of farmed fish and wild fish interactions should be based on the levels of perceived risk to wild fish populations and local ecosystems. The objective of this research should be to evaluate and quantify the risk.*