Preamble

Patricia Gallaugher, Director, Continuing Studies in Science, Simon Fraser University
Craig Orr, Watershed Watch Salmon Society

This Speaking for the Salmon workshop and think tank, held March 2-3, 2000, was prompted by the public controversy which arose from recent changes in provincial and federal government policies with respect to salmon aquaculture in British Columbia.

Invited scientists and leaders in the field of salmon aquaculture research provided current facts for workshop and think tank participants to consider in identifying what is known and not known about genetic, ecological and disease interactions between wild and farmed fish, and these formed the basis for recommendations for further research and steps to be taken to reduce the risks of farmed salmon to wild Pacific salmon.

Co-chairs report

Lawrence Dill, Professor, Biological Sciences
Rick Routledge, Professor, Mathematics and Statistics
Simon Fraser University
8888 University Drive, Burnaby, BC V5A 1S6

Reports from each of the breakout groups were followed by discussion focused on two issues:
(i) key research needs associated with the risks that farmed salmon pose for wild Pacific salmon, and
(ii) strategies for reducing these risks. Following is the discussion leaders’ overview.

The discussion highlighted the following research gaps in each of the three areas of potential interaction:

Genetic interactions
The most pressing research need is the extent and scale of local genetic adaptations. Local genetic adaptations, where present, are likely to have been generated by complex combinations of genes that take a relatively long time to evolve. In this context, it is fortunate that Atlantic and Pacific salmon do not interbreed with much success, and chinook and coho are playing a diminishing role in the aquaculture industry.

Nonetheless, there is no room for complacency on this issue. In particular, the potential impact of hatchery programs for Pacific salmon, though outside the scope of the meeting, was repeatedly mentioned. It is abundantly clear that these pose a far greater genetic risk to Pacific salmon than do fish farms at the present time.

In addition, other threats, including depleted stocks and climate change, call for immediate action on this research priority. Canadian scientists are just now beginning to assemble enough information to propose tentative boundaries on populations containing evolutionarily significant local adaptations in coho, and have made a start at the same task for sockeye. This work needs to be pressed forward.

More research is also needed on the long-term consequences of genetic interactions. Indeed, participants repeatedly noted the lack of funding for long-term research programs fundamental to the conservation of Pacific salmon.

There was also considerable discussion on transgenic fish. No one, at present, is apparently interested in growing transgenic salmon in British Columbia. However, the situation could change relatively quickly, and extremely stringent rules need to be put in place in advance to safeguard against possible releases of transgenic fish. Participants were also encouraged to consider the potential benefits of fish that were genetically modified to be sterile. (There is a current draft national policy on research with, and rearing of transgenic aquatic organisms, see also Devlin, p.63.)

Disease interactions
Disease and parasite transfers between farmed and wild salmon have had serious consequences on both sides of the Atlantic. The experience in the Bay of Fundy shows that disease can be particularly threatening when wild populations that are already depressed are confronted with an exotic disease. There was support for existing tight restrictions on importing eggs for aquaculture. By contrast, serious concerns were repeatedly expressed about other sources of exotic organisms, including pathogens. Live food importation and ballast water transfers in marine shipping were highlighted.

There are very few scientists located in British Columbia, either in government or academia, with expertise in fish diseases. This shortfall is troublesome in light of emerging challenges coming from aquaculture, climate change, and other sources.
Ecological interactions

It is clear that very little is known about the potential ecological interactions between farmed and wild salmon. Two key areas were highlighted in the discussion:

(i) juvenile competition in freshwater, particularly between Atlantic salmon and their closest competitor, steelhead, and
(ii) the ability of the progeny of escaped Atlantic salmon to survive in the ocean.

These and other unknowns make it impossible to predict the ultimate success of Atlantic salmon in competing with Pacific salmon.

Nonetheless, the recent discovery of feral populations of juvenile Atlantic salmon in the wild is highly significant. It proves that escaped Atlantic salmon can survive in the ocean, migrate into fresh water, and spawn successfully. It also proves that their offspring can survive in the freshwater environment. The only untested part of the life cycle is the early saltwater stage.

The possibility that Atlantic salmon will successfully invade the northeastern Pacific can no longer be characterized as remote. Perhaps the most important question is not “Can Atlantic salmon invade the northeastern Pacific?” but “How large an impact might such an invasion have?”

There is far too little evidence yet available to answer this question. If Atlantic salmon do successfully colonize, their impact may be as benign as that of the horse when it was introduced to North America by the Spaniards, or as devastating as the lamprey eel that decimated trout populations in the Great Lakes earlier in the 1900s.

We urgently need to learn more. But even if in the early going, these domesticated fish are barely able to sustain small populations in the face of aggressive competition from wild Pacific salmon, there can be no complacency. Atlantic salmon have the capacity to produce a large number of offspring. Only the fittest of these will survive and reproduce. This selection process may someday produce fish with substantially different competitive abilities than the original colonizers.

This possibility underscores a recurring theme in the discussions: the need for long-term research, with a time horizon of at least 15 to 20 years. Discussion focused on the needs both for long-term funding commitments to such research and for a special mechanism to administer the program. Although details of such a mechanism were not discussed, support was expressed for the following:

- that there was a unique opportunity for federal-provincial cooperation, and the issue ought to be placed before the Council of Fisheries Ministers.
- that it was important that opportunities for cooperation between industry, government, and academic institutions be fostered.
- that the provincial government be encouraged to use revenue from a proposed tax on farm fish production (“finnage”) to fund such research.

In addition, the discussion leaders stressed the need for a framework that guarantees the objectivity of the funding decisions, an impartial peer-review process for evaluating results, and full, timely, public disclosure of all results. The internationally acclaimed NSERC model provides an appropriate standard.

There is sufficient lack of certainty in the potential impacts associated with salmon farming to invoke the precautionary principle. Indeed, there was general agreement on this point in the closing discussion session. Of special concern is the risk of changes to wild Pacific salmon that are either irreversible or long-term. However, no attempt was made to generate consensus on specific precautionary measures to be recommended, as many participants felt that their role as scientists stopped at delineating the risks.

With that, the scientists passed the baton to government managers. It will be up to those managers to develop measures to ensure compliance with the precautionary approach, to which Canada is committed by international agreements. In so doing, it is essential that they face the evidence squarely, and that they pay particular attention to risks of changes with potentially long-term, serious consequences. The implementation and effectiveness of control measures must also be thoroughly monitored, and relevant scientific information must be gathered in a way that is demonstrably objective, with all results made freely available.
The Role of Science in Formulating Aquaculture Policy

Bud Graham, Assistant Deputy Minister
BC Ministry of Agriculture, Food and Fisheries
PO Box 9359, Stn. Prov. Govt., Victoria, BC V8W 9M2

On behalf of the Ministry of Agriculture, Food and Fisheries, we are pleased to provide both financial and technical support to this workshop. We look forward to a fact-based scientific discussion on the interactions between farmed and wild salmon. It is important to recognize that science creates knowledge by observation, deduction and experiment. However, science rarely has the ability to reach definitive conclusions on the risk or severity of human interactions with complex ecosystems. The inability of science to eliminate uncertainty around an issue is not unusual. Managers are constantly facing the challenge of interpreting new and sometimes conflicting scientific information. Adopting an adaptive management approach allows for changes based on new information.

Scientific study is not static but dynamic. Policy responses, therefore, must be dynamic and subject to modification based on new knowledge. Scientific study has helped formulate and amend past and current aquaculture policy in British Columbia. For example, the Canadian Fish Health Protection Regulations were a policy response to the desire of industry to increase shipments of fish into Canada and to manage the risk of pathogen transfer.

In the 1970s, the government approved the development of salmon farming as an economic opportunity on Canada’s Pacific Coast. The industry was originally founded on the use of coho and chinook salmon. However, it quickly became clear that neither species could be rapidly adapted to salmon farming in BC and that advances in aquaculture science made Atlantic salmon the preferred species for farmed salmon production.

In 1985, a policy decision was made to allow the importation of Atlantic salmon based on an evaluation of Atlantic salmon as a potentially competitive species, and the ability to manage risk of disease introduction through the Canadian Fish Health Protection Regulations. This decision was not universally endorsed but was based on the information available at the time. Today, Atlantic salmon make up the bulk (over 75%) of BC farmed salmon production. This fact makes the issue of potential interactions between wild and farmed salmon on the Pacific Coast different from on the Atlantic Coast where the predominant species cultured is also the predominant wild species. The rapid growth of the salmon aquaculture industry in the 1980s was accompanied by increasing public concerns about the impact of the industry on the marine environment and other coastal users.

A number of public inquiries took place regarding the industry in the late 1980s that led to some improvements to the regulation and management of the industry. However, continued debate regarding environmental issues led the Provincial government to undertake, in 1995, a comprehensive technical and scientific review of the salmon aquaculture industry. Five main areas of concern were identified for investigation:

- impacts of escaped farm salmon on wild stocks;
- disease in wild and farmed fish;
- environmental impacts of waste discharged from farms;
- impacts of farms on coastal mammals and other species; and
- siting of salmon farms.

The Environment Assessment Office established a Technical Advisory Team of experts to prepare comprehensive discussion papers and make recommendations on each of the five key issues. In addition, a Review Committee comprised of voluntary representatives from a wide variety of interests was set up to provide information, advice and comments to the Technical Advisory Committee.

The Technical Advisory Committee concluded that salmon farming in BC, as currently practised and at current production levels, presents a low overall risk to the environment. However, the technical team made a number of recommendations aimed at further reducing risks and to address issues associated with public confidence.

In October 1999, the province released its policy response to the Salmon Aquaculture Review (SAR). In developing this response, the provincial government
accepted the recommendations of the Environment Assessment Office and also considered any new scientific information received after the SAR report was released in August of 1997. In releasing this policy, the Provincial government confirmed that salmon farming was a legitimate industry that provides important economic benefits to residents of coastal communities. However, this industry must operate in a manner that will protect our marine environment and wild fish stocks. The Ministry of Agriculture, Food and Fisheries is pleased that the salmon farming industry has endorsed this policy approach, and is committed to work towards its successful implementation.

One of key elements of the provincial aquaculture policy is the creation of the Strategic Aquaculture Implementation Advisory Committee (SAIAC), a group that includes environmental, commercial and recreational fishery interests, local government, and First Nations, in addition to representatives from the salmon farming industry. SAIAC will provide a forum for the review of implementation of the provincial salmon aquaculture policy, and advise on sustainable salmon farming practice. It will serve as a policy forum not unlike the process agreement between North Atlantic Salmon Conservation Organization and the North Atlantic salmon farming industry.

The purpose of the workshop today is to examine current scientific information regarding salmon farming as a potential risk factor for wild salmon. The provincial salmon aquaculture policy recognizes these concerns, and has developed management approaches to try and address these issues. For example:

- Do genetic interactions occur between wild and farmed salmon?
- Can farmed Atlantic invade the ecological niches of wild salmon?

Both of these issues were considered by the SAR. The SAR concluded that the risk of crossbreeding was low, especially for Atlantic salmon. This assessment, combined with a commitment to improved husbandry practices stressing prevention, represents an important risk management response. The province will be working with the industry to ensure that farm husbandry practices are developed that will prevent, as much as possible, the escape of farmed fish; and, if an escape occurs, to have a recovery plan in place to recapture as many salmon as possible to minimize the number of salmon that do escape into the ocean. Failure to effectively control escapees will result in denial of re-stocking permits for specific farms.

The province is maintaining support for the Atlantic salmon monitoring programs that track the capture of Atlantic salmon in commercial fisheries and observed in fresh water. In addition, the province is continuing research on the culture of non-reproductive Atlantic salmon.

**Evidence that Disease Spreads from Farmed to Wild Salmon?**

The SAR concluded that the risk of transfer of pathogens/diseases through importation of stock is unlikely, given that BC’s import policies are amongst the most stringent in the world. This is based on the adoption of a regional policy that permits the importation of eggs only.

British Columbia’s new policy calls for the development of a fish health database that will amalgamate information from private, federal and provincial fish programs so that this information can be accessed in a timely manner. This knowledge will also assist us to further focus scientific research to address fish health concerns.

The use of the database in combination with a policy of more active surveillance will provide new information in this area and guide future policy and standards of practice.

These standards of practice will be based on science to ensure that the desired effect is achieved (i.e. effective disease control measures to reduce the spread of pathogens). Defined and enforceable standards outline the measures taken to ensure that the risks of impact are adequately addressed.

**Farming of Transgenics?**

The Provincial government has adopted as policy the Salmon Aquaculture Review recommendation that: *Government should continue to prohibit the commercial farming of transgenic salmon in marine netcages.*

The BC salmon farming industry agrees that this is an appropriate response.
Conclusion
The provincial government has adopted an adaptive approach to the management of the salmon aquaculture industry that addresses existing uncertainty, reduces risk and allows for sustainable development of the industry in BC. Fundamental to successful adaptive management are focused outreach initiatives and on-going monitoring to fill in gaps and determine if management adjustments are indicated. We look forward to participating in this workshop to discuss the scientific information available regarding the interactions of wild and farmed salmon. I am confident that the scientific information obtained will be important in framing management strategies for the industry and on-going research efforts by government, industry and universities.

Opening Remarks
John Fraser, Chair, Pacific Fisheries Resource Conservation Council
590–800 Burrard Street, Vancouver, BC V6Z 2G7

I am speaking to two audiences this morning. Some of you have come from a long way away for which we are very appreciative. Others live here and are part of the lifestyle and tradition of the west coast. Some of my remarks will seem to some of you as given, because you are part of this community. For others of you who have come from elsewhere, I hope that they will be somewhat helpful in putting what we are doing today into context.

We have asked you to deal with a series of questions that are directed at getting answers from science. However, just as much as if you were discussing what to do about greenhouse gas reductions, to assume that you are not doing so against a backdrop of political opinion would be disingenuous.

What you are being asked to do here today is to stay away from the polemics and as much as possible the politics, and try to give to people who have to make decisions in a democratic system some scientific information that they need to know, and to give through this conference and other things you will do, the scientific information that not only the people who get elected to make decisions have to know but that the public needs to know and understand. The gap between what we ask scientists to do, and our capacity to translate that into language that is exact but nonetheless not obscure so that people can understand what we are talking about, is a serious one and it affects the capacity of governance in democratic countries.

I want to begin my remarks by reminding us of something. Last summer the New York Times ran one of its usual quite magnificent sections on tourism and there were some pages devoted to Ireland. This was a terrific article on why you should come to Ireland, the people, the ambience, the songs, the pubs, the friendliness, travelling in the country, the beauty of the land - but then it said: “Don’t bring your fishing rod, because as a consequence of farmed salmon operations there are hardly any fish left to catch.” It wasn’t a scientific article but it was in the New York Times, and you can imagine what that does to people trying to promote the tourist trade in Ireland. You can also imagine what it does to the ordinary person who reads it, and says what is all this about anyway? This is why the workshop discussion while it has to concentrate on science, because without that you cannot make effective political decisions, must also take into account the decision-making point of view.

It could be said that we are on the cusp of significant change in British Columbia. For at least 120 years we in British Columbia have been engaged almost exclusively in the harvesting of wild stocks. (When I say “we” the harvesting I am talking about is since the Europeans came - our native people have lived off the fish for thousands of years.) In the early 1980s the trend to harvesting wild stocks of salmon began to change. Part of that was a consequence of things that were happening in the fishery and part of it was a consequence of the introduction of salmon farms.

In 1995, the provincial government imposed a moratorium on the expansion of salmon farming pending a review of the environmental impacts of salmon aquaculture. At that time, 121 licenced fish farm tenures had been approved, of which 85 remain in operation. An environmental assessment was launched and in August of 1997 the Salmon Aquaculture Review report was published. This report put forward 49 recommendations regarding aquaculture and these recommendations are under active review by the provincial Ministry of Fisheries.
In October of the year just past, the provincial Minister of Fisheries announced that the Government of BC will allow a limited expansion of the salmon farming industry in BC, and 10 new fish farms will be created to develop new technology. Environmental regulations covering escaped fish and fish waste will be put in place. However, the moratorium on new farms will be maintained with the provision that tenures with unproductive sites will be allowed to change locations and put their farms into production.

In October 1999 the provincial Minister of Fisheries stated:

“The provincial salmon aquaculture policy is geared towards bringing the industry into line with tough new environmental regulations while encouraging the development of new made-in-BC salmon farming technology.”

For those of you from other places who are confused about why the Province is doing this and the federal government is not—it is a matter of division of powers in Canada. Fisheries is a federal constitutional responsibility but fish farming, sales, administration is provincial.

The Government of BC licences the salmon farms and sets out the conditions of salmon farm tenure and since the inception of the industry the provincial government has taken the initiative in promoting salmon farming. The Government of Canada, on the other hand, has primary responsibility for the conservation and protection of the wild stocks, a responsibility that includes protecting the health of wild salmon.

I read to you now an extract from a letter received a couple of days ago from the federal Department of Fisheries and Oceans addressed to our Pacific Fisheries Resource Conservation Council:

“Fisheries and Oceans has recently completed the draft wild salmon policy. The policy focuses on the overarching principles that will guide the conservation and management of Pacific salmon in British Columbia and the Yukon. It is our intention to initiate a period of public consultation on the wild salmon program beginning in late March 2000. The results of the consultations and a revised wild salmon policy will be provided to the Minister of Fisheries and Oceans Canada for his consideration in the Fall of 2000.”

I want to point out that at both levels, as that public consultation takes place, you should not have any illusions that aquaculture will not find its way into the discussions, one way or the other. It will—that is why we need some good science about the interactions between farmed and wild salmon.

Both levels of government, as you might expect, have great interest in realizing the potential of the economic benefits accruing from salmon farming and the coastal communities of BC who tend to have a limited economic base. On the face of it salmon farming offers the potential for jobs and revenue where it is sorely needed. The October 1999 announcement by the provincial government to allow limited but controlled expansion was strongly supported by the federal Minister of Fisheries and Oceans. It was criticized as a small step by fish farming industry representatives in hope for more. Environment critics, on the other hand, saw the move as a write-off of wild stocks. Their concerns were based on what they perceived to be increased risks from interaction between Pacific wild salmon and farmed Atlantic salmon.

An excerpt from a letter written by Professor William Rees of the University of BC, in a sense sums up this latter concern:

“As you can see, this industry reduces global food supplies, disadvantages impoverished consumers in developing countries, and due to its great dependence on fossil fuels is inherently unsustainable. In short it does not deserve the support of public agencies which instead should be focusing on ways of restoring our wild salmon stocks.”
Another point of view was expressed by Mr. Yves Bastien, Commissioner for Aquaculture Development for the federal government:

“The dawn of the new millennium will be looked upon as the time when mankind went from fisheries to aquaculture.”

You could ask: What is the public to believe? British Columbians see themselves as stewards of the salmon resource. The public wants to know that there will be a wild heritage to pass on. Salmon are a precious heritage. They are historic, they are traditional, and they involve the lives of our native people before Europeans got here. Salmon have sustained at least four generations of traditional commercial fisherman, and offered unmatched opportunities for sports fishermen. Salmon have created a new class of volunteers dedicated to the preservation of salmon; more than 12,000 men and women in BC freely dedicate their time and energy to the preservation of salmon and their habitats. Salmon is an icon. Even in our schools there is a curriculum item called Salmonids in the Classroom. Salmon bring countless hundreds of thousands to a state of wonderment when they visit the rich red spawning grounds of the Adams River sockeye and other places. They are a magnificent resource. They are a treasure and they must be maintained.

The question is: Does salmon farming pose a risk to the health of wild salmon? Wild salmon are under great stress at the moment for a number of reasons. Some are clearly identified and understood, but others, such as ocean survival and climate change, are not so easy to explain or to predict. If an activity is likely to create another risk, the question is what can be done to eliminate or minimize that risk?

Five questions have been put on the table for discussion at this workshop and think tank:

1. Do generic interactions occur between wild and farmed salmon and, if so, how are such interactions manifested in the gene pool of wild salmon?
2. Can farmed Atlantic salmon invade the ecological niches of wild salmon?
3. What is the evidence that disease spreads from farmed to wild salmon?
4. What are the dangers associated with farming of transgenics?
5. What steps should be taken to reduce the risk of aquaculture to wild salmon?

In the present climate of debate about whether the promise of salmon farming is a blessing or a curse, it is indeed timely for us in British Columbia to hear what scientists have to say, particularly scientists from places where the aquaculture industry has been operating for many more years than it has been in British Columbia.

I hope that puts things in context. You have been invited here and we are very appreciative that you have come. We have put a lot of responsibility on your shoulders and on the intellectual, academic and professional expertise that you bring to these consultations. Let me assure you that what you do is necessary—that what we need is as clear an expression of what science knows as we can get. Politicians who have to make the decisions will have to make inferences from some of what you know and report. That is the responsibility of decision-making. You are very much a part, at least for a few days, of this community in trying to sort out what is the best and safest way to go, keeping in mind that once upon a time, and it was not that long ago, nobody would have considered any need for salmon farming, because we had one of the most bountiful resources of salmon in the whole world. We are not so sure of that now, and we may well have to look to other things.

QUESTION ONE
Do genetic interactions occur between wild and farmed salmon and, if so, how are such interactions manifested in the gene pool of wild salmon?

Genetic Pollution: Fact or Fiction for Atlantic Salmon?

Dr. Willie Davidson, Dean of Science
Simon Fraser University
8888 University Drive, Burnaby, BC V5A 1S6

Salmonids in general, and Atlantic salmon in particular, are among the most plastic of species with respect to behaviour, morphology, physiology, and life history. It
has often been assumed, without good evidence, that there is a strong genetic basis for the diversity of traits observed within and among populations of Atlantic salmon. This has led to the concept of local adaptations giving rise to genetically different populations. Indeed, it has been argued that each tributary of every stream in a watershed is home to a genetically distinct population. This presentation critically reviewed the evidence that has been put forward in favour of locally co-adapted gene complexes in Atlantic salmon, and then examined if it stands up to scrutiny in light of what is known about the life history strategies adopted by this species. The results of this analysis were used to assess whether or not there can actually be genetic pollution when aquacultured salmon breed with wild Atlantic salmon.

**Genetic Interactions Between Wild and Cultured Salmon**

Jeffrey J. Hard, National Marine Fisheries Service, Northwest Fisheries Science Center, Conservation Biology Division, 2725 Montlake Boulevard East, Seattle, WA 98112 USA

**Introduction**

Artificial propagation has been a prominent component of salmon production and management on both coasts of North America for most of the last century. Artificial salmon propagation is a versatile tool that has at least two major current uses; another use is emerging as a restorative method for Pacific salmon. One current use is farming, or closed captive culture of salmonids in fresh or marine waters to marketable sizes, which is used primarily to augment seafood production. Another use—that with the longest tradition—is ocean ranching, or the captive propagation of anadromous salmonids during the freshwater portion of their life history followed by release of juveniles to the sea, which has typically been used to support fisheries or to mitigate for lost salmon production due to habitat loss or degradation. Recently, propagation of Pacific salmon in hatcheries has been applied to supplement wild populations under decline or for reestablishment of extirpated populations. This emerging use of artificial propagation is sometimes referred to as captive rearing or captive broodstocking. Captive rearing programs typically release captively reared fish as live adults into natural habitat; captive broodstock programs release juvenile progeny of adult fish that are spawned in captivity. Both approaches have advantages and possible pitfalls as restorative tools, but neither has been rigorously evaluated. In general, artificial propagation (farming and ocean ranching) has demonstrated an ability to produce substantial numbers of fish to adulthood, but risks to natural populations are poorly understood.

Evaluating effects of salmon farming on wild salmon populations is the primary focus of this workshop. Most of the discussion of these effects in this presentation stems from ongoing research on risks of artificial propagation of Pacific salmon. I recognize that some of the issues raised in this paper are not entirely germane to Atlantic salmon farming in British Columbia. They are more relevant for farming of Pacific salmon, for which two species, chinook and coho salmon, currently constitute about 25% of farmed salmon production in BC (Noakes et al. 2000). In any case, the general consequences of artificial propagation for any production program can help to illustrate the range of potential effects of cultured fish on natural salmon populations, and I believe it is informative to evaluate the current evidence for these effects.

**Benefits and Risks of Artificial Propagation**

Because artificial propagation is a powerful means of producing salmon, its goals should be clearly defined at the outset of any propagation program (Waples 1999). Ideally, an objective and comprehensive assessment of risks and potential benefits should be undertaken before a new artificial propagation program is initiated, or if such an assessment has not already been conducted (Busack and Currens 1995). For programs already in place, undertaking such an assessment can be useful in characterizing a program’s utility and risk to natural populations.

Furthermore, adequate monitoring and evaluation of potential effects of hatchery on wild fish should be an integral component of any production program. Because a considerable degree of uncertainty over the effects of hatchery programs on wild fish exists, it is essential that salmon managers take a proactive and risk-averse approach to managing wild salmon populations in the presence of artificial propagation.
(Hard 1995a). Monitoring and evaluating risks of cultured fish to wild populations is a major challenge when cultured fish reproduce naturally—especially when hatchery fish cannot be distinguished from wild fish in nature. The primary potential benefits are increases in a composite (hatchery + wild fish) population’s abundance and productivity; such increases can reduce the extinction risk of a supplemented population. However, risks to wild populations include masking of the demographic status of wild populations by naturally spawning hatchery fish, adverse ecological interactions between hatchery and wild fish, reduced effective number of breeders in the composite population, genetic change resulting from domestication, and reduced genetic diversity among populations.

I focus here on genetic risks; consideration of ecological risks is dealt with by other workshop participants. One reason genetic issues are worthy of consideration is that a “disconnect” exists between the genetic and demographic effects of migrants on natural populations. Typically, many migrants are required to have substantial demographic effect, but relatively few (sometimes very few) are required to have a substantial genetic effect. Consequently, genetic risks to wild fish may be substantial without the presence of large numbers of hatchery fish on spawning grounds.

A document developed by federal, state, and tribal salmon co-managers in the state of Washington entitled “Artificial Propagation Guidelines and Benefit/Risk Assessment Framework,” describes these issues. I have drawn heavily from this document in my discussion of genetic risks. It is important to recognize that most of these risks are difficult to detect without carefully designed experiments; in many cases, the best that can be achieved is some measure of relative productivity of naturally spawning hatchery and wild fish. The table below outlines evidence for benefits and genetic risks in anadromous salmonids.

The evidence in Table 1 is summarized from a number of publications that have appeared recently in the scientific literature or that describe studies currently underway. The citations for these papers are provided in the reference list. What may not be imminently clear from this summary is the degree of uncertainty surrounding these effects on wild fish.

Although it is widely recognized that artificial propagation has the potential to benefit wild salmon populations by increasing composite abundance or stimulating production of naturally produced fish, these benefits have not yet clearly been demonstrated. Primary reasons for this disparity are that:

1) artificial propagation programs intended to augment natural fish production have seldom been implemented long enough to achieve these benefits in natural abundance or productivity,

2) it is difficult to measure the contribution artificially-produced fish are making to natural production, and

3) it is not clear whether any apparent increases in natural abundance or productivity are sustainable in the absence of artificial propagation.

Teasing apart the contribution of naturally spawning hatchery or farmed fish from that of wild fish is a major challenge in determining both the utility of artificial propagation as a restorative tool, and its risk to natural production. (It is very difficult to interrupt production at a farm or hatchery to evaluate its effects on natural productivity, and possible alternatives such as mass marking of cultured fish are not yet implemented for many programs.) Consequently, a comprehensive assessment of the ability of artificial propagation to provide such benefits must await resolution of these issues.

However, concern is growing about genetic risks (Hindar et al. 1991, Campton 1995, NRRC 1996). I focus the remainder of this discussion on three of these risks: reduced effective number of breeders (Nb), domestication, and reduced among-population genetic diversity and its fitness consequences. Two recent papers (Hard 1996b, Lynch 1996) discuss these and other considerations from the perspective of quantitative genetics and conservation of biodiversity.
<table>
<thead>
<tr>
<th>Benefit</th>
<th>Evidence</th>
<th>Risk</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased total abundance (hatchery and wild fish)</td>
<td>Many examples (but REALLY tested?); Supplementation: Snake R. sockeye and chinook salmon, Col. R. steelhead, White R. chinook salmon</td>
<td>Reduced effective number of breeders ($N_e$)</td>
<td>Little direct evidence for reduced $N_e$—but some evidence in Atlantic salmon (e.g., Tessier et al. 1997)</td>
</tr>
<tr>
<td>Sustained abundance of natural spawners</td>
<td>No examples clearly documented for supplementation (Waples and Ford 2000); escaped farmed salmon represent a risk. Some salmon introductions have been successful</td>
<td>Fitness loss associated with reduced $N_e$ (inbreeding depression)</td>
<td>Atlantic salmon (Ryman 1970), rainbow trout (Gjerde et al. 1983; Su et al. 1996), chinook salmon (Hard and Hershberger, unpubl. data)</td>
</tr>
<tr>
<td>Reduced among-population diversity (reduced $V_g$)</td>
<td></td>
<td>Limited evidence: chum salmon (Phelps et al. 1994, 1995), chinook salmon (Bugert et al. 1995), coho salmon (Weitkamp et al. 1995), Atlantic salmon (Hindar et al. 1991)</td>
<td></td>
</tr>
<tr>
<td>Fitness loss associated with reduced among-population diversity (loss of local adaptation)</td>
<td></td>
<td></td>
<td>Pink salmon (Gharrett and Smoker 1991; Gharrett et al. 1999), coho salmon (Hard et al. unpubl. data)</td>
</tr>
</tbody>
</table>
Risk 1: Reduced Effective Number of Breeders
Production of artificially propagated fish that have
opportunities to interbreed with wild fish in nature
might, under some circumstances, reduce genetic
variability in the mixture. This effect is difficult to
measure, and has seldom been documented. One way to
evaluate the potential magnitude of this reduction, as
well as the demographic effects of reduced genetic
variation, is to compare the effective population size—a
means of quantifying a population’s “size” in an
evolutionary sense and a measure of its standing genetic
variation (Falconer 1989)—to its census size. Several
studies of salmon have provided estimates of the ratio
of the effective number of breeders (N_e) to the census
number (N); the information is summarized in Table 2
(H refers to hatchery populations):

How do these ratios compare with
recommendations for maintenance of genetic diversity?
Several researchers have recommended a minimum
effective population size of 50 individuals per
generation to reduce short-term loss of genetic
variation, and 500 per generation to minimize longer-
term loss (Franklin 1980, Soule 1980, Frankel and
(1996) argued that an effective size of a few thousand
(1000-5000) per generation might be necessary to
reduce accumulation of deleterious mutations affecting
fitness. Working with salmon, Waples (1990) suggested
a minimum effective number of breeders per year of
100 to reduce the rate of loss of rare genes. Under an
assumption of N_e/N ~ 0.3 for chinook salmon
populations and a mean generation time of 4 years,
these considerations suggest that Nb between several
hundred and a few thousand may be necessary to ensure
long-term population persistence. The data in table 2
clearly indicate that population census size may

<table>
<thead>
<tr>
<th>Population</th>
<th>Nb/N</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shasta H. (CA) rainbow trout</td>
<td>0.90</td>
<td>Bartley et al. (1992)</td>
</tr>
<tr>
<td>Secesh R. (ID) spring/summer chinook salmon</td>
<td>0.24</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Johnson Cr. (ID) spring/summer chinook salmon</td>
<td>0.50</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Marsh Cr. (ID) spring/summer chinook salmon</td>
<td>0.23</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Valley Cr. (ID) spring/summer chinook salmon</td>
<td>0.69</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Innaha R. (OR) spring/summer chinook salmon</td>
<td>0.71</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Lostine R. (OR) spring/summer chinook salmon</td>
<td>0.54</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>McCall H. (ID) spring/summer chinook salmon</td>
<td>2.23</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Sawtooth H. (ID) spring/summer chinook salmon</td>
<td>0.21</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Innaha H. (OR) spring/summer chinook salmon</td>
<td>0.51</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Lookingglass H. (OR) spring/summer chinook salmon</td>
<td>0.39</td>
<td>Waples et al. (1993)</td>
</tr>
<tr>
<td>Sacramento R. (CA) winter chinook salmon</td>
<td>0.013-0.043</td>
<td>Bartley et al. (1992)</td>
</tr>
<tr>
<td>Sacramento R. (CA) winter chinook salmon</td>
<td>0.111-0.367</td>
<td>Hedrick et al. (1995)</td>
</tr>
<tr>
<td>Big Creek H. (OR) coho salmon</td>
<td>0.24</td>
<td>Simon et al. (1986)</td>
</tr>
<tr>
<td>Chiwawa R. (WA) spring chinook salmon</td>
<td>0.12</td>
<td>Ford et al. (unpubl. data)</td>
</tr>
<tr>
<td>Twisp R. (WA) spring chinook salmon</td>
<td>0.15</td>
<td>Ford et al. (unpubl. data)</td>
</tr>
<tr>
<td>Chewuch R. (WA) spring chinook salmon</td>
<td>0.18</td>
<td>Ford et al. (unpubl. data)</td>
</tr>
<tr>
<td>Methow R. (WA) spring chinook salmon</td>
<td>0.25</td>
<td>Ford et al. (unpubl. data)</td>
</tr>
<tr>
<td>White R. (WA) spring chinook salmon</td>
<td>0.84</td>
<td>Ford et al. (unpubl. data)</td>
</tr>
<tr>
<td>Lilliwaup Cr. (WA) coho salmon (H-wild mixture)</td>
<td>0.34</td>
<td>Hard et al. (unpubl. data)</td>
</tr>
</tbody>
</table>
dramatically overestimate the effective genetic size of a natural population. The N_e/N ratios for hatchery vs wild populations do not differ appreciably, but it is difficult to determine whether hatchery supplementation would alter rates of loss of genetic diversity without more comprehensive analyses of variation in Nb and N in these populations. In any case, these ratios highlight the importance of considering breeding population sizes and employing mating designs to minimize losses of genetic variability in salmon populations, especially those that are already at low population size or steeply declining in abundance.

Figure 1 shows schematically how a successful hatchery supplementation program might reduce the diversity of genotypes in a natural-hatchery population mixture from the original, wild situation. The boxes or their subdivisions represent hatchery and wild population components; the box sizes are meant to indicate relative population sizes. At the left, in a stable unsupplemented wild population, the genetic composition may be expected to change little between generations, depending on the population’s effective size. However, in a successful supplementation program, the genetic composition may change appreciably if selection of genotypes for hatchery culture is not representative of the wild population—even if the population mixture grows larger from supplementation (right). Change in genetic composition could be considerable if the population component reproducing in the wild does not rebound in productivity after supplementation is ceased (center). This result could be particularly problematic if genetic variability in the hatchery population is low through inbreeding or genetic drift (Ryman and Laikre 1991, Waples and Do 1994, Ryman et al. 1995).

This potential problem is primarily a theoretical concern at present. To my knowledge, no direct empirical evidence exists to demonstrate that this is a pervasive problem in supplemented salmon populations. However, no concerted efforts have been made to evaluate the issue, either.

A reduction in genetic diversity can be a problem because this diversity is thought to be necessary for adaptation. What is the evidence for this relationship in salmonids? Unfortunately, little research has been attempted to determine the consequences of loss of genetic diversity for fitness in salmon, in part because this research is difficult to carry out. Most of the work on inbreeding depression (a reduction in fitness caused by inbreeding, or matings between relatives) in salmonids has come from studies of non-anadromous rainbow trout (e.g., Kincaid 1983, Gjerde et al. 1983). Figure 2 summarizes estimates of inbreeding depression in growth and survival from two studies of rainbow trout (Gjerde et al. 1983) and chinook salmon (Hard and Hershberger, unpubl. data). In the plot, inbreeding depression is estimated as delta, a ratio of the change in phenotype in inbred groups relative to one or more outbred control groups (Lande and Schemske 1985). (Here, reduced fitness from inbreeding depression increases with delta.) Although considerable variation exists in the response of these traits to inbreeding for both species, these results indicate that inbreeding depression can occur in survival and growth of both species with relatively small increases in inbreeding. It is therefore important to minimize losses of genetic variation in cultured populations because there may be consequences for fitness and performance. How large these consequences are remains an open question.
Risk 2: Domestication
One risk of artificial propagation that has long been recognized—but until recently has been poorly characterized—is domestication of cultured fish. Because domestication, by definition, involves adaptation to the culture environment, it may result in reduced adaptation to the wild. Consequences for fitness may be expressed as reduced survival or altered behaviour, morphology, or reproductive success—traits that may have a genetic basis. When cultured fish have opportunities to interact with wild fish, lowered fitness may also affect wild fish, eroding local adaptations and increasing risk of extinction. In a recent summary of studies of hatchery and wild summer (SST) and winter (SST) steelhead, Reisenbichler and Rubin (1999) showed that the survival of hatchery steelhead to different life stages was lower than that of wild steelhead. As Figure 3 indicates, despite the advantage of higher survival during early life history that might be realized in a hatchery, the survival of hatchery fish to later stages—including adulthood—was depressed relative to wild fish (the vertical axis is relative survival of hatchery to wild fish). As discussed in their paper, this contrast between hatchery and wild fish indicates that hatchery culture can result in genetic change with strong implications for reproductive success in the wild.

Several studies have actually compared morphology and reproductive behaviour of domesicated and wild salmon. As described in Figure 4a and 4b, Hard et al. (2000) showed marked differences in morphology of adult captive and wild coho salmon. Captively reared adults had reduced secondary sexual characteristics compared to wild adults; captive fish had sharply reduced sexual dimorphism, smaller heads, less hooked snouts, greater trunk depth, larger caudal peduncles, shorter fins, larger hindbodies, and reduced body streamlining. These differences corresponded closely with reduced frequency and intensity of spawning behaviours (Berejikian et al. 1997). Wild males dominated access to spawning females, and were dominant or held the first satellite position in the majority of identified spawnings. Wild males showed significantly higher frequencies of crossover, quiver, and nudge behaviours than captive males (Figure 5); females established nesting territories earlier and constructed more nests than captive females and attacked captive males more often than wild males. As these authors noted, these effects are probably largely environmentally induced.

In a series of studies, Fleming and his co-workers (1989, 1992, 1993) detected similar differences in morphology and behaviour of hatchery-reared and wild coho salmon (Figure 6) and Atlantic salmon (Fleming et al. 1994, 1996 Fleming and Einum 1997). These studies consistently show greater differences in breeding success between cultured and wild males than between cultured and wild females, a result that is probably a consequence of more intense intrasexual selection in male than female salmonids. That is, male competition for access to females and breeding territories is thought to be higher than female competition for acquisition and defense of nesting territories, which in turn may reflect female preferences for male secondary sexual characteristics.

Collectively, these studies indicate that hatchery rearing and other types of captive culture can alter traits important to reproductive success in the wild. Traits like morphology, behaviour, and survival are influenced heavily by environmental variation; however, if these traits have some genetic basis, and they are altered through domestication over generations to reduce fitness, adaptations in wild fish may be eroded when wild and cultured fish interbreed. Evidence exists for genetic influences on many of these traits (Tave 1993, Hard and Hershberger 1995). Despite the fact that a great deal of uncertainty exists about the consequences of domestication in the wild, these results suggest that fish culture programs should be conducted cautiously and monitored carefully when cultured fish have opportunities to interact with wild fish.
Risk 3: Reduced Among-Population Diversity

When cultured fish—whether escaped from farms or released deliberately from hatcheries—interbreed with wild fish, one possible consequence is reduced genetic differentiation among populations. In lower Columbia River coho salmon, for example, production of hatchery fish from a variety of stocks (not all of which are native to the watershed) has been so pervasive over the past several decades that it is difficult to identify wild populations in the region without an appreciable genetic influence of hatchery fish (Weitkamp et al. 1995).

Natural spawning of hatchery fish may have affected coho salmon populations in this area of the Columbia River to the point that any distinct structure among the endemic populations has been lost. One possible corollary of the resultant interbreeding between hatchery and wild fish is depressed wild fitness (outbreeding depression). Although the declining abundance and productivity of coho salmon in this area over the past 25 years has probably resulted largely from habitat degradation and excessive harvest, these declines could also reflect, at least in part, outbreeding depression. Widespread evidence for outbreeding depression in populations of plants and animals (Endler 1986, Hard and Hershberger 1995) suggests that this process should also be a concern for salmonids.

As shown in Figure 7, outbreeding depression and its more familiar counterpart, inbreeding depression, represent opposing extremes of a continuum of genetic effects of reproduction. These extremes are thought to result from fundamentally different modes of gene expression (Lynch 1991). Conventional species
management has for the most part ignored outbreeding depression, typically acknowledging only a sharp decline in offspring fitness as individuals from different species interbreed. However, studies are accumulating to demonstrate that loss of fitness can result upon breeding among more closely related populations and may decay less abruptly than depicted by the conventional view indicated in the figure below.

![Outbreeding depression and inbreeding depression and genetic effects on reproductivity](image1)

Outbreeding depression is often thought to involve the breakdown of favourable epistatic interactions among loci (genes at different chromosomal locations), especially when these interactions have been favoured by natural selection during population differentiation and adaptation. (It is also possible to detect outbreeding depression due to loss of fitness that does not involve breakdown of favourable gene combinations; in this case, the consequences can be immediate as well as serious.) Recent models of outbreeding depression (Emlen 1991, Lynch 1991) have been proposed to show how fitness of crosses between populations changes over various genetic distances, but little empirical work is available to test these models. Consequently, the effects of outbreeding between salmon populations differing genetically by varying degrees must be considered unpredictable. As Figure 8 (kindly provided by Tony Gharrett and Bill Smoker of the University of Alaska) illustrates, one of the most important features of outbreeding depression through breakdown of favourable gene combinations is that fitness consequences may not be expressed immediately. First-generation hybrids retain intact components of parental genomes (upper panel), so that many epistatic interactions are preserved. However, these interactions may be disrupted in second-generation hybrids (or even later) after recombination has occurred (lower panel). In fact, it is even possible that outbreeding depression from epistatic interactions may be preceded by a fitness increase in first-generation hybrids.

![First Generation Hybrids](image2)

![Second Generation Hybrids](image3)

Figure 8. Effects of First and Second Generation Hybrids.
Outbreeding depression has received little experimental attention in fishes. The only experimental work on salmonids that I am aware of is a series of studies of even- and odd-year Alaskan pink salmon (Gharrett and Smoker 1991, Gharrett et al. 1999). As illustrated in Figure 9 (derived from data in Gharrett et al. 1999), these studies demonstrated reduced survival in second-generation hybrids relative to control releases, a result that is consistent with outbreeding depression through breakdown of coadapted genes. Attempts to determine whether hybrids also showed greater asymmetry in meristic characters, which might reflect developmental instability, were inconclusive. The substantial genetic differentiation of even- and odd-year pink salmon that have been reproducitively isolated for hundreds or thousands of generations might be expected to precipitate outbreeding depression in their hybrids and, therefore, may have questionable implications for management. Nevertheless, these results strongly imply that outbreeding depression and loss of local adaptations are possible in salmonids. Ongoing studies by University of Alaska and National Marine Fisheries Service scientists is focusing on breeding experiments between more closely related populations of pink and coho salmon in Alaska. These studies are examining a variety of life history characters for evidence of outbreeding depression.

![Figure 9. Even-and-odd-year pink salmon](image)

Conclusions

Artificial propagation of salmon, whether for farming, hatchery production to support harvest, or wild-stock supplementation, poses risks as well as potential benefits to wild salmon populations. This is particularly true when cultured and wild fish interact appreciably in the wild. The benefits of artificial propagation for wild populations have yet to be clearly demonstrated, and there is evidence that the genetic risks of artificial propagation may have substantial impacts on natural populations in some cases. The extent and consequences of these risks remain highly uncertain, but they could be substantial for releases of farmed or hatchery-raised salmon that have undergone appreciable genetic change in culture. Because our ability to detect such problems is likely to be very poor, especially early in a program’s development (Hard 1995a), judicious use and careful monitoring of cultured fish in the wild are essential to minimize risks to wild fish.

How can these risks to wild fish be reduced? It seems clear that a first step is to ensure that a hatchery or farming program’s production goal is evaluated with regard to conservation of wild salmon where viability of wild fish is a concern. Several safeguards to reduce genetic risks can be implemented:

- Using local broodstock.
- Maintaining an adequate effective number of breeders in every year (Ryman and Laikre 1991, Tave 1993, Waples and Do 1994).
- Where feasible (or where risks are high), limiting domestication by restricting duration of program (no. generations).
- For ranching, reducing proportion of life cycle spent in culture.
- Minimizing selection in captivity.
- Minimizing straying/gene flow between wild and captive fish.
- Rigorous monitoring of natural spawning to detect effects of cultured fish.

Of course, one obvious safeguard that should always be implemented is the ability to control and monitor fish releases and escapes. Finally, carefully conducted propagation programs and associated wild stocks can provide valuable information on where problems are likely to arise. Adaptive management of these programs can help to reduce risks and identify alternative production protocols. Ultimately, artificial propagation of fish that are genetically as well as ecologically compatible with naturally reproducing fish should minimize risks and enhance benefits to wild fish.
References


Berejikian, B. A. 1995. The effects of hatchery and wild ancestry and experience on the relative ability of steelhead trout fry (Oncorhynchus mykiss) to avoid a benthic predator. Canadian Journal of Fisheries and Aquatic Sciences 52:2476-2482.


Notes
i In this paper, I define “wild” populations to mean those that are endemic to a watershed, are naturally spawning, and are not excessively influenced by cultured fish. “Natural” may be a more accurate term, but “wild” succinctly captures the essence of these populations, and “natural” has often been used to describe naturally spawning populations regardless of their genetic heritage.
ii My intent here is to indicate that although supplementation of wild populations with hatchery fish may increase apparent abundance in the wild during this phase, a successful supplementation program should not require perpetual influx of hatchery fish. The ultimate objective is sustainable natural production, which is likely to occur only if the problems that prompted supplementation at the outset have been resolved.

Cultured/Wild Interactions in the East Atlantic Salmon: A Convergence of Opinions on Levels, Effects and Remedies

Dr. Jarle Mork, Professor
Norwegian University of Science and Technology
Biological Station, Bynesetveien 46, N-7018 Trondheim,
Norway, jarle.mork@vm.ntnu.no

Sewall Wright provides a very simple formula for the allele-changing effect when a proportion (p) of a local reproduction group are immigrants with allele frequency (p_i), while that of the natives is (p_n):

\[ \Delta p = -m \cdot (p_i - p_n) \]

The proportion (p) ranges between 0 and 1, depending inter alia on the relative fitness of immigrants to natives. The single locus allelic change by immigration is approximately a total-dose function, so that a dose m in one generation and doses of m/10 in ten generations have a similar effect on the local allele frequencies.
Escaped cultured salmon may have lower fitness than native fish. Studies have indicated that this affects males more than females, and it seems natural to assume that there are also differences based on the specific combination of farmed/wild stocks interacting. The effect of a lower fitness is to reduce \( m \) in (I).

The dominant farmed salmon stock in Norway has been kept for 6-7 generations under which its performance for selected commercial traits has changed considerably. While at the start more than 30 river stocks were represented in the brood stock, the number today is much lower and a few river strains dominate the one farmed stock that stands for more than 80% of the farmed salmon production in Norway. In addition to the systematic change by selection (noting that selecting for additive traits will reduce the allelic variability) of the farmed salmon gene pool, there will be a loss of allelic variability due to random genetic drift in the numerically limited farmed stocks. There is probably also an unintended selection for various traits favourable in a captive life going on in the farmed stocks.

Norway has some 650 salmon rivers. Most river stocks are small and may count 50 or less spawners per year. However, some are big and it is recognized that Norwegian salmon possess most of the genetic variability in Atlantic salmon as a species. Except for the northernmost Norwegian rivers, farmed escapees enter the natural population at high rates (depends on river, but 20-40% is not unusual), and have done so for many years. It has been established that farmed salmon mate with natives, i.e. that an introgression is going on. For many years, the number of escaped farm salmon in Norwegian coastal waters has far outnumbered the returning wild salmon.

The situation has caused concern for Norwegian wild salmon stocks among Norwegian authorities, and also for international salmon management [International Council for the Exploration of the Sea - (ICES)]. The Working Group for the Application of Genetics in Fisheries and Mariculture (WGAGFM) has quite regularly had the “interaction” aspect on its agenda since 1994. (The annual WGAGFM reports can be downloaded from the ICES server in Copenhagen: http://www.ices.dk.)

In 1997, the Norwegian Government appointed a committee by Royal Decree (named the Wild Salmon Committee, but often referred to by the name of its leader, the former Attorney General G. F. Rieber-Mohn). The committee report was in the form of an “Official document from the Government to the Parliament: NOU 1999:9. About the causes for the reduction in Norwegian wild salmon stocks, and suggestions for strategies and measures to improve the situation”. This 300-page document covers most aspects relevant to the management of salmon in Norway. It contains a ten-page English summary.

Both in the WGAGFM and in the Genetics Expert Group in the “Rieber-Mohn committee”, teams consisting of both quantitative and qualitative geneticists, placed much effort in sorting out the scientific from “political” types of arguments in the Norwegian debate, which has been dominated by representatives for the salmon farming industry and environmentalists, respectively. (Traditionally in Norway, quantitative geneticists are associated with the former, and qualitative geneticists to the latter group.)

The process has shown that when the discussion is based strictly on genetics theory and hard scientific facts, it is fully possible to create a platform for a common understanding of the problem by quantitative and qualitative geneticists. It has also been possible to identify topics which seem to have been constant sources of misunderstanding between these two scientific branches in the debate. For example, that the extremely central topic “genetic variability” does not—in everyday practice—mean the same to a quantitative and a qualitative geneticist. While the former would tend to think of variability in terms of traits and recombination by sexual reproduction, a qualitative geneticist would usually think of allelic variability.

Probably, this difference has created many misunderstandings and much unnecessary heat in the debate in Norway during the last decade. Clearing up misunderstandings like this one has proved to facilitate the discussions in mixed fora and allowed a higher degree of consensus on the expected genetic effects of a gene flow from farmed to wild Atlantic salmon.

The conclusion both in the WGAGFM and in the Rieber-Mohn Committee is that a gene flow from farmed to wild Atlantic salmon actually takes place, and that this is unfortunate and unwanted for the wild
stocks, as well as for the economy of fish farming. While the outcome of any one specific interaction may be unpredictable, the loss of allelic variability, which is bound to take place in the farmed salmon, will expectedly represent a genetic erosion when exported to the wild stocks. The self-cleaning effect by natural selection (which notoriously works through increased mortality) is not capable of dealing with the large immigration rates that are observed. Reduction and loss of local adaptations can thus be expected. Together and in the long term, the genetic effects from the interaction may severely reduce the evolutionary potential for the salmon as a species. The factors and forces involved in the interaction are for the most well known and are adequately formulated in population genetics theory.

The basic formula for genetic interaction by gene flow (after Sewall Wright)

When a local population (assume an allele frequency of \( q^\alpha \)) receives a proportion \( m \) of reproductively successful immigrants (assume an allele frequency of \( q^\beta \)), the genetic change in the local population per generation at each locus is:

\[
\Delta q^\alpha = -m (q^\alpha - q^\beta)
\]

Where:

\( \Delta q^\alpha \) change (range 0-1) in recipient allele frequency due to the immigration.

\( m \) = the proportion (range 0-1) of the reproducing individuals that are immigrants

\( m \) can also be expressed as \( Nw \), where \( N \) is the absolute number of immigrants and \( w \) (range 0-1) is their fitness coefficient compared to residents.

\( q^\alpha - q^\beta \) difference (range 0-1) in allele frequency between recipient and immigrant the impact of this factor depends on how systematic it is over time—i.e. whether the source is the same each generation (in which case the affect decreases by time as the allele frequency differences decrease) or not.

In the case of released GEO (genetically engineered organisms) this factor is probably of large (near to 1) magnitude in most cases.

Are There Local Adaptations in Salmon?

Premises:

1. Natural selection acts constantly (selection for increased fitness).

2. Whether this natural selection is efficient depends on, e.g., selection intensity and effective population size (\( N_e \)), and on the amount of gene flow (immigration) represented by the natural straying and, nowadays not least, on escapees from the farming industry.

3. If \( N_e \) is very small, all loci will tend to act as if they were neutral (genetic drift hampers selection effects each generation).

4. Whether substantial adaptations have developed depends also on the time passed (the age of the population), and the constancy of the selection regime.

Conclusions:

5. Both \( N_e \) and age of populations vary widely. Some wild salmon stocks probably fulfill the requirements for size and age, and some do not. Magnitude of adaptations are expected to vary accordingly.

6. The geographic boundary of a local gene pool might be wider than a local stream. Sometimes the management target (the adapted population) may be a set of small rivers, rather than each of them separately.

7. Immigration of non-adapted individuals is much more efficient in reducing (breaking down) an adaptation than natural selection is to remedy the impact, if the trait is determined by many genes (multi-locus traits). Many traits important for survival and reproduction in salmon have been shown to be inherited multi-locus traits. The precautionary principle applies.

Two important actions for Norwegian salmon management were suggested by the Rieber-Mohn Committee. First, management of Norwegian salmon must be simplified formally. Current practice is characterized by the involvement of numerous agencies with an unclear and complicated distribution of
authority, responsibility and roles. Next, national Norwegian salmon watercourses and fjords, as special protected areas for wild salmon, should be defined. The committee’s suggested list includes approximately 50 of the most important salmon watercourses and appurtenant migratory areas in fjords and along the coast.

References

Genetic Breakout Discussion from Think Tank

Participants
Willie Davidson, Faculty of Science, Simon Fraser University; Jarle Mork, Biological Station, Norwegian University of Science and Technology; Bob Devlin, Fisheries and Oceans Canada; Anne Kapuscinski, Department of Fisheries and Wildlife, University of Minnesota; Jeff Hard, National Marine Fisheries Science Center; Ray Peterson, Tri-Gen Inc.; Chris Wood, Fisheries and Oceans Canada; Terry Glavin, Pacific Fisheries Resource Conservation Council; Malcolm Windsor, North Atlantic Salmon Conservation Organization; Bud Graham, BC Ministry of Fisheries; Edward Black, Fisheries and Oceans Canada; Facilitator: Richard Paisley, Institute for Resources and Environment (Westwater), University of British Columbia; Rapporteur: Merrill Fearon, Save Our Fish Foundation

Disclaimer
These notes are not, nor were they ever intended to be, a verbatim transcript of the breakout session on genetic interactions. Rather, they attempt only to capture the gist of what was discussed.

Disclaimer # 2
The draft document entitled “Genetic Interactions” dated March 3, 2000 (document A, shown below), the table entitled “Flow Chart For Application of the Precautionary Approach to Salmon Conservation, Management and Exploitation” (document B, see Table 7, p. 77), the document entitled “Basic and Sufficient Formula for Inspection / Decision” (document C, not shown), and the document entitled “Are There Local Adaptations in Salmon?” (document D, not shown) are incorporated by reference into these notes and form part thereof.

1. The key questions for the break out group was whether genetic interactions occur, how such interactions, if they occur, are manifested in the gene pool of wild stocks, what are the particular dangers, if any, posed by “transgenics”, and how can “risks” be reduced.

2. The target audience for any products from this workshop was discussed at length. Most group members thought the target audience was the general public plus policy makers, stakeholders in both wild and farmed fisheries, and First Nations.

3. The subject of what “action” group members wished the target audience to take as a result of hearing our recommendations was discussed and most group members sought understanding from the target audience, supported funded, long-term, directed research, and recognized that science should be used in a less “episodic” and more “adaptive management” fashion. Most group members also wanted to see more in the way of monitoring, evaluation and feedback.

4. It was generally agreed by group members that the question of whether genetic interactions have occurred is “yes”.

5. Most group members felt it was important to distinguish between qualitative genetic impact and quantitative genetic impact when defining the term “genetic variation” and assessing its impact.

6. There ensued a great deal of discussion concerning whether it was possible to capture the genetic variation issue in a formula (or formulae). Most group members appeared to support the formulae presented in document C.

7. The relative “fitness” of the population and the 7 point answer to the question of whether there are local adaptations in salmon is captured in document D.

8. Most group members indicated their agreement with document C and document D.
9. Most group members also indicated their support for a “precautionary” approach to salmon farming and its genetic implications as expressed in document B.

10. There was some discussion of the “scale” of risks posed by fish farming as opposed to fish hatcheries and the mixed-stock wild fishery.

11. Most group members felt that, from the perspective of only genetic interaction, the farming here in B.C. of Atlantics might be preferable to the farming of Pacifics.

12. Group members reiterated their support for long-term experiments, long-term salmon funding and an adaptive management philosophy to the study of genetic interactions.

13. Most group members felt that, among other things, the possible interaction between Atlantics and steelhead had in particular not been well studied.

14. Group members also felt that it was important from a genetic perspective to keep populations of both wild and farmed salmon as large, diverse and genetically “fit” and “effective” as possible.

15. A drafting group produced document A and presented a draft of that document to the plenary at the end of the day.

---

**Document A — Genetic Interactions**

1. Genetic interactions occur between wild and farmed salmon.

2. The effect of these genetic interactions on the wild salmon depends on the genetic make-up of the farmed and wild salmon.

3. If the farmed salmon is of the same genetic origin as the wild but have reduced genetic variation, interbreeding between farmed and wild salmon will generally reduce genetic variation in the wild salmon population.

4. If the wild salmon population is locally adapted, interbreeding with farmed salmon will likely reduce its local adaptation.

5. Natural populations differ with respect to their level of local adaption because of different evolutionary histories and ability to respond to environmental change.

6. The boundaries of these adapted populations may thus be wider than a local stream, for example a “local” region or watershed. Little is known about these boundaries.

7. Immigration of non-adaptive individuals is much more efficient, in the short term, in breaking down an adaptation than natural selection is in remedying the impact.

8. The long-term effects of genetic interaction are poorly understood.

9. Genetic interaction is not necessarily restricted to interbreeding; it can also include reproductive interference.

10. Because the impacts and effects of genetic interacting are so poorly understood, and known to present risks, then the precautionary principle should guide management decisions.

In the application of the precautionary approach, the group recommended:

- aim to prevent interbreeding between wild and farmed salmon.
- the industry develop different options for both mechanical and biological containment.
- long-term, funded research focused on key uncertainties.
- monitoring and evaluation as an integrated part of policy to manage the aquaculture industry and its effects on wild salmon.
- place the burden of proof on producers.
QUESTION TWO

Can farmed Atlantic salmon invade the ecological niches of wild salmon?

What Determines the Ability of Farm Salmon to Invade Wild Populations?

Dr. Ian Fleming, Research Scientist
Norwegian Institute for Nature Research
Tungasletta 2, N-7485, Trondheim, Norway,
ian.fleming@ninatrd.ninaniku.no

Introduction

Drawing on information from the North Atlantic, particularly Norway, I discuss determinants of the ability of farm salmon to invade wild populations and how this information might be extended to assess the potential for such invasions in the Pacific Northwest.

Insights from the North Atlantic

Large numbers of farm fish escape and enter the rivers of native salmon throughout the North Atlantic, with more than 80% of the fish in some spawning populations being of farm origin. The impact of such invasions is the subject of mounting concern, especially given a global decline in native salmon populations.

Escaped farm Atlantic salmon show a strong tendency to invade nearby rivers, particularly as salmon begin to mature. Their entry into the rivers is often later than that of native Atlantic salmon, which typically enter fresh water several months prior to spawning. Despite differences in the timing of river entry, there are no clear spatial or temporal patterns in the spawning of farm relative to native salmon, thus reflecting the natural variability that exists among salmon populations.

It is well established that escaped farm salmon do spawn successfully in rivers, both in the North Atlantic and the Pacific Northwest. The potential for nest destruction by farm salmon thus exists, and has been realized in North Atlantic rivers. The breeding performance (mate and territory acquisition, egg deposition and fertilization) of farm salmon, particularly that of males, however, is significantly impaired relative to that of wild salmon. Breeding performance also appears to decline with both life stage of escapees and the number of generations of artificial rearing. Furthermore, the competitive and reproductive performance of farm salmon appears to decline with increased competition for breeding resources (i.e. spawning sites and mates). This suggests that healthy, dense spawning populations of native fish will be more resistant to invasion by farm salmon than populations already in a poor state.

The first large-scale experiment to quantify the lifetime success (adult-to-adult) and interactions resulting from farm salmon invading a native population was undertaken in Norway. Experimenters released sexually mature farm and native salmon that had been genetically screened and radio tagged into a Norwegian river where no other salmon could ascend. A series of experiments under laboratory and semi-natural conditions was also conducted to investigate underlying causes of the patterns observed in the river.

The observational and experimental results indicated that breeding was the major bottleneck impeding invasion. The farm salmon, reared to maturity, were competitively and reproductively inferior, achieving less than a third of the breeding success of the native fish. Moreover, the inferiority of farm salmon was sex-biased, being more pronounced among farm males, and gene flow thus occurred mainly through native males breeding with farm females. The presence of farm salmon also resulted in increased interspecific hybridization with brown trout.

Selection against farm genotypes occurred during early life stages, but not thereafter. Evidence of resource competition and competitive displacement existed, as the productivity of the native population was depressed by over 30%, based on the river’s stock-recruitment relation. While stock-recruitment relations are notoriously variable, this depression was the second largest in 16 years and occurred despite low density/competition conditions (i.e. absence of older salmon cohorts) that should favour smolt production.

It has been suggested that the intensity and form of intraspecific competition are altered in salmon from different populations that have not co-evolved, resulting in deleterious consequences. Farm salmon are typically derived from non-local sources. Moreover, domestication selection associated with fish farming has been responsible for altering important fitness-related traits, e.g., by increasing growth hormone production and growth rate, modifying competitive ability, and decreasing predator-response behaviour. Impacts of increased growth rate may be further...
compounded by the effects of spawning time on the timing of juvenile emergence that results in a prior residence advantage during competition. All these factors likely influenced the outcome of competition for resources in the large-scale experiment and, ultimately, the productivity of the native population (Figure 10).

The lifetime reproductive success (adult-to-adult) of farm fish was less than a fifth of that of native salmon. More importantly, such annual invasions of farm salmon may impact population productivity, disrupt local adaptations, and reduce the genetic diversity and long-term viability of wild salmon populations.

**Implications for the Pacific Northwest**

1. Position of farms relative to spawning rivers will influence the likelihood of invasion.
2. Nest destruction within native salmon rivers by escaped farm females is a near certainty, although though the extent of the impact is uncertain.
3. Successful spawning and early rearing will be significant impediments to invasion and establishment. However, once overcome, as has occurred in the Pacific Northwest, establishment may only be a few years away.
4. Successful invasion and establishment will depend on the state of the native populations, and is more likely in depleted, low-density populations.
5. Use of “all-female” lines in farming is unlikely to solve much. This is because: (a) breeding performance of farm females is significantly greater than that of farm males; (b) potential for fertilization by farm males present from earlier invasions, particularly that by mature male parr, may be considerable; and (c) farm females can still destroy the nests of native females. All-male lines would be a better solution.
6. The high level of male maturity as freshwater parr in Atlantic salmon (up to 100%) will: (a) increase the likelihood (migration to sea unnecessary) and speed of establishment (shorten generation time); and (b) increase the likelihood of interspecific hybridization (parr appear to be the principal male route of interspecific hybridization) and thus egg loss within Pacific salmon populations.
7. Juvenile Atlantic salmon are likely to compete for resources with Pacific salmonids. The outcome of this competition remains uncertain, though some scenarios suggest negative consequences, particularly in light of the directed artificial selection that farm salmon have undergone.
8. Decreased productivity of Pacific salmonid populations is a real possibility.

**Figure 10. Environmental and Domestication Effects.**

References


Will Farmed Atlantic Salmon Invade the Ecological Niches of Wild Pacific Salmon?

Mart R. Gross, Professor of Conservation Biology, Zoology Dept., University of Toronto
Ramsey Wright Zoological Labs, 25 Harbord Street, Toronto, ON, M5S 3G5, mgross@zoo.utoronto.ca

Introduction
Among the important issues in conserving wild Pacific salmon in British Columbia are the potential impacts of salmon culture, including escaped farmed Atlantic salmon. I have recently reviewed these issues in detail (Gross 1998). The problems are a variety of types, including science, socio-economic and political, and their interactions. Here I briefly comment on a political dimension that is impairing salmon science, and then I address our knowledge on the likelihood of invasion of Atlantic salmon and their impact on Pacific salmon.

The Political Dimension in Salmon Science
There is a strong political influence on the application of scientific knowledge to salmon conservation and even to the kinds of information that are collected. In 1982, my lab at Simon Fraser University initiated studies of fish culture as an enhancement tool by contrasting the breeding success of wild and hatchery-produced Pacific salmon (e.g. van den Bergh and Gross 1989, Fleming and Gross 1989, Fleming and Gross 1992). We found that hatchery-produced coho are radically altered in morphology and breeding performance by hatcheries. This information, available in the scientific literature, met a largely unreceptive audience within government science (e.g., 1989 Canadian Fisheries Meetings) and had virtually no influence on fisheries policy for roughly 10 years (e.g., Fisheries and Oceans Canada Wild Salmon Policy Discussion Paper, March 2000, http://www-comm.pac.dfo-mpo.gc.ca/wsp-sep-consult/). In the mid-to late 1980s, Norwegian fisheries scientists, especially Bror Jonsson at the Norwegian Foundation for Nature Research and Cultural Heritage (NINA), invited a comparable research program on escaped farmed Atlantic salmon entering wild rivers. In 1990 we presented results at the first International Meeting on Farmed Salmon (Loen, Norway) to yet another unreceptive audience. It took about 10 years before the legitimacy of escaped farmed fish impact was widely accepted and began entering policy (e.g., North Atlantic Salmon Conservation Organization).

In the mid-1990s, the Clayoquot Biosphere Project (CBP) hosted a meeting with First Nations groups that felt their salmon concerns were not being addressed by Fisheries and Oceans Canada or the Provincial ministries. Having moved my lab to the University of Toronto in 1987, I was surprised to learn that Atlantic salmon, some from Norway where we had already helped to establish their impact concerns, were now farmed throughout Clayoquot Sound. I therefore brought together interested government scientists from Fisheries and Oceans Canada, BC Ministry of Agriculture, Fisheries and Food and BC Ministry of Environment, Lands and Parks to work with my Toronto laboratory and the CBP to investigate the principal question of this paper: “Will Atlantic Salmon Invade the Pacific?” In 1996, we completed a Canadian national NSERC Strategic grant application for a comprehensive scientific study of the potential for invasion and impact on native salmon species. However, BC, Fisheries and Oceans Canada and Provincial ministries withdrew key scientists, provided biased reviews, and blocked the research. Small and poorly funded local and in-house initiatives were launched, giving a semblance of scientific research being conducted. This intervention controlled the kinds of questions that could be addressed, and therefore today we lack even the most basic information for understanding the potential for Atlantic salmon invasion. Another case of the manipulation of scientific research by individuals within government institutions has been addressed in cod (e.g., Hutchings et al. 1998).

Invasion Theory
The theory of invasion biology (e.g., Moyle and Light 1996, Ricciardi and Rasmussen 1998) provides some perspective on what we might expect for Atlantic salmon. There are five general stages to a biological invasion:

(1) arrival
Species arriving due to human activity are classified as ‘exotics’ and their rate of arrival is roughly correlated to their probability of establishment.
(2) resistance
Three forms of resistance can block successful invasion—abiotic (e.g., incompatible temperature, chemistry, flow, physical structure); biotic (competition, food unavailability, predation, disease, parasites); and demographic (fecundity, social structure, age at maturity, etc.). Some 90-95% of newly arriving species fail to establish themselves due to one or more ‘resistances’.

(3) establishment
Conservation biologists use as a rule of thumb a 5-10% establishment rate; recent data based on more than fifteen thousand records of introduced fishes in the US suggest that roughly 3% are successful at establishment (Williams and Meffe 2000). Drainages with low species richness tend to have higher invisibility possibly due to reduced biotic resistance (e.g., Gido and Brown 1999).

(4) integration and spread
As a rule of thumb, 2-3% of established introduced species are able to expand their ranges (di Castri 1989). The majority of fish invaders do not manage to expand their ranges, primarily due to abiotic resistance (e.g., Baltz and Moyle 1993). Integration may be accompanied by local extinctions/extirpations, niche and behaviour shifts, changes in abundance, or functional-ecological shifts in native species.

(5) altered community
Integration always alters the receiving community, but the impact ranges from minor to severe. In fish, about 50% of integrated introductions cause measurable ‘harm’, including reduced abundance of natives (OTA 1993). However, recent data suggest that an invasion is five times more likely to increase fish species diversity than lower it.

Will Atlantic Salmon Invade the Pacific?
The first stage of invasion—arrival—occurs frequently. The introduction of Atlantics for farming in British Columbia began in about 1985. The first reported escape of Atlantic salmon was in 1991, and by 1996 all life stages had been reported to escape (alevins, parr and adults). From 1991 through 1998, the reported average escapement rate was 30,689 individuals per year (Noakes et al. 2000). The Pacific is therefore ‘seeded’ on an annual basis with a variety of genetic and developmental combinations of Atlantic salmon, increasing the probability of arrival into the right biotic and abiotic situation for establishment. The second stage—resistance—appears to be weak. Abiotic resistance is weakened by naturalization to local conditions in aquaculture, and by the new niches created through human alteration of rivers. Biotic resistance is weakened by the innate ability of Atlantics to survive in the Pacific and the open niches that exist there due to the decreased numbers of wild salmon. Demographic resistance is weakened due to the high reproductive capacity of Atlantic salmon, and the magnitude, frequency and geographic extent of seeding. The third stage—establishment—is highly likely. From 1990 through 1996 there has been an increasing trend of adult Atlantic salmon entering freshwater rivers (A. Thomson, Atlantic Salmon Watch—ASW data summarized in Gross 1998). Recruits from spawning have recently been identified, by the recovery of surviving juveniles, in definitely two (Amor de Cosmos and Tsitika) and possibly three (Adam) BC rivers (February 2000 data; A. Thomson FOC ASW). Adults have an extensive range in the Pacific, including at least one discovery in the Bering Strait. Therefore, while theory suggests only a 3-10% probability of establishment of invaders, repeat arrivals can bring this to 100% (Gross 1998). The fourth stage—integration and spread—is in theory a rare event of 2-3%. By contrast, my working knowledge with Atlantic salmon in Norway, and wild Pacific salmon in western North America, suggests that Atlantic salmon are capable of integrating into the Pacific fish community. This discrepancy between theory and impression can be resolved by modeling (see below). The final stage—altered community—will therefore result but the important question that is rarely addressed and must be evaluated is the resulting costs and benefits of this alteration. Some potential costs include indirect genetic impacts (e.g., parr removal of eggs and decreased population viability; novel selection), competition for food and space, habitat alteration (e.g., movement of gravel beds), and disease spread (through amplification and resistance as carriers). These costs may result in (a) a decrease in the numbers of wild Pacific salmon, and (b) extirpation of native species within drainages. To appreciate these costs, they must be evaluated against the potential benefits of integration and spread. Such benefits can include (a) increased species richness.
and (b) decreased industry costs. I address this cost-benefit analysis below.

**Modeling Costs and Benefits of Atlantic Salmon in the Pacific**

There is a need for a balanced cost/benefit approach to the issue of Atlantic salmon in the Pacific. In such analyses, it would be agreed that if the benefits outweigh the costs, then escapement might be seen in a more neutral light if not as a potentially positive benefit. Conversely, if benefits are less than the costs, then Atlantic salmon escapement is a tangible concern. Modeling the costs and benefits of invasion will help to shed light on the parameters that lack information and require further study, and bring a more balanced perspective to the table. I describe a preliminary form of the analysis below.

The first step is to determine whether Atlantic salmon will successfully invade—this includes their establishment and integration and spread. This is calculated by:

\[
\text{Probability of Invasion (pl) per arrival} = p \\
(\text{establishment}) x p (\text{integration and spread}) = 3\% \times 2\% \\
\text{[these are minimum estimates]} = 0.06\% .
\]

Let the ‘arrival’ be estimated from the number of reported escapees divided by ‘2’ to allow for males and females. Therefore, the arrival rate may be 15,345 per year (30,689/2). This of course assumes that each escapement is independent, and it assumes that any disfunctionality of the fish is taken into account by the values used to estimate establishment and integration and spread.

The annual probability that there is at least one successful invasion is calculated from: \(1 - (1 - p)^n\) where \(n\) is the arrival rate. This is 1 - 0.001, which is effectively 1. Therefore, the probability of successful invasion is 100%.

The second step, given that we know there will be invasion, is to assess the costs and benefits of this invasion. The net benefit (NB) is modeled by:

\[
\text{NB} = \sum_{i} p_i (B_i - C_i)
\]

Where \(i\) = individual issues resulting from invasion; issues can be positive (benefit \(B_i\)) or negative (cost \(C_i\)), and \(p_i\) = probability of individual issue occurring.

Examples of four major issues to consider are: (1) reduced abundance of natives; (2) extirpation of natives; (3) increased biodiversity; and (4) decreased industry costs. Each of these events, \(i\), have their own benefits and costs and probability of occurrence. From comparative data the probabilities are:

\[
p_1 = 50\%; \ p_2 = 20\%; \ p_3 = 80\%; \text{ and } p_4 = 100\% .
\]

Next, the benefits and costs of each issue need research to establish their magnitudes in a common utility function. Since all four probabilities are high, they are all worth researching. Unfortunately, the research on issues 1 through 3 was not allowed to proceed in the mid-1990s and therefore it is impossible to make more accurate and precise assessment of Atlantic salmon in the Pacific today.

**Philosophical Comment**

Some people would consider that the establishment of a new 6th Pacific salmonid is a ‘benefit’. The comparative data suggest that there is an 80% probability that the invasion of Atlantic salmon will increase species richness (although decreasing existing species abundances). This merits consideration. It was not that long ago in thousands of years that fewer than 5 Pacific salmon species existed in what we call British Columbia today; if our descendants colonized this British Columbia many thousands of years in the future, it would be unlikely that 5 Pacific salmon species would exist. There is no magic in the number 5 if one believes in ecology and evolution. Although Atlantic salmon are classified as ‘exotics’, it may be more philosophically appropriate to consider humans as not distinct from, but part of nature, and thus the arrival of new species by human means is but part of the fabric of ‘natural events’. Why is it that the colonization into British Columbia by advancing Pacific salmonids is considered natural and good, while the colonization by species introduced by humans is considered ‘exotic’ and bad? This distinction may be valid, but the criteria for such a distinction remains to be determined. The cost-benefit analysis that I have described helps reveal and quantify the relevant parameters.

Finally, environmentalists should concede that a possible benefit of Atlantic salmon in the Pacific is the reduced costs to industry of not having to put complete
safeguards into place, which in turn may generate increased economic wealth that provides for a standard of living in humans that can in turn be directed toward reduced human impact. Ensuring zero risk of invasion will require infinite expenditures and bankrupt the current farming industry. By contrast, the model helps to see that, with quantification, the environmental costs may be such that there is no net benefit to the industry, and it should be abandoned.

Summary
To proceed with a legitimate and balanced perspective on the issues concerning Atlantic salmon invasion into the Pacific, we need to work toward a cost/benefit analysis of the kind briefly introduced here. To achieve this will require extensive research on biological, social and economic questions. We also need specific research on utility functions so that we can weigh reduced abundances of existing Pacific salmon species against an increase in species richness. Until we have completed this research, and are in a position to formally address these questions, the only operating principle that makes good sense is the precautionary principle.

Acknowledgements
Andy Thomson of the Department of Fisheries and Oceans and Atlantic Salmon Watch helped with data; Rick Routledge helped with modeling; Bryan Neff helped with the manuscript and modeling; Patricia Gallaugher together with Laurie Wood, helped organize everything. Thank you.

References

Do We Know What We Don’t Know? Atlantic Salmon in British Columbia: A Review
John P. Volpe, Dept. of Biology & Centre for Environmental Health, University of Victoria jvolpe@uvic.ca

Introduction
The presence of free ranging Atlantic salmon (Salmo salar) in coastal British Columbia has generated considerable debate. Do the promised economic benefits of Atlantic salmon culture outweigh the various associated environmental risks? The recent discovery of multiple year classes of putatively wild reared juvenile Atlantic salmon on Vancouver Island has intensified this debate (Volpe et al. 2000, Volpe 2000).

Here I review historical introductions of Atlantic salmon to B.C. and compare these events to the present situation. I then discuss the value of information brought to bear on the issue of Atlantic salmon colonization of B.C. and demonstrate why it is unwise to rely solely on these data in formulating policy for B.C. I conclude by presenting preliminary results of an ongoing research program focused on quantifying the potential ecological effects of Atlantic salmon on native Pacific salmonids, particularly steelhead trout (Oncorhynchus mykiss).
Historical Introductions
From 1905 to 1934, significant effort was expended in attempting to introduce Atlantic salmon to coastal B.C. for the purpose of angling. Estimates of total number stocked (eyed eggs and alevins) are not consistent, reported as 5.5 million (Castledine 1991), 6 million (Needham 1995), 7,588,806 (Burt et al. 1992 in Alverson and Ruggenerone 1997) and 13.2 million (McKinnell et al. 1997). Primary release sites were the Cowichan River on Vancouver Island and the Fraser River system in the south mainland. Some other systems received plantings but not to the same extent. Eggs and alevins were used almost exclusively for stocking. Very little information exists regarding survivorship to smolt or any other demographic information relating to the success of the stocking efforts. Only a handful of returning adults were reported and there was no indication of natural reproduction (Carl and Guiguet 1958).

The failure of these introductions has been presented as evidence that current aquaculture escaped Atlantic salmon will also fail to colonize (Needham 1995). Such arguments ignore the obvious fact that the coastal environment has changed dramatically in the intervening years. Indeed, the very factors that resisted Atlantic salmon colonization years ago have now been altered to favour colonization. Consider the following points characterizing the historical introductions:

1. Stocking was limited to use of eggs and alevins only; natural mortality was likely very high.
2. Cross-country transport of eggs and alevins and rudimentary facilities in B.C. likely affected quality of individuals introduced. Further, the stocking programs were haphazard and stochastic—these introductions pre-dated modern protocols for maximizing hatchery efficacy. Eggs and alevins were planted when available; often years or decades separated stocking events. Where and how each batch of Atlantic salmon were introduced was left up to personnel at each site. Again, in the absence of standardized protocol, variance in treatment affecting survivorship from one stocking event to the next is likely.
3. Stocking efforts were spread over 29 years. Even using the high estimate of 13 million, this represents ~ 448,276 eggs and fry released per year. To put this in perspective, this represents only 0.08% the annual input of the current federal Salmon Enhancement Program (SEP). Currently, on any given day, there are more Atlantic salmon in B.C. marine net cages than were stocked between 1905-1934.

4. Atlantic salmon were introduced into habitats already at or near saturation with native competitors. The amount of available resources and the associated magnitude of competition for those resources can play a significant role in the success or failure of an introduction. Recruitment data from 1905-1934 are not available but every indication suggests that juvenile rearing habitat was at, or near, carrying capacity, thus ensuring strong competition for introduced individuals.

Today, these conditions have changed significantly—all towards increasing the likelihood of Atlantic salmon colonization.

1. The majority of aquaculture escapes today are adults. A total of 707,635 Atlantic salmon were reported escaped from B.C. and Washington State marine facilities from 1991 to 1998 (Thomson 1999). An unknown number of escapes go unaccounted or unreported making confident estimates of annual escapees very difficult. One estimate of unaccounted losses suggests 10-30% of the cage population may be lost in this way (Moring 1989). Error estimates cannot be assigned to these numbers; they are thus very rough estimates at best. Suffice to say that a significant number escape to the wild each year and the situation is unlikely to change so long as current net-pen technology is used.
2. Escapees today are healthy, high condition factor adults, reared locally, and immunised against common pathogens.
3. Net-pen operations are clustered on the northeast and midwest coasts of Vancouver Island. Thus, consistent, spatially invariable points of release are established. This has the effect of concentrating the “introduction effort”. Not surprisingly, we have found the incidence of occurrence of adult Atlantic salmon in rivers to be inversely proportional to their distance from net-pen clusters (Volpe unpublished data).
4. Abundance of native salmonid stocks have declined sharply over the past 70 years resulting in a surplus of underused habitat available to a potential transplant such as Atlantic salmon. Vancouver Island stocks of steelhead, the native niche equivalent to Atlantic salmon, are at an all time low and recruitment levels in most systems are at all time lows. For example, the 1998 smolt production of Keogh River steelhead, one of the few populations with reliable long-term data, was only 16% of the long-term average (since 1977) (Ward and McCubbing 1998). Any biological system that experiences an 84% decline of abundance of a high-level consumer will also have a diminished capacity to retard the invasion of a niche equivalent species—in this case, Atlantic salmon.

Current State of Knowledge and Ongoing Research
In response to public concerns regarding potential environmental effects of the B.C. salmon aquaculture industry, the B.C. Office of Environmental Assessment (EOA) launched a review in July 1995. Expansion of the industry was halted pending the findings of the review. In August 1997 the final report of the Salmon Aquaculture Review (SAR) was released (full text available at http://www.eao.gov.bc.ca/project/AQUACULT/SALMON/). When concluded, the SAR was the largest review of its kind ever conducted in B.C. The report is telling, as much as for what it does not say, as for what is does. Over 100 pages are devoted to potential ecological and genetic impacts (of not only Atlantic salmon which now make up ~ 80% of production but chinook and coho which make up the balance). In those pages the authors cite 128 reports encompassing all pertinent scientific knowledge available at the time. Of these, 38 deal specifically with Atlantic salmon, but only seven deal specifically with Atlantic salmon in B.C (five are non-refereed annual ASWP reports (see below), one on predation inside cages, and a 1997 review paper). The majority of Atlantic salmon materials (82%) deal with issues in and around the north Atlantic. Following the release of the EAO’s report, the moratorium was lifted. “A cautious yellow light” for expansion was granted, in spite of a virtual absence of relevant (i.e. Pacific basin) data. It is not possible to apply these foreign data to the current situation in B.C., without an expectation of error so great that predictions are rendered meaningless.

To predict the potential impact of Atlantic salmon in B.C. will require local research initiatives in order to assess local sources of variation. Impact (I) has been defined as I=R x A x E where R is the range (m2), A is the mean abundance, and E is the effect per capita or per biomass unit of Atlantic salmon (Parker et al. 1999). This definition may prove to be overly simplistic or reductionist (as the authors point out), but even so, at present, we lack sufficient data to evaluate even one of the three parameters!

Range is likely the parameter we have the most data on. Since 1992, the B.C. provincial government and federal Department of Fisheries and Oceans have sponsored the Atlantic Salmon Watch Program (ASW). The ASW is a monitoring program where captures (and observations) of Atlantic salmon are reported via a toll-free telephone number (1-800-811-6010 at the Pacific Biological Station, Nanaimo). Often, carcasses are sent to the Pacific Biological Station for species confirmation and further analysis. These data are compiled and reported annually, including summary catch data from Alaska and Washington State (Thomson and Candy 1998; most recent but available back to 1993). The most northerly capture of an Atlantic salmon was from the Bering Sea (55°N, 159°W) (Brodeur and Busby 1998). The most northerly possible release sight was approximately the north end of Vancouver Island (Note: aquaculture is not permitted in Alaska).

Reports to the ASW Program are predominated by marine captures by commercial fishers. Various problems exist with the applicability of the ASW data. Foremost, the data are opportunistic, collected in the absence of experimental design or controls. For instance, since it is not known how many Atlantic salmon are actually captured annually, predictions of what proportion of captures are reported are not quantifiable. Many fishers do not report Atlantic salmon and instead freeze the carcasses to be used during the halibut season (pers. obs., J. Volpe). Further, it is not possible to identify or quantify possible biases in the data (eg. is one gear type more likely to capture/report than another?). The ASW provides qualitative baseline data on Atlantic salmon range for relatively little investment; however, gaps in the data must be remedied before these data can be confidently applied in a quantitative manner.

In 1994, a freshwater survey program for Atlantic salmon was initiated by the Provincial Ministry of Environment (Lough and Law 1997, Volpe 1998, 1999, 2000) and funded predominantly through the B.C. Habitat
Conservation Trust Fund. The primary objective of the freshwater survey program was to identify evidence of natural reproduction of Atlantic salmon in coastal streams. A secondary objective was to collect distribution and abundance data on ascending adult Atlantic salmon. The primary method of survey was snorkeling pre-selected reaches (1–9 km) of rivers with histories of Atlantic salmon activity or high likelihood to be so. The freshwater survey program suffers from similar limitations as the ASW, most notably, data are collected in the absence of controls. There are no controls allowing calibration or error estimates to be generated. For instance, during a survey in a river where juvenile Atlantic salmon are present at some known density: What are the chances of not seeing one? What are the chances of missing half? How much more likely is a surveyor to see a parr than a fry? Juvenile Atlantic salmon exhibit considerably different behaviour patterns and micro-habitat preferences compared with native salmonid species (Volpe, unpublished data). This makes them less likely to be observed by survey crews who are used to dealing with native species exclusively. Less than 1% of potential Atlantic salmon rearing habitat has been surveyed and, despite the obvious limitations of our techniques, three Vancouver Island systems have been identified as supporting putatively wild-reared juvenile Atlantic salmon (Volpe et al. 2000, Volpe 1999, 2000). Without appropriate controls, however, one cannot make the obvious extrapolation to the number of systems likely to be supporting Atlantic salmon if 100% survey coverage was applied.

The limitations of the federal ASW and provincial freshwater survey programs become more evident when attention turns to quantifying the abundance (A) term. In the absence of appropriate designs and controls it is not possible to use common management tools such as catch per unit effort (CPUE), let alone, define confident abundance estimates.

Per capita effect (E) is the most difficult parameter to characterize and, not surprisingly, the parameter with the least data associated with it. Effects can be partitioned into five classes—each of which must be considered before conclusions can be drawn. Effects could be on individuals, genetic structure, population dynamics, community, and ecosystem processes (Parker et al. 1999). What little data are available deal almost exclusively with effects on individuals during the freshwater juvenile phase.

Niche preferences of the eight native coastal salmonid species suggest that juvenile Atlantic salmon will share the greatest niche overlap with juvenile steelhead trout. Indeed, steelhead (including the non-anadromous form, rainbow trout) until recently were named *Salmo gairdneri*, reflecting the species similarity to *S. salar*. Prior to this research program, juvenile performance of Atlantic salmon and steelhead had been directly compared on only three occasions (Gibson 1981, Hearn and Kynard 1986, Jones and Stanfield 1993). Results of these examinations all showed steelhead to be the more aggressive species, and from this, competitive superiority was inferred. These conclusions likely played a significant role in the conclusion by the SAR that Atlantic salmon posed a minimal threat of invasion in B.C. When the experimental designs of these three papers are examined, however, a shared flaw is revealed. In all three cases, intraspecific was not separated from interspecific agonism. Failing to do so convolutes the results as one cannot discern if poor performance is due to effects of conspecifics or interspecific individuals (Underwood 1986). Reevaluating the relative performances of Atlantic salmon and steelhead in sympathy under a more rigorous design shows the relationship between the two species is more complex than previously imagined. Steelhead are more aggressive than Atlantic salmon, as previously concluded, but this does not automatically lead to a competitive advantage. Steelhead show a pronounced bias towards intraspecific agonism. The per capita effect of steelhead on themselves is much greater than the per capita effect of Atlantic salmon (Volpe, unpublished data).

A prior residency effect was also observed, adding complexity to the results above. Groups of fish with a three-day residency period dominated subsequently introduced challengers. It made no difference which species were the residents, or if the challengers were intra- or interspecific; residents always dominated—including Atlantic salmon residents dominating steelhead challengers (Volpe, unpublished data). During the 1905–1934 introductions, little or no opportunity to
establish a prior resident advantage would have been possible for introduced Atlantic salmon due to the high abundance of native salmonids. Today in most Vancouver Island rivers, the majority of steelhead/Atlantic salmon habitat remains unerased. This results in a considerable increase in opportunity for juvenile Atlantic salmon to establish a residency advantage, which in turn should positively affect survival.

Genetic effects are not as well defined. A small pilot project found Atlantic salmon x Oncorhynchus spp. (six species) hybridization attempts were unlikely to produce appreciable numbers of viable offspring (B. Devlin pers. com., in SAR 1997). Logistical problems with the experimental design, however, does not completely exclude the possibility of production of viable progeny via hybridization. This was a very small pilot study. The narrow breadth of genetic diversity represented by the few individuals of each species used in the crosses was unrepresentative of each species as a whole. What effect this may have had on the results is unknown. More importantly, because the various species sexually mature at different times, considerable use of cryopreservation of sperm was used. Again, the degree to which results of crosses using cryopreserved gametes were affected was not defined. A rigorous examination of this question is long overdue. Further, when hybridization is attempted, regardless if viable progeny are produced or not, the loss of gametes to the native population reduces each population’s $N_e$, and thus is considered a genetic effect.

Potential population effects such as changes in abundance, distribution, age or size structure of native species or Atlantic salmon, have yet to be considered, let alone, investigated. Similarly, community effects (species richness, trophic structure) and ecosystem effects (shifts in nutrient availability, primary productivity) also await consideration, both in the juvenile freshwater and adult marine stages of life.

Conclusion
The title of this paper poses a question. One might conclude, based on actions to date, that there is little we do not know and that these gaps in knowledge are small enough so as not to be a concern. I would take issue with this position and submit that from an ecological/genetic point of view, we know very little indeed—and we don’t even understand that.

Acknowledgments
I would like to thank the organizers of the Speaking for the Salmon Workshop for inviting me to participate. This work was supported by a grant to JPV from the B.C. Habitat Conservation Trust Fund.

Note:
1 In 1998 B.C. salmon farmers produced 30,165 mt (dressed) of Atlantic salmon. This is ~ 6.7 million individuals if we assume an average weight of 4.5 kg per individual. With an average harvest rate of 50% annually, the average net cage population of Atlantic salmon in B.C. coastal waters at any one time is ~ 6.7 million • 2 = ~13.4 million.

References


Gibson, R.J. 1981. Behavioural interactions between coho salmon (Oncorhynchus kisutch), Atlantic salmon (Salmo salar), brook trout (Salvelinus fontinalis) and steelhead trout (Salmo gairdneri) at the juvenile fluvialite stages. Canadian Technical Report on Fisheries and Aquatic Sciences 1029.


A discussion framework was presented to guide the discussion of interactions by life stage in either the marine or freshwater environments, given the assumption that farmed salmon have escaped and are known to be reproducing in some coastal streams, and that escapes are likely to continue at present levels in the short term. The group was asked to concentrate on concerns, known applicable research data, and research requirements. Although initially accepted by the group, this discussion format proved to be too detailed for the three hours allotted and, as well, there was considerable overlap of the suggested categories for discussion.

The group chose to discuss the potential for marine interactions between farmed Atlantic salmon and wild Pacific salmon and the potential for freshwater interactions between those species. A very short time was left to look at potential interactions between escaped farmed and “wild” Pacific salmon. The discussions did not consider the potential genetic or disease transfer considerations as these were being discussed in the other groups.

1. Marine Interactions

The discussion of the potential for marine interactions focused on the question of impacts of caged fish and the cage sites themselves on wild populations. There was general agreement that the accidental release during sea cage introduction of Atlantic salmon smolts was not a significant ecological issue given the small numbers of escaped fish and the small likelihood of their survival. There was also some agreement that fish escaping from the pens (regardless of life stage) were “not likely” to have significant ecological impact on wild salmonids in the marine environment.

The issue of possible predation by caged fish on wild salmon populations in and around the net pens was discussed. Most of the participants felt that the research to date demonstrated that there was no evidence to indicate that the fish in cages were feeding on wild salmon juveniles. It was suggested that the caged fish could be competing with the wild fish for “natural” feed, but most felt that this either did not occur, or was insignificant, given the relatively small foot-print of existing farms in contrast to the huge foraging area available.

The potential for marine ecological interactions (if any) was agreed to be either in the _attraction or displacement_ of wild salmonids to or away from the cage sites. The group acknowledged that there could be attraction of wild fish to the cage sites (possibly for feeding), but there was no empirical evidence for any conclusions. The issue of lighted
farm sites and the potential alteration of species distribution outside the cages in response to attraction to the lights was discussed, but no studies have been conducted on this question.

Some in the discussion group felt that there could be physical displacement of Pacific salmon by the cage systems in areas where wild fish would otherwise congregate during migration (e.g. tidal “back-eddies” where adult migrating wild fish tend to aggregate). There was no consensus on the likelihood or scale of this impact and no definitive research was cited. (Note: this issue has been discussed in the past and has resulted in a recommendation that farms not be located in known schooling areas/migration routes for wild salmon.)

2. Fresh Water Interactions

Most of the discussion of Atlantic/Pacific salmon interactions focused on possible interactions in fresh water. There was general agreement that there was little likelihood of disruption of in-river migration patterns of Pacific salmon, given the assumed later timing of feral Atlantic river entry (although we do know that coho have been observed spawning in Broughton Archipelago streams as late as the end of February).

There was discussion of the likelihood of inter-breeding of Atlantics with Pacifics and although the research to date indicates that any resulting progeny would be unviable, it was acknowledged that more work should be done in this area. It was also pointed out that timing differences (Atlantics are assumed to have more of a winter steelhead spawn timing) would likely minimize or eliminate any breeding period interactions with wild Pacific salmon.

The potential for nest superimposition was discussed and the possibility of Atlantic spawners disturbing Pacific reds was considered possible, although the potential occurrence was considered low given the relatively small numbers of Atlantics presently observed in rivers. It was acknowledged that the level of risk is dependent on the successful colonization of Atlantics and a subsequent increase in their relative numbers.

The group’s greatest acceptance of possible interactions between Atlantic and Pacific salmon in streams related to juvenile interactions. The issues of spatial and food competition were discussed and it was generally agreed (although not by the whole group) that more research is needed to document those interactions. Again, the level of impact is extremely density dependent; if there is successful Atlantic colonization and a continued reduction in the numbers of Pacific salmon in a given stream, the spatial and available forage balance between the two species could be significantly altered. The area of juvenile interactions was the most commonly agreed upon aspect of the “research needs” question, and that research should be ecosystem focused rather than exclusively laboratory.

Table 3 summarizes the concerns expressed and the state of knowledge and potential level of impact of the concerns for interaction between feral Atlantic populations and wild Pacific stocks.

<table>
<thead>
<tr>
<th>Concern</th>
<th>Has it been examined?</th>
<th>Has it been demonstrated /documented?</th>
<th>What is the potential for impact on native stocks?</th>
<th>Is the relationship density dependent?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competition in the ocean</td>
<td>No</td>
<td>No</td>
<td>Unknown</td>
<td>Yes</td>
</tr>
<tr>
<td>Disruption of migration by interference</td>
<td>No</td>
<td>No</td>
<td>Relatively low risk</td>
<td>Yes</td>
</tr>
<tr>
<td>Disruption of breeding behaviour</td>
<td>No</td>
<td>No</td>
<td>Risk is anticipated but magnitude is unknown</td>
<td>Yes</td>
</tr>
<tr>
<td>Nest superimposition</td>
<td>No</td>
<td>No</td>
<td>Risk is anticipated but magnitude is unknown</td>
<td>Yes</td>
</tr>
<tr>
<td>Competition between juveniles for food and space in freshwater</td>
<td>Yes</td>
<td>Yes</td>
<td>Potentially high needs to be evaluated</td>
<td>Yes</td>
</tr>
<tr>
<td>Habitat displacement in freshwater amongst juveniles</td>
<td>Yes- in lab</td>
<td>Yes but appropriate controls lacking</td>
<td>Risk is anticipated but magnitude is unknown</td>
<td>Yes</td>
</tr>
<tr>
<td>Are wild salmon attracted to or displaced from net-cage sites</td>
<td>No</td>
<td>No</td>
<td>Possible interruption of seaward or adult return migration patterns</td>
<td>Yes</td>
</tr>
</tbody>
</table>
3. Interactions of Farmed and Wild Pacific Salmon

Although brief, the discussion of potential interactions between escaped farmed Pacific salmon and wild fish was consistently clouded by comparisons being drawn between current enhancement (hatchery) practices and the small numbers of escaped farmed Pacific salmon. Some in the group felt that the very small numbers of Pacific salmon currently being farmed would have little to no ecological significance compared with the millions of “wild” enhancement fish being released (sometimes far from their natal streams).

The group agreed to use the wild/feral Atlantic salmon interaction table provided as a comparative model for wild/feral Pacific interactions with a cautionary note that the density relationships are significantly different given the relatively minimal numbers of escaped farmed Pacific salmon reported. There was acceptance that there could be genetic and disease interactions although it was noted that, in general, cultured fish (whether of farm or SEP origin) have poor breeding success when compared with their wild “cousins”.

Table 4, originally generated for interactions between feral Atlantics and wild Atlantics, also applies to Pacific salmon. However, the degree of risk is reduced overall as a result of the different density relationships. In addition, the impact of SEP enhanced fish may/will tend to mask the potential effects of escaped farmed Pacific salmon.

4. Recommendations

- Escapes should be minimized through improved farm containment systems; the above potential interactions should decrease rather than increase as escapes of farm fish are reduced.
- There should be increased and active monitoring/research of a larger number of streams to determine the extent of Atlantic salmon occupation, interaction, and colonization.
- The monitoring should be linked to and help direct research programs that are ecosystem based (informed by existing and yet to be conducted lab based work) to evaluate impacts.

5. Suspected or Unknown Interactions of Concern

Tables 3 and 4 list a variety of species interaction concerns that have “No” entries to the questions: “Has it been examined?” and, “Has it been demonstrated/documented?” The fact that the concerns have been raised and there is no supporting research to substantiate or deny those concerns lends to the conclusion that more research needs to be done in a number of areas. Obviously, the research would be

<table>
<thead>
<tr>
<th>Concern</th>
<th>Has it been examined?</th>
<th>Has it been demonstrated /documented?</th>
<th>What is the potential for impact on native stocks?</th>
<th>Is the relationship density dependent?*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competition in the ocean</td>
<td>No</td>
<td>No</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Disruption of migration by interference</td>
<td>No</td>
<td>No</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Disruption of breeding behaviour</td>
<td>Yes</td>
<td>No - unknown for F1 and later generations</td>
<td>Low</td>
<td>Yes (negative association)</td>
</tr>
<tr>
<td>Nest superimposition</td>
<td>Yes</td>
<td>Yes</td>
<td>Medium</td>
<td>Yes (negative association)</td>
</tr>
<tr>
<td>Competition between juveniles for food and space in freshwater</td>
<td>Yes - in lab</td>
<td>Yes</td>
<td>High</td>
<td>Yes (negative association)</td>
</tr>
<tr>
<td>Habitat displacement in freshwater amongst juveniles</td>
<td>Yes - indirectly</td>
<td>Yes but appropriate controls lacking</td>
<td>High</td>
<td>Yes (negative association)</td>
</tr>
<tr>
<td>Hybridization</td>
<td>Yes (at F1)</td>
<td>Yes</td>
<td>High</td>
<td>Yes (negative association)</td>
</tr>
</tbody>
</table>

1 Relative numbers of farmed Pacific salmon in wild inconsequential compared with hatchery produced “wild” enhanced fish and natural wild stocks. Note also that the prevalence of “enhanced” Pacific salmon could mask the potential effects of escaped farmed fish.
prioritized according to the indicated likelihood of “Potential for impact on native stocks”.

The concerns\(^1\) that have not been addressed by appropriate research can be listed (in order of potential significance) as:

**Marine Ecological Interactions**
- Physical displacement impacts of net cage systems on migrating adult and juvenile wild salmonids (i.e. siting).
- Attraction of wild salmonids (esp. juveniles) to net cage sites (lighted and not lighted) and whether normal migratory patterns are affected.
- Competition and/or depletion of natural feed organisms in the vicinity of net cages.

**Fresh Water Ecological Interactions**
- Juvenile interactions in freshwater rearing habitats (spatial and forage competition).
- Superimposition of later spawning Atlantic salmon on wild Pacific salmon and trout redds.
- Breeding disturbance (e.g. precocious male Atlantics interfering with wild salmonid breeding behaviour and possible egg consumption).

\(^1\)Note: These concerns are presented as potential ecological impacts only and do not consider genetic or disease impacts.

6. Risk Assessment Discussion
The question of risk of impacts of farmed salmon on wild salmon and vice versa was discussed at some length, although there was no consensus reached on a definition of risk. For that reason the initial question “What is the risk to native stocks?” was changed to read “What is the potential for impact to native stocks?”

It was evident in this discussion group that a great deal of time could be spent looking at methods of assessing risk, discussing relative risk (eg. SEP fish versus farmed fish), and finally, defining acceptable risk. It was obviously beyond the scope of the workshop’s primary purpose to attempt resolution of this rather philosophical issue.

7. Priorities For Research
As part of the open discussion amongst the entire Think Tank during the afternoon, members of the ecological interactions discussion group were asked to identify their highest priority research issues or issues of general concern. The resulting suggestions, in the order in which they were offered, follows:
- Will wild spawned Atlantic salmon survive through an entire lifecycle?
- Given that Atlantic salmon smolts have been documented in B.C. streams, what impact are they having, if any, on the spawning success of wild Pacific salmon?
- Research that is undertaken to evaluate the colonization potential and ecological interactions between feral Atlantic salmon and wild Pacific salmon should not be conducted solely using cultured Atlantic salmon stock, because of the rapid evolution that is likely to occur within a feral wild reproducing population of Atlantic salmon. Instead, research to evaluate ecological interactions should focus on the impacts of wild spawned Atlantic salmon.
- It was generally agreed that while stream monitoring for the presence/absence of feral and wild spawned Atlantic salmon is important and should be expanded, it must be integrated with and help inform appropriate ecosystem-based research.
- A large scale ecosystem-based research program should be undertaken to rigorously evaluate the ability of feral Atlantic salmon to colonize British Columbia waters and their impact on wild Pacific salmon. Ideally, such an experiment would encompass as many as twenty streams each with a diverse community of native Pacific salmon and trout species. Ten of the streams would be randomly selected as experimental streams and be seeded with Atlantic salmon either once or on an ongoing basis while the remaining ten streams would be used as controls.

Facilitator Note
The group of people who gathered to discuss the issue of ecological interactions between farmed and wild salmon brought an extremely varied set of expertise and viewpoints to the table. It was obvious that preconception was, at times, unwilling to yield to an
analysis of what is known and what needs to be known. In spite of the difficult (and often hard to quantify) issues innate to the topic, the participants did manage to agree that there are genuine questions to be answered and that further research and monitoring of the issues is required.

**QUESTION THREE**

*What is the evidence that disease spreads from farmed to wild salmon?*

**The Impact of the Salmon Louse (Lepeophtheirus salmonis) on Wild Salmonid Stocks in Europe and Recommendations for Effective Management of Sea Lice on Salmon Farms.**

*Dr. Patrick Gargan, Senior Research Officer, Central Fisheries Board, Dublin, Ireland  
paddy.gargan@cfb.ie*

**Abstract**

The impact of the salmon louse (*Lepeophtheirus salmonis* (Kroyer)) on populations of sea trout and salmon in Ireland and other European countries is outlined and recommendations are made for the management of marine salmon farms aimed at minimising such impacts. The paper describes the growth of the salmon farming industry in western Ireland during the 1980s and the resulting infestation of sea trout post-smolts with the salmon louse. Data are presented from 52 rivers around the Irish coast sampled annually over an eight year period and lice infestation parameters from rivers close to and distant from salmon farming areas are presented. Correlations between lice levels on sea trout at river mouths and distance to the nearest salmon farm are described.

The effect of whole bay fallowing in spring and the effect of maintenance of good lice control measures on salmon farms on sea trout recovery is presented. New strategies such as Single Bay Management, communal smolt sites and the development of off-shore sites are described. The results of sampling programmes at sea targeting wild salmon smolts in other European countries is presented. In summary, the paper describes the adverse consequences of the development of marine salmon farming with particular reference to the salmon louse on wild salmonid stocks in Ireland, Scotland and Norway and sets out the measures that can be taken to reduce or prevent these adverse impacts.

**Irish Sea Trout Catches**

Little accurate long-term data are available on Irish sea trout catches outside the Connemara region. During the 1970s and 1980s there was evidence of a slow decline in sea trout stocks from the Burrisheoole, north of Connemara, attributed to afforestation and hillside erosion due to overgrazing by sheep. Rod catch data from fifteen Connemara fisheries covering the period 1974-1986 (Figure 11) shows no evidence of a serious decline. Rod catches began to show a decline over the 1986-1988 period. By 1989 this had resulted in a population collapse in many mid-western and Connemara sea trout fisheries (Anon 1992). This is exemplified by the Connemara district rod catch data, which constitutes a large proportion of the mid-Western region, where the catch fell from an average of 9,570 sea trout over the 1974-1988 period to 646 sea trout in 1989 and 240 sea trout in 1990.

Catch per unit effort (C.P.U.E.) data for two fisheries in this district, the OwenGowla and Invermore (Table 5) indicate that the catch collapse was not related to reduced effort but that an actual collapse in C.P.U.E. occurred. Data from the Burrisheoole Fishery, where full downstream and upstream trapping takes place, confirmed that sea trout finnock sea survival fell from an average of 20% over the period 1971-1987 to 1.5% in 1989 (Poole et al. 1996).

Sea trout rod catches in fisheries in other areas around the Irish coast distant from salmon aquaculture areas continued to remain stable and no population collapse or breakdown of population structure occurred.

Marine salmon farming began in Ireland in the early 1980s and had reached 10,000 tonnes by 1991 (Figure 11). In these early years the bulk of production was in the Connemara area. The development of salmon farming in Connemara in the late 1980s coincided with a dramatic reduction in sea trout rod catches in Connemara fisheries.

**Areas of Scientific Investigation in Ireland**

The Sea Trout Action Group (STAG) was formed at the end of 1988 amid growing concern about declining catches of sea trout in the West of Ireland. The Group
comprised representatives of all those interested in the welfare of sea trout, including fishery managers, scientists, anglers and state bodies. Salmon farmers were also represented. After two years of investigation, STAG concluded that the weight of available evidence indicated that the increase in the number of lice emanating from salmon farms was a major contributory factor in the sea trout collapse (Anon 1992a). After the sea trout stock collapse in 1989/1990, the Minister for the Marine setup the Sea Trout Working Group in 1991 to investigate the cause of the sea trout problem and to try and find a solution leading to a recovery of depleted stocks. After consideration of a wide range of possible causes or contributory factors, the Working Group (Anon 1992b) concentrated on eight areas of investigation:

- commercial exploitation
- predation
- food chain problems
- disease
- afforestation
- the weather
- migratory stress
- sea lice

After investigation, all but three probable causes (disease, migratory stress and sea lice) were discounted (Anon 1993). After considerable study and analysis, disease and migratory stress were discounted as possible primary causes of the sea trout stock collapse and the investigation centred on sea lice (Anon 1994).

**Sea Trout Sampling Programme**

In 1989 sea trout were observed in the lower pools of the Delphi Fishery in Connemara in Western Ireland in late May with heavy infestations of juvenile sea lice (*Lepeophtheirus salmonis*). These sea trout were post-smolts, which had returned prematurely from the sea after only two or three weeks, and had little or no sea growth on their scales. Sampling of rivers began in 1990 to determine if this phenomenon was widespread. Sea trout post-smolts and some sea trout kelts were recorded in all Connemara rivers sampled with infestations of sea lice, predominantly juvenile lice, indicating recent transmission. The scale of the sampling programme was extended in 1991 and subsequent years and included rivers at varying distances from salmon aquaculture sites. The number of rivers sampled and the numbers of sea trout captured over the 1991–1999 period is shown (Table 6).

The sea lice infestation data from this sampling programme has been analysed by the Sea Trout Working Group (Anon 1992, 1993, 1994 and 1995). The data covering the period 1993-1997 has been published elsewhere by Tully et al. 1999. This sea lice infestation data on sea trout, covering the period 1992-1999, is presented in summary form (Figure 12). In this summary presentation, each river where a mean

---

**Table 5. Sea trout rod catch per unit effort data, Owengowla and Invermore Fisheries 1985-1993**

<table>
<thead>
<tr>
<th>Year</th>
<th>Owengowla</th>
<th>Invermore</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Catch</td>
<td>Rod Days</td>
</tr>
<tr>
<td>1993</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1992</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1991</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1990</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1989</td>
<td>0</td>
<td>46</td>
</tr>
<tr>
<td>1988</td>
<td>127</td>
<td>313</td>
</tr>
<tr>
<td>1987</td>
<td>337</td>
<td>425</td>
</tr>
<tr>
<td>1986</td>
<td>1070</td>
<td>565</td>
</tr>
<tr>
<td>1985</td>
<td>1253</td>
<td>462</td>
</tr>
</tbody>
</table>
intensity of thirty or more lice per fish was recorded in any year over the period is indicated in grey. Locations where a mean intensity of less than thirty lice per fish were recorded are shown in black. The location of salmon aquaculture installations (with approximate production tonnage) is also shown. It is apparent that there is a coincidence with the location of salmon aquaculture and the high infestation of sea lice on sea trout.

Sea trout in some rivers close to salmon farms did not record heavy sea lice infestations. However, on no occasion over the sampling period were heavily liced sea trout recorded distant from salmon farms and sea trout rod or stock collapses were not recorded in these rivers. Typically, sea trout recorded in rivers close to aquaculture sites recorded high numbers of lice, the lice being predominantly at the juvenile stage, with some individuals recording many hundreds of lice. Sea trout recorded in rivers distant from aquaculture recorded lower lice levels, the lice being predominantly pre-adult and adult stages.

**Symptoms of the Collapse**

Fisheries close to salmon aquaculture sites in the mid-Western Region recorded the “sea trout problem” which can be described as follows:

- Premature return to freshwater of sea trout post-smolts after only one or two weeks at sea with no sea growth on scales.
- Many had heavy infestations of juvenile lice indicating recent transmission.
- Collapse of sea trout rod catch and population structure only in bays with salmon farms.

**Source of Sea Lice Infestation**

Sea lice infestation on sea trout can arise from two sources, wild salmonids and farmed salmon. Sea trout, grilse (or summer salmon) and spring salmon are the three possible sources of lice from wild fish. Trapping data from three locations in Connemara indicated that after the sea trout population collapse in 1989/1999 there could not have been sufficient sea trout population over-wintering at sea in the Connemara area to constitute a significant lice source in spring to infest migrating smolts. Summer salmon cannot be considered as a possible lice source as the infestations on sea trout appear in May before the grilse return to the coast in June. Spring salmon are a potential source of sea lice infestation but runs of spring salmon are not present in many estuaries where lice infested sea trout have been recorded; i.e. Bertraghtboy and Kilkieran Bays. Were spring salmon to constitute the primary source of lice infestation on sea trout, then lice infested sea trout postsmolts should have been recorded in all rivers around the Irish coast with a significant spring salmon run and sea trout population collapses should have occurred. Sea lice infestation on sea trout has not occurred in rivers with large spring salmon runs away from salmon farming areas (i.e. Slaney, Feale, Owenduff) and sea trout population collapses have not occurred in bays without salmon farms. Tully et al (1999) found no correlation between the presence of spring salmon rivers and infestation of sea lice on sea trout in Ireland.

Tully and Whelan (1993) studied the production of nauplii of *L. salmonis* from farmed salmon and wild sources and its relation to infestation of wild sea trout off the west coast of Ireland. The study concluded that at least 95% of lice emanated from farmed salmon.

**Table 6. The number of rivers sampled and the numbers of sea trout captured over the 1991–1999**

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of rivers Sampled</th>
<th>Number of Sea trout Captured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>13</td>
<td>134</td>
</tr>
<tr>
<td>1992</td>
<td>14</td>
<td>235</td>
</tr>
<tr>
<td>1993</td>
<td>53</td>
<td>835</td>
</tr>
<tr>
<td>1994</td>
<td>32</td>
<td>594</td>
</tr>
<tr>
<td>1995</td>
<td>41</td>
<td>632</td>
</tr>
<tr>
<td>1996</td>
<td>25</td>
<td>415</td>
</tr>
<tr>
<td>1997</td>
<td>31</td>
<td>595</td>
</tr>
<tr>
<td>1998</td>
<td>31</td>
<td>698</td>
</tr>
<tr>
<td>1999</td>
<td>29</td>
<td>666</td>
</tr>
<tr>
<td>Total</td>
<td>4804</td>
<td></td>
</tr>
</tbody>
</table>
Figure 12. Location of seatrout rivers sampled for sealice infestation 1992-1999
Correlations
In addition to sampling of sea trout in rivers, sea lice sampling of farmed salmon has been undertaken on all salmon farms since 1991. Farms are sampled fourteen times per year and a large body of information has been collected. The Sea Trout Working Group used this information to correlate infestation of sea lice on sea trout in rivers to lice levels on salmon in adjacent farms. The Working Group’s last published report (March 1995) concluded that in 1992 and 1993 a statistically significant relationship was shown between lice infestation on sea trout and distance to the nearest salmon farm. Analysis indicated that variations in lice infestation levels on sea trout demonstrated their maximum range in the vicinity of salmon farms, whereas at distances remote from farms the overall infestation levels were always at the lower end of the observed range.

In 1994, no significant relationship was observed, coincidental with reduced lice levels on salmon farms (Anon 1995). As a result, in recent years research has focused on managing lice levels on salmon farms at as low a level as possible, particularly prior to the critical spring period for sea trout migration.

Sea Trout Marine Survival in Ireland
Total upstream and downstream trapping facilities on two sea trout systems in western Ireland, the OwenGowla and Invermore fisheries, allow calculation of sea trout marine survival. Both rivers enter bays with extensive salmon aquaculture. Marine survival data for these Connemara fisheries can be compared with long-term data from the Burrishoole fishery, north of Connemara (Figure 13) Burrishoole finnock marine survival has averaged 20.7% over the 1971-1987 period (Poole et al., 1993). Recorded marine survival of finnock (sea trout that migrate to sea and return in the same year) from OwenGowla and Invermore has been very low in comparison with Burrishoole data for all years with the exception of data for the OwenGowla system in 1994. It is noteworthy that 1994 was the only year in the time series where whole-bay fallowing over the January-March period was practised in the bay into which the OwenGowla enters, Bertraghboy Bay. No fallowing took place in Kilkieran Bay into which the Invermore enters in 1994 and sea trout marine survival was below 1%.

The sea trout marine survival data presented above suggests that the practice of whole bay fallowing in early spring have a very positive effect on sea trout finnock marine survival to sea trout fisheries within such bays.

Management Initiatives in Ireland
In 1990 many of the sea trout fisheries in the mid-Western zone closed for angling and have not since reopened. Legislation prohibiting the retention of rod and net caught sea trout in the area was introduced and an aquaculture free zone was established along the north Mayo/Sligo coast (Anon 1994a).

A sea trout rehabilitation programme began in 1994, funded at a cost of approx £1.5 million under a European Union Structural Fund for Tourism. This programme set out to rear and stock out five million native Connemara sea trout fry into the 26 affected sea trout fisheries in the Mid-Western zone over the 1995-1999 period (Figure 14) and to correct any major habitat problems in freshwater. It was recognised at the start that the success of the programme was dependent to a large extent on sea survival of released sea trout fry. Electro-fishing and smolt trapping data on the Owengowla has indicated that the fry release programme has been successful in
maintaining or increasing sea trout smolt runs. Despite a large-scale stocking of sea trout fry into the OwenGowla fishery since 1995, the very poor sea trout finnock marine survival data recorded in the OwenGowla fishery in recent years indicates that there is likely to have been few additional sea trout returning as a result of the fry release programme. The fry release programme would have contributed more significantly to sea trout return in bays such as Killary and Ballynakill with better sea trout marine survival.

Since 1990, management initiatives have been taking place on salmon farms to improve husbandry and maintain low sea lice levels. Many farms have smolt sites distant from grower sites and keep generations separated until grower fish are harvested. Whole bay fallowing in spring has taken place in certain years in a small number of bays and has proved very successful in increasing sea trout marine survival in adjacent rivers. New bath treatments for sea lice have been developed and have proven effective in trials but are not yet available for general use. More conventional oral treatments have lengthy withdrawal periods. It is now recognized that a suite of both oral and bath treatments are required for effective lice control.

Monitoring of lice levels on salmon farms is ongoing and farms are required to act if ovigerous lice levels (females with egg strings) are greater than two per fish. However, it is not known what is the safe level of ovigerous lice with regard to lice infestation. Few two-sea-winter salmon are now being held and new aquaculture legislation has been introduced to regulate the industry.

**Salmon Aquaculture and Wild Fisheries in Scotland**

The salmon aquaculture industry in Scotland produces about 100,000 tonnes annually, primarily along the west and north-west coast. The same symptoms of the Irish sea trout problem are apparent in sea trout fisheries in salmon farming areas in west and north-west Scotland. The Report and Action Plan of the West Highland Sea Trout and Salmon Group (Anon 1995a) considered that the decline in sea trout stocks, which resulted in an acute shortage of sea trout in the West Highlands, was too sudden and too widespread to be readily explicable in terms of essentially local effects such as changes in flow regime, water quality or predation pressure. The problem appeared to be a dramatic reduction in the survival of post-smolts and kelts at sea. Although salmon farming cannot be blamed for the early period of sea trout decline in the West highlands, there is a widespread perception that increased infestation of wild sea trout by sea lice from salmon farms may be an important factor in the collapses of north-west sea trout populations (Walker 1996).

To date, sampling of rivers for prematurely returning sea trout post-smolts has been undertaken on a limited number of fisheries in comparison to the Irish programme. However, premature returning lice-infested sea trout have been captured in west coast rivers and many sea trout stocks have suffered a collapse in the vicinity of salmon farms. In general, lice infestation on sea trout in the west and north-west has been significantly higher than in other areas, although both high and low lice levels were found on sea trout in rivers close to salmon farms (Anon 1996). Sea trout populations have declined to levels at which insufficient eggs are being deposited to maintain smolt production (Anon 1999). Rod catches have declined to such an extent in the last decade that many fisheries are closed.

Salmon stocks have also collapsed in rivers in some fjordic Scottish lochs where there is intensive salmon farming. It is possible that this may be due to the more prolonged exposure time of salmon smolts to sea lice infestation (Walker 1996).

**Salmon Aquaculture and Wild Fisheries in Norway**

The salmon aquaculture industry in Norway is very large, producing 400,000 tonnes annually. The scale of the industry has lead to severe problems for salmonid fisheries. Many Norwegian rivers have very large runs of escaped farmed salmon with spawning stocks in some rivers made up of 90% farmed fish. Many rivers on the west coast have been devastated by the parasite Gyrodactylus salaris and entire stocks have been lost. Salmon and sea trout stocks have been very badly affected by heavy infestations of the sea louse, Lepeophtheirus salmonis.

Much research has been undertaken on sea lice infestation on salmonid stocks in Norway (Bjorn 1996, Birklund 1996, Finstad et al. 1995, Grimnes and Jakobsen 1996). In recent studies the Institute of Marine Research and the University of Bergen have captured many hundreds of wild salmon postsmolts at
sea by trawling with an aquarium cod end net. Results suggest that 48-86% of wild salmon smolts migrating from two fjords were killed as a result of sea lice infestation in spring 1999 (Holst and Jakobsen 1999). Some salmon postsmolts recorded greater than one hundred lice per fish. The sea lice load on escaped farmed salmon in salmon farming areas can be very high and makes a significant contribution to lice infestation pressure.

Sea trout stocks have collapsed in salmon farming areas and very high lice infestation levels have been recorded. Studies in five counties along the northern and western coasts of Norway compared lice infestation on early returning sea trout post-smolts captured less than 3 km from a fish farm or more than 20 km away. On those caught in rivers close to farms, levels of close to 400 lice per fish were recorded compared to a median intensity of 2 lice per fish in distant rivers (Anon 1996). Chalimus stages dominated the heavy infestations. In another experiment a group of sea trout smolts were treated with Ivermectin to give immunity to attack by sea lice while a second group were untreated. The untreated group returned prematurely to freshwater after two weeks with heavy sea lice infestation while the treated group remained feeding at sea and did not return prematurely (Finstad and Birkland 1996). Since 1997, the necessity of maintaining effective control of sea lice on salmon farms in spring has been recognised and a national programme for the control of sea lice has been set up in Norway.

ICES Workshop on the Interactions between Salmon Lice and Salmonids

The International Council for the Exploration of the Sea held a Workshop on the interactions between salmon lice and salmonids in Edinburgh, Scotland, in 1996 (Anon 1996). All the available information on sea lice on farmed salmon and wild salmonids was examined and the following trends emerged from the data:

• Highest levels of sea lice on sea trout in Ireland, Scotland and Norway were recorded in salmon farming areas.

• Comparable levels in infestation have not been recorded outside salmon farming areas.

• Sea trout stock collapses have only been recorded in fisheries close to salmon aquaculture.

• The data suggest that lice emanating from marine salmon farms may transfer to wild trout stocks, although the scale of this transmission cannot as yet be determined.

Monitoring of Lice on Salmon Farms and Trigger Levels for Treatment

In Ireland, each salmon farm is monitored for lice fourteen times annually. In the spring period monitoring is undertaken twice monthly. Lice counts are undertaken on thirty salmon from a standard cage and thirty from a random cage. The same standard cage is sampled each month. Lice counts are available within one month allowing real time information on lice levels.

The trigger level for lice treatment on farms in Ireland is set close to zero in spring and not above 0.5 egg bearing females per fish. High levels of mobile lice also trigger treatment. Outside the spring period, a trigger of 2.0 egg bearing females per fish is set before treatment is necessary. When lice levels above the target are recorded, farms are advised to get lice levels under control. Sanctions for not complying include compulsory harvesting and no increase in stepped production tonnage.

Although salmon farms are well monitored for lice and a target is set for lice levels on salmon farms in Ireland by the regulatory authorities, it is still not known what level of lice can adversely impact on neighbouring salmonid fisheries. No cap is in place on the total lice production on a bay basis, which in some cases may be more critical with regard to lice management, when large production tonnage is involved.

In Norway, sea lice have been a major health problem on fish farms for many years. In recent years sea lice have been recognized as a serious threat to migrating salmonid smolts from Norwegian rivers (Eithun 2000). A National Programme for control of lice on salmon farms was established in Norway in 1997, which had three primary measures:

• A programme for counting lice on all fish farms.

• A programme of medical treatments, emphasizing the period prior to migration of wild smolts.

• The use of cleaner fish as a supplement to medical treatment.
As part of the programme, regulations made by the Norwegian Animal Health Authorities came into force in 1998. The purpose of the regulations are to lay down minimum measures to reduce the incidence of sea lice on salmon farms. These include:

- Mandatory counting, recording and reporting on the incidence of sea lice.
- Mandatory delousing when target levels are not met.
- Administrative fines when regulations are violated.

The long-term goal of the programme is to have no adult lice present on fish farms during the period prior to the migration of wild fish to sea.

In Scotland, a National Treatment Strategy for sea lice was launched by the Scottish Salmon Growers Association in 1997. The strategy has not been fully implemented because of a lack of available licensed treatments and the severe negative impacts of ISA on the Scottish salmon farming industry. The success of the strategy will be improved when new, fully authorized medicines become available. The result will be an overall reduction in the numbers of lice around the Scottish coast and farm louse numbers will be at their lowest when wild salmon and sea trout smolts are migrating (Rae 2000).

**Is Sea Trout Stock Recovery Possible?**

Data from the Erriff Sea Trout Fishery in Western Ireland indicates that effective lice management of sea lice on salmon farms can lead to a recovery of sea trout stocks in adjacent fisheries. Only one salmon farm operates in Killary Harbour, into which the Erriff Fishery flows, and lice levels have been maintained at very low levels in recent years. A sea trout kelt trap has been operating on a branch of the Erriff fishery since 1985 and results from this trap serve to illustrate how the sea trout stock on the fishery has recovered.

The length frequency distribution of kelts over the 1985–1988 period shows two peaks, one of the smaller finnock kelts and a second representing one-sea-winter maiden fish and previous spawners in the 35-50 cm length range (Figure 15). This latter peak is absent from the 1990-1993 data at a period when sea lice levels on sea trout in the Erriff were high and sea lice levels were also high on the adjacent salmon farm. Erriff sea trout stock levels were very low and large numbers of heavily lice-

**Figure 15. Length frequency distribution of sea trout kelts on the Erriff Fishery**

![Length frequency distribution of sea trout kelts on the Erriff Fishery](image-url)
infested sea trout post-smolts were recorded in the Erriff fishery at this time. Since 1994 the peak representing the larger sea trout has begun to reappear indicating that a greater proportion of the stock are surviving at sea to return as older age classes. Killary salmon farm began operating a separate smolt site in 1994 and since then farm has operated as a single generation site operation.

Ovigerous lice levels at Killary salmon farm were close to zero over the spring period 1996-1998. It is apparent from the 1998/99 data that the sea trout population has made further recovery over previous years. Although the sea trout population structure has not recovered fully to that seen prior to 1990, the length frequency distribution of kelts recorded in recent years is encouraging and indicates that maintenance of very low lice levels in adjacent bays plays a significant role in the rehabilitation of sea trout stocks.

Management Initiatives Required on Salmon Farms for Effective Lice Control
The concept of “single bay management” was introduced in Ireland in the early 1990s in an attempt to control lice on salmon farms. The concept involves all salmon farms in a bay co-operating with regard to exchange of information and an agreed code of practice. The management initiatives which are promoted as part of this initiative are:
- the use of single generation sites
- annual fallowing of sites
- synchronization of lice treatment within a geographical area
- early harvesting of two sea winter fish
- maintenance of near zero lice levels in spring
- availability of both oral and bath lice treatments.

Experience to date has shown that maintenance of very low lice levels on salmon farms over the February–April period is the most effective means of increasing sea trout post-smolt survival in adjacent sea trout fisheries. This objective must be achieved if sea trout stocks on the Western seaboard are to recover.

New Developments in Salmon Farm Management
Sea lice are one of the most serious problems facing the salmon farming industry world-wide and new developments are underway in an attempt to eradicate the parasite. These include:
- development of new technology to move farms offshore
- location of farms in low salinity areas
- keeping farms sites distant from other farms
- use of cleaner fish (Wrasses)
- use of hydrogen peroxide
- use of pyrethroids
- use of delousing compounds from different chemical groups (e.g. hydrogen peroxide and organophosphates) to avoid resistance.

Conclusion
The development of salmon farming has dramatically increased sea lice infestation pressure on wild stocks of sea trout and salmon in Norway, Scotland and Ireland. The local impact of parasite infestation on wild stocks can have very serious consequences and can be greater than biological or genetic threats from farmed stocks in many areas. Experience has shown that the most effective way of reducing the lice infestation pressure and increasing marine survival of wild stocks is to operate whole-bay fallowing in spring. Should whole-bay fallowing not be possible, then it is important to operate only single generation farm sites and critical to ensure that lice levels are as close to zero as possible prior to the migration of wild smolts in spring. Proper lice management on salmon farms can result in recovery and maintenance of wild salmonid fisheries locally.

References
Anaemia (ISA) virus. This disease has caused major losses in the Atlantic salmon farming industry on both sides of the Atlantic Ocean, and has now been detected in wild fish in Canada (New Brunswick) and Scotland. While this review considers the case of ISA, the lessons learned may help us to plan and cope for future disease epidemics.

Taxonomy of the Virus
The ISA virus was unknown to science prior to its surfacing in epidemic proportions in the Norwegian salmon farming industry in 1984. Nylund (1997) suggested that ISA might have first arrived in Norway via the importation of rainbow trout (Oncorhynchus mykiss), although he provided no evidence to support his conjecture.

This virus has not yet been completely described, or named. However, it is most probably a member of the Orthomyxoaviridae family (i.e., a member of the flu group; Krossøy et al. 1999, Falk et al. 1997, Mjaaland et al. 1997), and may be the first detected species in a new genus within this family (Krossøy et al. 1999).

Tests Used to Detect the Virus
Three tests are used to identify the presence of ISA virus in Atlantic salmon (Lovely et al. 1999). They are: 1) an ISAV specific immunofluorescence antibody test (IFAT), 2) a reverse transcriptase polymerase chain reaction (r-PCR) test, and 3) a virology test which cultures the virus and tests for cytopathic effects (CPEs) on a cell line (salmon head kidney line SHK-1 is preferred, but others like Chinook Salmon embryo line CHSE-214 can be used; Bouchard et al. 1999).

The IFAT test gives false positives, which discourages its use. The r-PCR test provides the fastest result, but most investigators also prefer to have a final confirmation of the presence of the virus by a documentation of CPEs in the cell culture line. This, however, is time consuming, and test results can take a month or more to obtain.

Virus Detection and Chronology for the Epidemics in the Aquaculture Industry
ISA was first reported in a hatchery on the Southwest coast of Norway, where it was associated with a mortality of parr (Håstein 1977). Clinical signs began to break out at sea cage sites in subsequent years, and smolt
survival at some farms dropped from 86% to 18% by 1988. The spread of the disease was extremely rapid. From a level of zero infections prior to 1984, it grew to the point in 1990 where 101 new farms were infected in a year. Following the implementation of aggressive control programs, infection levels fell to the point that generally less than 10 sites become infected per year (Jarp and Karlsen 1997), although in 1998 about 15 sites were hit.

Outbreaks of ISA were first observed in Canada in 1996, where the disease was initially termed Haemorrhagic Kidney Syndrome (HKS) (Lovely et al. 1999, Mullins 1998, Byrne et al. 1998). The disease spread rapidly, and 21 sites tested positive for ISA in 1997, more than 35 in 1998 (about 40% of all sites); at present, there are 17 that are positive for the disease. Of these 17, 10 hold unvaccinated fish from the 1998 year class and seven contain smolts that were vaccinated against ISA and went to sea in the Spring of 1999 (Stewart, P. Has the ISA eradication program worked? Fish Farming 12(9) p.1).

This disease became the first of the Canadian sea cage industry where an eradication order was issued as a control measure. The industry was put in a very difficult position as initially no compensation was offered for the fish that were slaughtered. At present the number of sites testing positive for ISA is decreasing, however, the virus is still causing severe damage. So far, $20 million (Canadian) has been spent to compensate farmers for ordered eradication, and uncompensated losses may total as much as $40 million (Canadian) (DFO 1999). The Canadian East coast salmon industry is annually worth about $120 million (Canadian).

In Scotland, ISA was first reported in 1998. It spread rapidly to farms on the west coast of Skye and Shetland Islands, and by December 1999 11 sites had confirmed infections and a further 24 were suspected of being infected (about 10% of all Scottish sites; Scottish Executive Press Release, 15 December 1999).

The first reports of ISA in the Chilean salmon industry surfaced in March 2000. Scientists found the virus in farmed coho salmon (Oncorhynchus kisutch) at a single site. The Association of Chilean Salmon and Trout Farmers is disputing the identification (Rick Ramseyer, Fishmonger News Network, March 16, 2000). Chilean salmon officials downplay ISA virus reports but scientists at Atlantic Veterinary College stand by their research).

No outbreaks of ISA have yet been reported from the USA, although infected Canadian sites occur in close proximity (< 10 km) to American farms.

Strains of ISA
A recent comparison of a limited portion of the genome of a small number of ISA isolates from Norwegian and Canadian farmed Atlantic salmon showed that the Canadian version of the virus was about 80-90% identical to that of the Norwegian version (Blake et al. 1999). This is considered a fairly significant difference, and led the authors to suggest that the Canadian epidemic may not have resulted from a recent importation of the infection from Norway, but rather from a distinct North American genomic variant. I have not encountered any studies that report on comparisons of the Scottish strain of ISA to those of either Norway or Canada.

Symptoms of ISA in Atlantic Salmon
Clinical and disease symptoms include the fish becoming lethargic or moribund, lifting of scales off the body, a protuberance of the eyes, skin lesions, pale gills, swollen livers, petechiae, agglutination of the red blood cells, anemia, necrosis and/or hemorrhages in the pyloric caeca, intestine, liver and the kidneys (Bouchard et al. 1999, Rodger 1998). After experimental injections, in Atlantic salmon the virus seems to show up fastest and most consistently in the head and mid-kidney (Rimstad et al. 1999).

Transmission
The disease is “highly contagious and lethal” (Totland et al. 1996, p. 25), and horizontal transmission can occur in the laboratory in both freshwater and seawater. The virus is believed to be carried in skin mucus, faeces, urine, and blood of infected fish (Totland et al. 1996, Nylund et al. 1994), and enters the body through the gills, or wounds such as those caused by sea lice (Totland et al. 1996, Nylund et al. 1994). Consumption of virus-contaminated food by salmon did not result in infections, so gut-passage apparently destroys the virus (Totland et al. 1996). Virus particles have been shown to retain their infectivity outside the body of the host in seawater (at 6°C) for at least 20 (Nylund et al. 1994).
The disease does not appear to be vertically transmitted from infected parents to their offspring (Melville and Griffiths 1999). There is one report of an outbreak of ISA in first feeding fry at a site in Norway that could have implied vertical transmission of the disease. However, it is believed that the virus got into the facility by another, as yet unidentified, route (Nylund et al. 1999).

At present, the Atlantic salmon is the only salmonid that has shown large-scale mortalities when infected with this virus. Rainbow trout (Nylund 1997, Nylund et al. 1997) and brown trout (Salmon trutta) are asymptomatic, and presumed to become life-long carriers of the ISA virus once infected (Rolland and Nylund 1998, Nylund 1997, Nylund and Jacobsen 1995, Nylund et al. 1995). The European eel (Anguilla anguilla) has also recently been identified as a carrier, and Canadian and European agencies are testing other marine species to see if they harbor the virus.

Rolland and Nylund (1998) used a combination of injections of blood from infected to fish to uninfected fish, and cohabitation experiments of infected fish with uninfected fish, to show that the disease could be transmitted under laboratory conditions from anadromous brown trout to Atlantic salmon. This confirmed earlier work by Nylund and Jacobsen (1995). Mortalities for salmon in these trials went to 100% in 50% of their experiments.

Mortality Patterns

Laboratory trials, which often involved artificial injections of fish with virus, under controlled conditions, frequently showed infections beginning at about two weeks after exposure and high rates (>70%) of mortality in the next few weeks (e.g., Totland et al. 1996, Nylund 1997, Jones et al. 1999).

By contrast, mortality patterns showed seasonal patterns and were less severe at farm cage sites. In New Brunswick (Hammell and Dohoo 1999), there were distinct temporal peaks in mortality rates in early July, early September and late October. The approximately eight-week latency period for the infection may drive this pattern, subsequent to the initial outbreak. Mortality rates did not decrease as water temperatures declined in October. However, outbreaks were also recorded throughout the year.

Hammell and Dohoo (1999) defined outbreaks as mortalities within a given cage of greater than 1 fish/1000/day. In the 78 cages they considered, outbreaks lasted a mean of about 37 days, and resulted in losses of a mean of about 12.2% of the fish present. These values may be conservative, because they do not take into account situations where farmers “prematurely” terminated the outbreak by slaughtering the fish. Considering only sites where the outbreak ran its full course, about 45% of cages lost 5% of the fish present; about 15% of cages lost >5% but <10%; and 78% of the cages had total mortalities of less than 20%.

Resistance

Animals may be “resistant” to a disease because they have high tolerance (i.e., are infected, but do not show clinical signs) or because they are not susceptible (i.e., do not become infected).

Fish vary in their susceptibility to disease, in some cases due to their genetics (e.g. Gjøen et al. 1997). When genetic variation for disease resistance exists, it may be possible to select for disease resistance. Gjøen et al. (1997) evaluated the heritabilities for survival of 121 full sib groups of Atlantic salmon challenged with furunculosis (Aeromonas salmonicida), cold water vibriosis (Vibrio salmonicida), vibrio (V. anguillarum) and ISA. In these experiments, in the ISA treatment the cumulative mortality of Atlantic salmon was highest and heritabilities for survival were the lowest, indicating that salmon may have the least potential of the species tested for development of resistance to ISA through selection. In addition, the authors presented evidence that survival after challenge with the other diseases tended to be negatively correlated with survival after a challenge with ISA. In other words, if you select for resistance to these other diseases, you may increase susceptibility to ISA.

Epidemiological Studies

Two studies, one each for Norway (Jarp and Karlsen 1997) and Canada (Hammell and Dohoo 1999), have examined the epidemiology of the outbreak of ISA in their respective salmon farming areas. The goal of both was to identify factors that could contribute to the eruption and maintenance of ISA epidemics, and, if possible, to quantify the disease risk each of these factors posed.

In Norway, risk factors identified included:

- Siting farms < 5 km from a processing plant, which increased the risk of ISA by a factor of 13.
- Having your farm located < 5 km from an infected farm, which increased the risk by 8 times. Further reductions in
this risk were not achieved when farms were sited more than 10 km away from other sites.

- Taking smolt deliveries from a number of different producers, which increased risk to an undetermined degree.

In New Brunswick, risk factors included:
- Stocking cages with > 12,000 fish, which increased risk by a factor of 3.92 compared to cages receiving < 5000 fish, and those receiving 5000-12000 fish were 2.4 times more likely to test positive for ISA than those with < 5000 fish. This risk was evaluated independently of fish density.
- Increased density of fish in the cages increased ISA risk, but the relation was complex and appeared to be more of a threshold effect than a continuing increase in risk with continuing increases in densities. Cages containing 2-5 fish/m³ were 3.6 times more likely to develop ISA than those with less than 2.5 fish/m³, whereas those with > 5 fish/m³ were 2.7 times more likely to become ISA cages compared to those with < 2.5 fish/m³.
- Sites with fewer sea lice treatments got more ISA.
- Increased site traffic (shared divers, shared barges, increased numbers of smolt deliveries, etc.), increased risks.

Overall, these studies highlighted the importance of developing procedures and regulations that would reduce the risk of a farm encountering infective particles, and eliminating factors which stress fish and reduce their natural immunity. By inference, any factor that could contribute to either of these problems is worth avoiding at a cage site.

**Remedial Measures**

ISA is not going to be eliminated from regions where it has now established itself. Industry control strategies require rigorous measures to reduce the number of infective particles in the environment, good husbandry to reduce stress in the fish which could predispose them to epidemics, the development of vaccines, and possibly the implementation of selective breeding programs to develop lines of farm fish that are resistant to ISA.

Once sites test positive for ISA, eradication of fish at infected farms is done in all jurisdictions. In addition, husbandry measures being introduced include providing good growing conditions at the farms, the fallowing of sites after a culture cycle for a period of at least 6 months, and the growing of single year classes of smolts at each site. Site traffic issues are being examined and dealt with through a combination of regulations and individual and collective initiatives. Zoning is also being employed in all jurisdictions, with severe restrictions being imposed on fish farming in areas where ISA is present, compared to disease free areas.

For the industry, disinfection may be an option (Fraser 1999, Torgensen and Håstein 1997). This could be done to equipment that is moving between or among sites, or at processing plants to effluent and wastes. Available disinfectants include sodium hypochlorite (100 - 1,000 mg/l in fresh water for 30 min), formaldehyde (0.5% for 16h), formic acid (pH < 4 for 24h), heat (50º C for > 5 min), ozone (8mg/l/min for 4 min), and UV radiation (5mj/cm²), and iodophor (100 mg/l for a 20 min bath; 200 mg/l for low pressure spray).

New Brunswick salmon farmers inoculated their smolts in 1999 with a new ISA vaccine. Data are still being compiled, but it is clear that the vaccine did not, by itself, stop the epidemic. New farms have tested positive for ISA during 1999, including seven which had used the vaccine (Stewart, Paul. *Has the ISA eradication program worked?* Fish Farming V. 12, No. 9, p. 1). Joint government/industry research has just begun at Canada’s Department of Fisheries and Oceans Biological Station in St. Andrews, New Brunswick, evaluating the efficacy of the present vaccine. Vaccines are not used in either Scotland or Norway, due to EU regulations that call for eradication rather than vaccination.

Selection for natural resistance through breeding programs may be problematic. Only one study (Nylund 1997) has investigated the resistances of different farm strains or wild populations of salmon to ISA. In this laboratory experiment fish were injected with ISA, and while more of the farm strain fish died and did so faster than their wild counterparts, mortality of the wild fish was still high (> 70%) at the point the experiment was terminated. There was also evidence for a negative
correlation between resistance to bacterial diseases, and
resistance to viral diseases. In other words, genetic
selection for viral resistance could make the fish more
susceptible to bacterial diseases, and vice versa.

**Danger to People**
The virus does not cause agglutination of erythrocytes
from mammals (including humans) or birds and is
unable to replicate at temperatures above 25° C (Falk et
al. 1997). Thus, it does not appear to pose a threat to
humans and the sale of fish slaughtered in eradication
programs is permitted.

**ISA in Wild Atlantic Salmon and Farm Escapes**
The first reports of ISA in escaped farmed Atlantic
salmon, and wild Atlantic salmon, occurred in 1999. In
New Brunswick, Canada, four escaped farm salmon of
58 that were sampled entering the fish ladder in the
Magaguadavic River were confirmed as positive for
ISA. Prior to that, disease screening of escapees in this
river in 1998 (N = 61) were all negative for the virus. In
1997, based on visual inspections, five escapees (N =
35) were diagnosed as suspect for the virus, but
confirmation was not obtained because disease testing
laboratories were overloaded with samples as the ISA
epidemic took off.

Fifteen wild salmon were collected as broodstock
from the Magaguadavic River in the summer of 1999.
They were held in three tanks in an isolated facility on a
brackish well water supply. Subsequently, three fish
held in the same showed signs of illness and died.
Disease screening confirmed the cause of death was
ISA. The remaining 12 fish then had gill mucus smears
and blood samples withdrawn for an initial ISA
screening, and tissue samples were taken after
spawning for a final round of testing. Only one fish was
found to be disease-free in all tests.

It is unlikely that the well water used in the holding
facility was the source of the infection. It is also
unlikely that all these fish had ISA at the time they were
moved into the holding facility. It is more probable that
at least one individual in each tank had the disease, and
passed it along to uninfected tank mates.

These fish were artificially spawned and the eggs
reared in quarantine. Resultant first-feeding fry have
been tested for ISA (17 January 2000, 60 fry), and all
tests were negative.

Shortly after the Magaguadavic results were
reported, on 4 November 1999 The Scottish Executive
issued a press release announcing that ISA had been
found in salmon parr in the Rivers Conan, Easaidh and
Tweed, in brown trout in the Conan and Easaidh, in sea
tROUT in Laxo Voe, Shetland, and River Snizort in Skye,
rainbow trout freshwater farms in Aberdeenshire and
Kinnrossshire, and European eel in Loch Uisg, Mull.
The parr were not reported as having any disease
symptoms.

These results confirm that wild salmon may
harbour the virus and get ill from it.

**Implications for Wild Fish**
In North America, the ISA epidemic could not have
occurred in a worse place or at a worse time. In the area
where aquaculture is practised, wild salmon stocks are
severely depressed and in many cases on the brink of
biological extinction (Anon. 1999, DFO 2000). There
are no positive scenarios that can be attributed to the
presence of this disease.

Given the heavy degree of mortality caused by the
virus in Atlantic salmon, it may be that the Atlantic
salmon is a new and vulnerable host. Presumably, the
other species that are asymptomatic carriers have
coevolved with ISA virus, and can now tolerate it.
Given that only a few tens of fish are returning to North
American rivers in the area where the virus is ravaging
the salmon farming industry, the chances of a similar
coevolution in Atlantic salmon appear slim.

Salmon farming did not “create” the ISA virus.
Clearly, it existed before. However, in salmon farming,
where large numbers of fish are confined in close
proximity to each other, ideal conditions prevail for a
quick spread of an infection. Diseased fish shed virus
particles into the water, where they can reach new
hosts. Both wild and farmed salmon contract the
disease. Either group could now serve as a source of
infection for the other.

The best protection against ISA for wild salmon
populations is to minimize their probability of
encountering the virus. Clearly there is no hope of
vaccinating all wild parr in rivers. This argues for an
aggressive program of good husbandry at fish culture
stations and eradication of fish at cage sites when the
virus appears. This concords with the industry’s desire
to stop the spread of ISA among cage sites.
Atlantic salmon may carry the virus without immediately showing symptoms of the disease. However, when the infected individuals become stressed by environmental conditions, their immune system may succumb and they will then manifest symptoms. Thus, it is important to limit the spread of the disease as much as possible. The absence of the symptoms in fish having this virus does not guarantee that there will not be a future problem.

For those fish that do become infected, it will be critical to maintain healthy freshwater and ocean habitats in order to reduce stress and give their immune systems the best possible chances of fighting off the virus. If certain human activities are fostering the spread of potential pathogens, we may have to curtail other human activities to compensate for the risks that we are introducing to wild salmon populations.

References
Summary of Disease Break-out Group from Think Tank

Group participants
Dorothee Kiesser, Fisheries and Oceans Canada; Paddy Gargan, Central Fisheries Board of Ireland; Fred Whoriskey, Atlantic Salmon Federation; George Iwama, Agricultural Sciences, University of British Columbia; Harald Rosenthal, Institut f. Meereskunde a.d. Universitietaet Kiel; JoAnne Constantine, BC Ministry of Fisheries; Josie Osborne, Nuu-chah-nulth Tribal Council; Al Castledine, BC Ministry of Fisheries; Ted Needham, Heritage Aquaculture; Richard Alderson, Heritage Aquaculture; Mary Sue Atkinson, Pacific Fisheries Resource Conservation Council; Ron MacLeod, Save Our Fish Foundation; Facilitator: Bill Pennell, Fisheries and Aquaculture Program, Malaspina College; Rapporteur: Ruth Joy, Mathematics and Statistics, Simon Fraser University.

The group discussed the question posed by the program’s organizers (“Does disease move from salmon farms to wild stocks?”) and found it too narrow and so broadened the scope of the issues to be considered. Although we dealt only with salmon, we took pains to emphasize and delineate the broader context within which wild, hatchery-produced and farmed salmon exist. This would include the environment of salmonids and all factors affecting fish health, including the epidemiology and etiology of salmonid diseases.

We affirmed that our task was to determine areas of uncertainty with respect to the transmission and impact of fish diseases and research priorities in the area of salmonid health, with special reference to wild salmon stocks and possible effects on them from commercial aquaculture. Although we agreed not to attempt to set priorities in regulation, we took note of areas where regulation was the obvious solution to a potential problem. In several cases recommendations were made regarding organizational structures required to effectively deal with disease issues.

All of our recommendations were essentially in line and similar to those of the Salmon Aquaculture Review (SAR).

The group spent some time discussing the context of the question before moving into the specific issues. We agreed that it was important to set out the context of the issues before dealing with specifics.

The Fish Health Context

Disease is not simply the presence of a pathogen in an individual fish or in a population of fish. Pathogens must first infect a host, by-passing host defences, and the fish must be susceptible to that particular agent. The host then may deal with the pathogen, which may be carried in the fish at some concentration or eliminated. All of the pathogens known to be the etiologic agents of diseases of salmonids in British Columbia are found in wild fish individuals in most wild populations, although their prevalence varies. All of the diseases found on salmon farms also occur in many, usually most, wild populations, and are considered enzootic to B.C.

Antibodies to specific diseases are frequently found in wild salmon individuals, often in a high percentage of the population, indicating that the fish have encountered the pathogen and have dealt with it through their immune response systems.

Several factors determine whether a fish that has come into contact with a pathogen (e.g. bacterium, parasite, or virus) will show clinical signs of disease, survive or die. The main factors are the ability of the pathogen to enter (infect) the host, the virulence of the pathogen (its ability to create pathology in the fish), and the resistance of the host. The latter factor is very important and is affected negatively by stress. The number or concentration of pathogens (challenge levels) is also a factor in both infection rate and the ability of the fish’s immune system to deal with the pathogen once the fish has become infected.

Enzootic diseases have usually been in the environment for a long time so that fish may have developed the ability to adjust to them. Under most circumstances symptoms of disease do not occur even though the pathogen may be present in the environment and often in the fish themselves. In wild salmon, disease is commonly witnessed in fresh water under circumstances of stress. This may include the stresses of adult migration, maturation, and spawning, or environmental stresses such as high temperature or poor water quality. This is not to say that stress is always required for a disease outbreak to occur, but that it is a very common factor in disease.

There is no reason to suppose that disease does not also affect wild salmon during juvenile fresh water phases and ocean feeding migrations, but it is very
difficult to study this because diseased fish presumably are vulnerable to other proximate causes of death such as predation. There is some evidence to show that fish may sometimes have a sub-lethal level of disease that reduces performance without causing immediate mortality. This should not be overlooked as an aspect of disease in wild or farmed stocks.

On salmon farms, susceptibility to disease can be affected by a variety of management practices, as well as poor water quality and other natural phenomena (e.g. toxic or noxious phytoplankton blooms). Disease on salmon farms is controlled by many management practices designed to prevent disease, reduce the likelihood of transmission of disease agents amongst farmed fish stocks, and reduce stress. Improved nutrition and husbandry practices have reduced the occurrence of diseases and minimized the impact of disease among farmed stocks. Improvements in vaccinology, the increased use of vaccines and immune modulators that improve the fish’s immune response to specific diseases, and use of therapeutants have also assisted in reducing impact of disease.

Exotic pathogens are somewhat different in that they are new to the resident fish on either farm or wild populations and these fish may not have evolved the ability to co-exist with them. They may be both more infective and more virulent. (This applies in reverse to non-native fish species which may be much more susceptible to enzootic pathogens than local fish.) Consequently there is usually much greater concern over the introduction of exotic pathogens than concern over enzootic ones, because the former can potentially cause greater harm to wild stocks as well as to farmed fish. The group also felt that we should be careful to differentiate between exotic diseases and diseases that are newly recognized or now able to be identified.

The health of any fish stock, hatchery, wild, or farmed, will be determined by the general health of the fish (host), the quality of the environment, and the nature and concentration of pathogens in contact with the fish.

It was accepted by the group that pathogens move from wild populations to farm fish being grown in private hatcheries and salt water farms, and that this is likely a two way street with pathogens having the potential to move from farms to wild populations. The latter has not been demonstrated in British Columbia, but because all of the diseases seen on salmon farms are enzootic diseases, it would be very difficult to detect their movement into wild populations.

The Environmental Context
The ability of fish populations to deal effectively with enzootic pathogens is strongly influenced by the environment. This includes feeding opportunities and nutritional plane, and water temperature as key natural variables, and many other potential problems caused by human activity. The latter include damage to fresh water habitat, siltation, and chemical pollutants. As noted earlier, disease outbreaks in wild fish populations are sometimes seen on spawning grounds or along fresh water migration routes. A frequent situation in rivers is high temperature combined with low water flows. Fish are presumably stressed and succumb to enzootic bacteria, viruses, or parasites with resulting high mortality. Similar scenarios have been observed for salmon eggs and alevins, and more rarely for juveniles.

In the marine environment little is known about diseases of wild salmon, although it is thought that feeding opportunities vary from year to year and contribute to the normal high mortality seen during the marine phase of the salmon’s life history. Random variations in climate, climate regime cycles ranging from El Niño to decadal shifts and possibly global warming, are all of interest in this context, because changes in climate are thought to influence feeding opportunities. This is a relatively new area of research and not well understood.

The Management Context
Over the last 20 years, about 500 million salmon have been released from B.C. hatcheries each year, or otherwise enhanced (e.g. spawning channels). About two-thirds of these are produced in intense culture environments of hatcheries in which fish are reared for periods of a few weeks to a year after incubation. Vaccines are generally not used in these hatcheries, but various therapeutants are used to control disease in response to specific disease outbreaks. Only enzootic diseases have been seen in these hatcheries and these include most of the diseases seen on salmon farms. The potential for creating a pathogen reservoir effect in hatcheries has been noted, although there is no evidence to substantiate such effects. Juvenile hatchery fish that
have experienced a disease outbreak are usually treated and then released on schedule. Only occasionally are they destroyed. These fish join wild (non-hatchery) fish in rivers, estuaries and coastal waters. It is worth noting that the SAR pointed out that there have been no apparent changes in hatchery disease profiles (frequency and type of diseases) since before the establishment of an aquaculture industry in B.C.

The discussion group felt that some of the issues on the subject of disease transfer from salmon farms to wild stocks are potentially duplicated and amplified in the enhancement hatchery systems. They did not discuss this further, but felt that it was an important part of the wider context of discussions.

**Exotic Pathogen Introduction—The Broader Context**

The first disease topic discussed was the potential of exotic pathogen introduction (see below). The group wished to emphasise that, although the introduction of exotic pathogens into British Columbia via salmon egg importation was unlikely, there are other potential avenues of exotic disease introduction that are not being controlled. This includes the very large ornamental fish industry that is neither regulated nor monitored in any degree, and through which millions of fish of many species enter British Columbia each year from many countries. This also includes the importation of live fish from the United States and some off-shore countries to food markets in British Columbia and in some cases the importation of fresh fish flesh from other countries. The potential for exotic pathogen introduction through these means is obvious but not well investigated. Because of a lack of regulation and monitoring (and enforcement of such regulations that do exist), the risks from these activities are probably very much greater than from any controlled introductions of salmon eggs for aquaculture.

Harald Rosenthal pointed out another area of risk not discussed by the group. This is the exchange of large volumes of ballast water in coastal waters worldwide. In addition to invertebrate species introductions, it is possible that pathogens could also be introduced by this route.

Again, the group did not pursue these topics but felt that they should be clearly mentioned as an important part of the context within which particular salmonid disease issues are discussed.

**Research Context**

As noted in the introduction, the task of the group was to determine scientific issues where additional research was required for clarification of issues related to the potential transmission of disease agents and impact of disease on wild stocks and on salmon farming. It was noted by several members of the group that any research recommended must be effective and relate to the practical aspects of salmon farming in the context of potential impacts on wild stocks. It would be unsuitable to recommend studies that are poorly defined and incapable of definitive outcome. The setting up of long term databases was deemed important in several areas, but expensive studies leading only to an apportioning of blame without helping to find solutions would definitely not be recommended. Cost is a factor in all research, and the cost must be in some reasonable proportion to the expected benefits. Finally, research must be connected to specific problems and wherever appropriate and possible, to the potential interaction between wild and farmed stocks.

It was noted that there is always research being done in other countries and regions that will be applicable here, but communication and application of research is part of modern science. Partnerships and collaborations are now the main avenue to research funding. The new AquNet network of centres of excellence, in which UBC is a partner, is such an example, and promises to create much collaborative research in aquaculture.

**Disease Issues**

**Exotic Pathogens**

To date there are no exotic salmonid pathogens known in B.C., although whirling disease is an exotic parasite found now in the United States’ portion of the Pacific Northwest. It is thought to have arrived in transfers of hatchery trout. Atlantic salmon eggs have been brought into British Columbia since 1985, but there is no evidence that any pathogens have accompanied them. This is due to a combined federal and regional salmonid introduction policy that is very rigorous.

The Canadian Fish Health Protection regulations permit introductions only from certified sources. This means that testing for specified diseases has been done to a defined protocol and the donor hatchery has not
been shown to harbour these diseases. These regulations have been augmented regionally so that only eyed eggs may be brought into British Columbia. These eggs are disinfected and then held in quarantine for 120 days during which time they develop and hatch and are inspected according to strict protocols. Effluent from the quarantine facilities is disinfected. The juvenile fish are then reared out of quarantine but inspected several more times. This is a rigorous procedure and has apparently worked to date. The system is adaptive so that sources of eggs may be prohibited if there are problems in their region, or for any other reason to reduce risks. There have been relatively few eggs imported into B.C. in recent years.

The group therefore felt that exotic disease importation via imported eggs was very unlikely, but several members of the group pointed out that there is always a risk, and that it would not be accurate to say that the risk is zero. The group was at pains to add that other risks existed that were potentially quite significant: The importation of ornamental fish, food fish, and in some cases fresh fish products. There is no organised system of dealing with these sources of risk, presumably because of the complexity and cost of doing so.

**Response to Emergencies**

From time to time disease problems arise on farms or in nature that have an uncertain origin. Three such events have occurred in B.C. in recent years, and although none of these events proved serious and none of them involved exotic diseases, it is clear that a more organised response system is needed. This is not a research issue but one of government policy and procedure. This will require a reporting agreement with industry (see below).

**Databases, Surveillance and Reporting**

The need for a good database of mortalities on farms, hatcheries and wild stocks was emphasised. This is needed to discern trends, catch outbreaks of emergent diseases before it is too late for effective action, and to better understand the effectiveness of various farm management strategies. A new Fish Health Database is now being organised by the province in collaboration with DFO and the industry. This will include reporting from DFO and provincial hatcheries, salmon and trout farms, and private smolt hatcheries as well as opportunistic reporting of disease in wild stocks. The latter is described as opportunistic because it is not envisioned to sample apparently healthy fish populations for pathogens, but rather to investigate and report on any instances of disease outbreaks in these populations.

**Enzootic Disease**

The major issue that has been raised with respect to enzootic (indigenous) disease agents is one of reservoir creation, that is, that salmon farms would increase the concentration of pathogens (for example bacteria or virus particles) and that this local increase in concentration would add to the challenge faced by wild salmon as they migrate past or otherwise move around fish farms. There is no evidence that this happens but it is plausible and there is no reason to think that it might not happen. To date, the documented movement of disease etiologic agents has been from wild stocks to salmon farms by various routes. It would be possible to devise research programs to investigate the issue of pathogen movement from farm to wild stock, but this would be expensive and would not lead to any solutions to the problem, if it exists and is significant. It would be a blame-laying exercise.

Instead, the group felt that improvements to fish health on farms is the best means of reducing the potential for impact on wild stocks. Although simplistic in its statement, this concept serves the industry and preserves the health of wild fish at the same time. There are several approaches to improving health of farmed fish, and none are new. They are all noted and emphasised in the Salmon Aquaculture Review (SAR) report and recommendations.

1. **Therapeutant development and improvement**

   Continue to develop new and improved therapeutants for known diseases. These should be safe and efficacious to reduce environmental and human health effects and they should be safe for the fish.

   B.C. does not have a severe sea lice problem, but should one develop we will need an effective means of treating fish that is environmentally acceptable.

   There are some therapeutants available in other countries that have not been approved for use in B.C. and this needs to be addressed.
2. **Vaccine Development and Improvement**

Vaccine development over the last ten years has led to an order of magnitude reduction in the use of antibiotics on fish farms. There are several new vaccines now being developed, some of them for virus diseases and some for intractable bacterial diseases such as BKD. The continued work in this area is likely to lead to further reductions in antibiotic use and to further increases in health status on farms.

3. **Stress Reduction in Farmed Fish**

Stress is known to be a major factor in the outbreak of clinical disease in all organisms, and there is a large body of research on fish stress and fish health. Better understanding of fish behaviour has led to stress reduction, and indicators of stress allow farmers to detect stress and seek its causes before disease occurs. Further research in this area will increase the ability of farm managers to reduce stress in their fish.

4. **Nutrition**

Several people in the group pointed out that nutritional status strongly affects fish health and that formulated diets used on fish farms have improved very greatly over the past 15 years. Better feeding techniques as noted above also improve nutritional plane for all individual fish which improves health in two ways: one, all fish are better nourished and so are in better condition, and two, there is less stress due to agonistic relationships. Feed is presented in a manner that prevents territorial contests and so dominance does not emerge as a factor in the pens.

5. **The industry representative in the group, Dr. Ted Needham, suggested that work was specifically needed on five diseases:**

- **Bacterial** — Bacterial Kidney Disease
  - Furunculosis
- **Viral** — IHN and VHS
- **Sea Lice**

**The Organization of Research**

It was suggested that communication of research needs and research progress is a vital part of doing effective research. Priorities change, sometimes rapidly, and the industry should be an important part of setting priorities and helping to create practical research opportunities.

One approach to this would be to form a working group including government, the research community, and the industry to meet regularly to review these matters. Others in the group approved of this idea and pointed out that a Fish Health Working Group was now in the process of being formed as a part of the SAR implementation. This working group will include DFO, industry and government. This new working group could be expanded to include the research community and fulfill the above need.

**QUESTION FOUR**

*What are the dangers associated with farming of Transgenics?*

**Biosafety Assessment of Transgenic Aquatic Organisms: The Case of Transgenic Salmon**

*Dr. Anne Kapuscinski, Professor, Department of Fisheries and Wildlife, University of Minnesota*  
*1980 Folwell Avenue, St. Paul, Minnesota, USA, 55108, ark@fw.umn.edu*

Research and development to produce transgenic fish began in earnest in the mid-1980s. Since then several salmonid species have been major targets of genetic engineering to enhance growth. A scientific review of what was known regarding how changes in performance traits of fish might alter their ecological roles led to the conclusion that there were some real risks that required thorough assessment based on modern evolutionary biology and ecology (Kapuscinski and Hallerman 1990, 1991, 1994). Crucial gaps in knowledge about the ecological competency of transgenic fish were identified nearly 10 years ago and virtually none have been filled (Hallerman and Kapuscinski 1993). The American Fisheries Society published a position statement on transgenic fish that, among numerous recommendations, called for thorough
ecological risk assessment research and great caution in uses that could lead to environmental releases of transgenic fish (Kapuscinski and Hallerman 1990a). The U.S. Department of Agriculture eventually adopted voluntary guidelines for environmental risk assessment of genetically modified fish and shellfish, but these were limited to small-scale research and development projects (Agricultural Biotechnology Research Advisory Committee—ABRAC 1995). Now that the potential commercialization of at least one line of transgenic Atlantic salmon is close at hand, public and private sector interest in the biosafety of these organisms has risen tremendously (Kaesuk Yoon 2000).

A relatively non-technical definition of a genetically engineered organism (GEO) is an organism that has been constructed by isolating nucleic acid molecules (the molecules that encode genetic information) from one organism, and introducing these molecules into another organism in a manner that makes them part of the permanent genetic make-up of the recipient, i.e., capable of being inherited by offspring.

Alternative terminology to GEO used by different parties includes transgenic organisms, GMO (genetically modified organism), LMO (living modified organism, the term used in the International Biosafety Protocol), and even genetically enhanced organism. The term, genetically engineered organism (GEO), more clearly signals the scientifically documented differences between this new technology and traditional, selective breeding in terms of possible types of phenotypic alterations (Scientists Working Group on Biosafety 1998). Two examples of this distinction are covered below.

Recent public attention has focused on a small subset of traits undergoing genetic engineering. A much greater diversity of traits are now subject to genetic engineering in different organisms.

<table>
<thead>
<tr>
<th>Many Traits</th>
<th>Recent Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faster growth</td>
<td>Fish, trees, algae</td>
</tr>
<tr>
<td>Herbicide resistance</td>
<td>Crops, trees</td>
</tr>
<tr>
<td>Pesticide production</td>
<td>Crops, trees</td>
</tr>
<tr>
<td>Disease resistance</td>
<td>Fish, shellfish, crops, trees</td>
</tr>
<tr>
<td>Altered tolerance of physical factors (salinity, temp., light)</td>
<td>Crops, trees, fish, algae, microorganisms</td>
</tr>
<tr>
<td>Bioremediation, process ag. or industrial wastes</td>
<td>Microorganisms</td>
</tr>
<tr>
<td>Biocontrol</td>
<td>Insects, microorganisms</td>
</tr>
<tr>
<td>Secrete pharmaceuticals or novel biochemicals</td>
<td>Crops, trees, fish, algae</td>
</tr>
</tbody>
</table>

I do not have the time today to review what should be considered in assessing the ecological hazards of each type of altered trait. The relevant science is brought together for you in a user-friendly format in a risk assessment manual (Scientists Working Group on Biosafety 1998: Appendix A) that I will briefly describe towards the end of this presentation.

A/F Protein, a company based in Massachusetts with research and development facilities of its subsidiary AquaBounty Farms on Prince Edward Island, is closest to commercialization of transgenic salmon in North America. This company’s Atlantic salmon bear a construct consisting of the chinook salmon growth hormone gene linked to the promoter sequence that controls antifreeze production in the ocean pout (an arctic water marine fish). The transgenic salmon grow dramatically faster than controls, from 2.5 times faster to 6 times faster (Stevens et al. 1998, Fletcher et al. 1998).

AquaBounty Farms has applied to the U.S. Food and Drug Administration for commercial approval. The company is interested in selling these fish to net pen salmon farms, from which large escapes of farmed salmon are common and well documented. Company spokesmen have proposed to sell only triploid sterilized transgenic fish to net pen operations. Questions and recommendations about quality control of sterilization
are discussed below. In areas with wild Atlantic salmon runs on the brink of extinction, the escapes of large numbers of triploid fish could still pose ecological risk if they entered into courtship behaviour with fertile wild fish, thus making a significant portion of wild matings infertile (reviewed in ABRAC 1995).

There also are gaps in regulatory oversight of transgenic fish commercialization not covered in this paper. For a review of regulatory gaps in the United States, see Hallerman and Kapuscinski (1990), Kapuscinski and Hallerman (1994) and Kaesuk Yoon (2000). For problems in international governance of trade and unintended transboundary movements, see Kapuscinski et al. (1999).

The resulting genetically engineered fish cannot be equated with selectively bred faster growing fish. Rather, they illustrate a fundamental difference of genetic engineering: the ability to dramatically alter the regulation of gene expression through insertion of novel combinations of promoter and structural genes. The promoter DNA sequences regulate the level, tissue specificity, and even the timing of protein produced through expression of the structural gene (in this case, growth hormone).

The Atlantic salmon produced by AquaBounty Farms exhibit two forms of novel gene regulation that cannot be achieved by selective breeding: (1) novel tissue site of gene expression; and (2) novel timing of expression of the growth hormone gene. Whereas growth hormone is expressed only in the pituitary gland of all normal salmon (and of all known teleost fish), the transgenic growth hormone is expressed in the liver of AquaBounty Farms salmon. Furthermore, the fish’s growth rate is delinked from the normal environmental cue to stop producing growth hormone during periods of cold-water temperatures. This happens because the antifreeze promoter “switches on” the production of growth hormone year round. A recent scientific paper on these fish reported another genetic side effect: exposure to constant light does not suppress smoltification in these fish, as happens in normal salmon (Saunders et al. 1998). No empirical risk assessment research has been done to estimate the ecological effects of releasing fish whose physiology—growth, smoltification, foraging behaviour and perhaps other traits—is delinked from normal environmental cues. We need public risk assessment research to examine this complex issue.

<table>
<thead>
<tr>
<th>Genetic engineering differs from traditional breeding</th>
<th>Novel gene regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salmon with antifreeze promoter/ GH gene</td>
<td>growth hormone expressed in cold waters:</td>
</tr>
<tr>
<td></td>
<td>growth unlink from seasonal temperature cue</td>
</tr>
<tr>
<td></td>
<td>(smoltification unlink from light cues)</td>
</tr>
</tbody>
</table>

A second fundamental difference between genetic engineering and traditional breeding is that the former allows expression of novel proteins never found in the unmodified species or its close relatives. Examples in fish and shellfish are the ongoing research to engineer broad disease resistance in catfish and oysters through insertion of the gene for a strong lytic peptide, cecropin B, derived from the giant silk moth (Buchanan et al. 2000, Cooper and Tiersch 2000); and to develop transgenic tilapia expressing human insulin genes (Mackenzie 1996, Mansour et al. 1998). Depending on the biological activity of the novel protein and the end use of the GEO, the expression of novel proteins raises a host of ecological and human health safety questions (reviewed in Scientists Working Group on Biosafety 1998). If the GEO enters and thrives in the natural environment, will a novel protein harm its predators and other beneficial non-target organisms? If so, to what extent could this alter the species composition of aquatic communities? If the GEO is consumed by humans or used in animal feeds, what are the possible health effects of the novel protein? Has the inserted transgenic construct induced pleiotropic effects or changes in the three dimensional conformation of the novel protein that can affect food safety?

<table>
<thead>
<tr>
<th>Genetic engineering differs from traditional breeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>• novel proteins never found in unmodified species.</td>
</tr>
<tr>
<td>• crops/trees expressing herbicide resistance; pesticides (some Bt varieties secrete active toxin, not protoxin): pharmaceuticals</td>
</tr>
<tr>
<td>• soil bacterium converting ag. Waste to ethanol fish producing human insulin toxin, not secrete active</td>
</tr>
</tbody>
</table>
The there are relatively few published studies reporting experiments appropriately designed to test for ecological risks of GEOs that can thrive in the wild. A common shortcoming of most of these studies is that they examine only one trait at a time that might affect risk. But, to get a realistic picture of possible ecological risk or safety, we need a way to assess joint effects of all the traits that might affect fitness in the wild. There could be unpredictable fitness trade-offs and interactions among two or more altered traits (Muir and Howard 1999). Furthermore, recent research on genetically engineered organisms suggest that the values of fitness-related traits vary depending on the specific genes inserted, the species modified, and the genetic background of the engineered organisms. Thus, risk assessment research needs to be case-specific.

If GEOs escape into the environment, we want to know if their offspring will fare better or worse than unmodified counterparts in the face of at least four components of natural selection. Briefly, do GEOs show differences in: viability (referring to survival to sexual maturity), the component most familiar to people in terms of Darwin’s “survival of the fittest;” fecundity, measured by clutch or spawn size; sexual selection, i.e., any traits that give a mating advantage; and developmental selection, which refers to the age at sexual maturity? These fitness components are essentially critical check points in an organism’s life history that can be measured to assess its net fitness (Muir 2000).

They found four significant differences between the genetically engineered medaka and unmodified medaka from the same source population in aquarium tests.

<table>
<thead>
<tr>
<th>Performance Data on this Population of Medaka</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 30% Viability Disadvantage</td>
</tr>
<tr>
<td>• 400% Mating Advantage*</td>
</tr>
<tr>
<td>• 12.5% Developmental Advantage</td>
</tr>
<tr>
<td>• 25% Fecundity Advantage</td>
</tr>
<tr>
<td>* compared wild-type males 25% larger than smallest males</td>
</tr>
<tr>
<td>– Muir &amp; Howard (1999)</td>
</tr>
</tbody>
</table>

They also developed a simulation model that allows testing for joint effects of the differences in two or more of these selection-related traits. The model had a number of simplifying assumptions explained in Muir and Howard (1999). (It should be possible to modify the model in the future to remove these assumptions.)

<table>
<thead>
<tr>
<th>Deterministic Simulation Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Incorporate data on the different traits</td>
</tr>
<tr>
<td>• Wild population of 60,000</td>
</tr>
<tr>
<td>• Near stable age distribution</td>
</tr>
<tr>
<td>• Introduce 60 adult genetically engineered fish</td>
</tr>
<tr>
<td>– Muir &amp; Howard (1999)</td>
</tr>
</tbody>
</table>

Viability Selection Graph: When they simulated 60 invading genetically engineered fish with only a 30% viability reduction and no change in other fitness traits, the population quickly recovered from an initial decline and the transgene was totally eliminated from the wild population in approximately 20 generations. This straightforward result is consistent with the prevalent claim that GEOs will not pose an ecological risk because inserted genes will usually carry a genetic load that will weed out the GEOs from an invaded population.

Sexual + Viability Selection Graph: However, if the invading genetically engineered fish have a 400% mating advantage (in the males) and a 30% viability disadvantage in their offspring, the simulations produced an opposite outcome, suggesting high ecological risk. The transgene spread rapidly through the population due to enhanced mating advantage but

Muir and Howard (1999) applied this net fitness approach to ecological risk assessment on growth-enhanced transgenic Japanese medaka (Oryzias latipes) bearing a human growth hormone gene construct. The medaka serves as a good model system for risk assessment studies because it has a short generation time (approximately 2 months), thrives in aquaria and lends itself easily to microcosm and mesocosm tests of ecological questions.
the reduced viability of offspring drove the population to one-half its size in less than six generations and to extinction in about 40 generations. The authors call this the Trojan gene effect. The next logical step in risk assessment will be to test these model predictions over many generations on fish living in indoor and confined simple ecosystems.

Similar research to measure the net fitness of the A/F Protein transgenic salmon appears to be missing. Data on fitness traits need to be available for independent verification of biosafety claims by scientists not associated with the company. Unaffiliated scientists should have access to the genetic constructs needed to independently reproduce experiments. This is a pressing issue because these salmon are presently under review in the United States and Canada for commercialization.

In the face of huge gaps in critical information and inherent uncertainties in assessing the biosafety of transgenic salmon, interested parties can turn to the Manual for Assessing Ecological and Human Health Effects of Genetically Engineered Organisms (Scientists Working Group on Biosafety 1998). A 12 member, interdisciplinary group of independent University scientists wrote this scientifically grounded manual in order to help consumers, scientists, regulators, policymakers, and biotechnology developers evaluate likely impacts of GEOs in a variety of settings and applications.

Both volumes of the Manual can be downloaded from the website, www.edmonds-institute.org. This decision-support tool is applicable to all taxa from microorganisms to vertebrates; for aquatic organisms used in aquaculture, it therefore applies to all fish, shellfish, other invertebrates, and algae. The risk assessment questions and scientific guidance in the manual were designed to address the use of GEOs either in small-scale, confined research and development projects or in large-scale commercial uses involving varying degrees of environmental release.

The overall design of the Manual was inspired by a pre-existing guide, the Performance Standards for Safely Conducting Research with Genetically Modified Fish and Shellfish (Agricultural Biotechnology Advisory Committee 1995), that had been developed through the input of over 100 people from academia (ranging from molecular geneticists to aquatic ecologists), government agencies, environmental groups, and the aquatic biotechnology industry. The Performance Standards were adopted in 1996 by the U.S. Department of Agriculture solely as voluntary standards for research and development projects.

**Performance Standards for Safely Conducting Research with Genetically Modified Fish and Shellfish**

- www.nbiap.vt.edu
- static and interactive versions
- adopted by USDA as voluntary
- addresses only fish and shellfish
- addresses only confined small-scale R&D

Like the Performance Standards, the Manual consists of an interconnected set of flowcharts of assessment questions, supporting text providing scientific information for different questions, a worksheet tracing the path of analysis for a specific use of a GEO, and a glossary. In guiding the reader through a case-specific hazard identification, the flowchart questions address specific characteristics of the GEO, potentially accessible ecosystems, and potential ecological interactions of the GEO.

When hazards are identified, readers are directed to appropriate recommendations for ways to minimize risk of research and field trials with the GEO. (Most of these recommendations do not apply to commercial-scale
releases because containment is generally infeasible.) When readers are considering commercial release of a GEO despite evidence of significant hazards, they might consider mitigation schemes. The Manual stresses that the development of risk management and mitigation is in its infancy at this time. The Manual offers a systematic way of thinking through risk analysis, not a cookbook to follow blindly. What sorts of biological information are needed to identify hazards of a GEO? What experiments and field studies does this require? Is there enough information at hand to allow a scientifically defensible risk assessment? Finally, having the entire risk assessment process out in the open makes it easy to revise appropriate parts of the Manual as new biosafety information comes to light.

**Design of the Manual**
- Systematic, case-by-case hazard identification
- Recommendations to minimize risk
- Does not prescribe acceptable risk
- Way of thinking not a cookbook
- Transparency—worksheet traces analysis path
- Revise in light of new information

In the Manual, an overview chart summarizes the possible paths of questions and answers followed in the assessment of a specific GEO in a specific environmental setting. The questions are asked in the most parsimonious order for clearly identifying a hazard or reason for safety. The questions tend to appear in the order of the easiest to the hardest to answer. No assessment uses all the paths or questions. For instance, to evaluate a genetically engineered fish showing the Trojan gene effect like the medaka discussed earlier.

Risk management flowcharts [used in original presentation] help the user select and implement confinement measures to reduce or prevent the identified risk. A guiding principle is to implement multiple types of barriers, not just one type, in order to reduce the probability of total failure due to the inherent vulnerability of a given barrier. **Physical barriers** induce 100% mortality through such physical alterations as imposing lethal water temperatures or pH to water flowing out of fish tanks or ponds before the effluent is discharged to the environment. **Mechanical barriers** are devices such as screens that hold back any life stage of the GEO from leaving the project site. **Biological barriers**, such as induced sterilization, are those that prevent any possibility of the GEO reproducing or surviving in the natural environment. Physical barriers are not a viable option for net pen or cage farming of salmon because there is no “end of the pipe” effluent that can be so treated. Mechanical barriers are highly problematic in net pen farming. Materials such as extra predator barrier nets and rigid netting can help, but cannot alone prevent large escapes of GEOs due to storm damage, predator damage, or wear and tear. The newer bag technology needs to be tested for its ability to prevent fish escapes. The exclusive farming of all-female, triploid transgenic salmon that are functionally sterile is a feasible biological barrier for transgenic salmon. But sole reliance on biological barriers in net pen farms would violate the risk management principle of applying multiple barrier types.

The methods for producing monosex triploid salmon are well established and readily applicable on a large scale (e.g., Donaldson et al. 1996, O’Flynn et al. 1997). Sterilization of a transgenic line of salmon involves initially developing an all-female line of transgenic salmon, then fertilizing transgenic eggs with milt from the sex-reversed females and inducing triploidy on the newly fertilized eggs. Triploidy induction must occur every time the all-female transgenic line is bred to produce offspring for growout. The critical risk management question is whether to screen every individual destined for growout for the all-female triploid condition or only a sub-sample of each production lot. Screening for the all-female condition only needs to occur once in the development process. The most common screening method is progeny testing, although male-specific DNA probes provide a faster alternative in chinook salmon and perhaps someday in other species (Devlin et al. 1994, Donaldson et al. 1996, Clifton and Rodriguez 1997). Screening for triploidy must occur in every generation of production fish. Under experienced hands, one can expect rates of successful triploidy in the 90th percentile in large-scale production, but this will vary with fish strain, egg quality, age of spawners, and induction conditions.
In conclusion, the precautionary principle should guide ecological risk assessment and regulatory decisions regarding proposals to farm transgenic salmon. The precautionary principle is consistent with two tenets of scientific analysis. First, a precautionary approach fits with seeking to minimize type II statistical error (Dayton 1998). The potential for harm is greater if risk assessment conclusions commit a type II error compared to a type I error. Recovery from most harms to ecosystems or human health involve large time lags and some harms are irreversible. Type I errors, in contrast, are usually limited to short-term economic costs.

Scientific Justification Precautionary

- Greater harm under type II error exists but not detected than error impact erroneously none
- Scientific Uncertainty: expect surprises
- GEO behavior, novelty of trait(s) variability
- evolution of released GEOs
- insertion of multiple genes (gene stacking)

Second, the precautionary principle fits with the understanding from systems research that some uncertainty is inherent in all biological systems (Holling 1995, Kapuscinski et al. 1999). Uncertainty arises in part from gaps in knowledge about the behaviour of a GEO, the novelty of traits modified, variability of the environment, and limits to predicting the evolution of released GEOs. Uncertainty is also inescapable because some responses of living systems will be surprises that simply are unknowable before the fact. The advent of inserting multiple genes into transgenic organisms will only increase uncertainty due to increases in potential interactions between inserted genes and their expressed proteins.

References

Risk Assessment of Genetically-Distinct Salmonids: Difficulties in Ecological Risk Assessment of Transgenic and Domesticated Fish

Robert H. Devlin, Fisheries and Oceans Canada, 4160 Marine Drive, West Vancouver, B.C. V7V 1N6, devlinr@dfo-mpo.gc.ca

Types of Genetically-Distinct Fish
Genetically-distinct fish can arise both from natural selection and from anthropogenic activities such as species and strain introductions, commercial fishing, enhancement, selective breeding, domestication, and, more recently, genetic engineering (Carvalho and Hauser 1995, Sheridan 1995, Dunham and Devlin 1998). In constant environments, natural selection may act to narrow genetic constitutions of populations to allow the most fit genotypes to survive, but in most natural situations, differences in and fluctuations of ecological and physical parameters in allopatric and sympatric groups results in maintenance of genetic diversity. Thus, genetic change in natural populations is a regular and necessary consequence of selective forces. However, intensive human resource extraction activities, or indirect effects arising from pollution or habitat alteration, place selective forces on populations which may affect their genetic constitution. Similarly, actions designed to enhance productivity (numerically or phenotypically, or both) of fish species (hatcheries, stream restoration, or aquaculture activities) are all activities which to some extent differ from natural productivity, and have the potential to alter population genetic structures.

Widespread application of genetically-distinct fish both nationally and internationally, and research on transgenic strains currently under way with approximately 35 aquatic species worldwide, has prompted a plethora of speculation regarding potential ecological impacts if such strains were to gain access to natural environments. Unfortunately, and particularly for transgenic fish, very little empirical data exists from which accurate predictions of impact may be ascertained. The task is further complicated by our poor understanding of genetic effects on phenotype and fitness, and the difficulty in predicting such effects from laboratory experiments (Devlin and Donaldson 1992).

Interactions Among Genetically-Distinct and Wild Fish
Genetically-distinct fish may interact with wild conspecifics and other species in ecosystems through reproductive interaction, competition for spatial and energy resources, exchange of pathogens, and nonspecific effects arising from unique physiological differences (Tiedje et al. 1989, Kapucinski and Hallerman 1990, 1991, Devlin and Donaldson 1992, Hallerman and Kapucinski 1992). Transgenic fish represent a subset of genetic changes that can alter the phenotype of fish, and scientific analysis of the risks associated with this technology should be based on
genetic and physiological characteristics, rather than by the process (biotechnology) by which they were created (Tiedje et al. 1989). We have developed growth-enhanced transgenic coho salmon (Figure 15) as a model system to assess physiological, genetic, and ecological differences between wild and domesticated fish, with the objective of providing objective data for risk/benefit assessments by producers, regulators, and the public (Devlin et al. 1994, Devlin 1997, Dunham and Devlin 1998, McLean and Devlin 2000). Growth enhanced transgenic fish have also been produced for tilapia (Martinez et al. 1996 and 1999, Hernandez et al. 1997, Chen et al. 1997, Rhaman et al. 1998, Rhaman and Maclean 1999), catfish (Dunham et al. 1992), carp (Zhang et al. 1990, Fu et al. 1998), loach (Zhu et al. 1986, Enikolopov et al. 1989, Tsai et al. 1995, Kim et al., personal communication), and arctic charr (Pitkanen et al. 1999).

![Figure 16. Normal (left) and growth-enhanced transgenic (right) coho salmon at one year of age.](image)

The impact, or lack thereof, of genetically-distinct fish on wild populations will depend on three major factors:

1) **The size and frequency of introductions**

Clearly, larger and more frequent introductions of genetically-distinct fish have a greater potential to impact natural populations through disruption of population genetic structures that have evolved local adaptations for maximum survival (Bams 1976). However, the introduction of low levels of new genetic variability into populations may not always be bad; indeed, such a strategy of gene flow between populations is actually an evolved characteristic of the salmonid life history in the form of straying. Straying of new genotypes into populations is probably capable of allowing all genetic information to be exchanged among all stocks (Devlin and Donaldson 1992), and local forces are then able to select, on a continuous basis, appropriate fine-scaled population genetic structures for existing environmental and ecological parameters.

Theoretical considerations of introductions of new genetic material into populations can predict either good, bad, or neutral outcomes (Knibb 1997, Muir and Howard 1999, unpublished simulations), but clearly such determinations are highly dependent both on the scale (frequency and number of individuals vs. recipient population size) of the introductions and on the genetic difference which exists between the donor and host population (Devlin and Donaldson 1992). Indeed, very small differences in fitness (on the order of a 1-2%) can have very pronounced effects on the persistence of transgenes in populations when examined over long periods of time (centuries). Most importantly, at this time, we do not have sufficient scientific capability to accurately measure important genetic differences between genetically-distinct strains, nor do we possess adequate understanding of the genetic control of phenotype and fitness to allow accurate advance prediction of the direction, or magnitude, of potential effects.

2) **The genetic constitution of introduced fish**

Genetic effects on phenotype can be caused by one major gene as in the case of transgenic animals, or may arise from the action of many smaller genetic effects from throughout the genome in the case of domesticated or selectively-bred fish. For genetically-modified strains, extensive backcrossing to wild strains can minimize differences arising from intense genetic bottlenecks which occurs during the synthesis of transgenic animals in the laboratory, but for selected lines, such backcrossing would destroy the very nature of the genetically-selected phenotypes. In the case of transgenic animals, a very good genetic understanding can be
acquired (i.e. defined gene sequences, copy number, sites of chromosomal insertion, etc.), whereas with strains modified by selection almost no knowledge of the genetic basis of phenotypic change is likely to be known. Because of these differences, the introduction of transgenic or domesticated strains with similar phenotypes into wild populations would have very different consequences. In the case of transgenic animals (assuming they have been backcrossed sufficiently to natural populations to contain comparable and appropriate genetic diversity), effects arising from genetic interbreeding with wild populations will depend on the action of the single transgenic locus which can be molecularly identified and tracked in the ecosystem. For selected lines, interbreeding with wild strains will yield hybrid genotypes consisting of both selected and wild genotypes that, in most cases, will be intermediate in phenotype between the two parental lines. Subsequent generations (F2 and beyond) will yield complex combinations of genotypes arising from Mendelian segregation of the two genomes, and effects on fitness may arise from outbreeding depression. The longevity and impacts of these unpredictable genotypes on the long-term viability of a population or species is beyond our capabilities to predict at this time. Domestication and selection can lead to very dramatic alterations in phenotype equivalent to that achieved by transgenesis. For example, for rainbow trout, domestication has yielded strains that grow as rapidly as undomesticated strains containing GH transgenes (unpublished results). Thus, for some traits, both domestication and transgenesis have similar capacities for improving performance characteristics and for potentially impacting on ecological systems (Devlin 1998). Domesticated aquaculture strains are often genetically distinct from wild fish (Crozier 1993, Withler et al. 1994, Wilson et al. 1995, Danielsdottir et al. 1997, Mjolnerod et al. 1997, Clifford et al. 1997, Clifford et al. 1998, Norris et al. 1999), and the genetic basis of phenotype in selected and domesticated strains is much more complex than for transgenic strains. In this regard, prediction of genetic impacts of transgenic fish may be easier than for domesticated lines. In both cases, selection during subsequent generations will act on hybrid genotypes to maximize fitness, and the consequent novel genotypes will also have unpredictable phenotypes and potential impacts.

3) The fitness of introduced fish relative to wild type
As mentioned above, a major obstacle in predicting impacts of genetically-distinct fish (including both domesticated and transgenic strains) on wild populations stems from our rudimentary understanding of the relationships between gene action, phenotype, fitness, and ecological interaction. How genetic differences measured between populations relate in real terms to effects on the physiology of the animal, and how such changes translate into changes in survival and reproductive ability (fitness), are so poorly understood that accurate prediction of how new phenotypes will interact with existing populations and ecological systems is very uncertain.

Dramatic alterations in phenotype have been achieved by transgenesis which could affect fitness in both positive and negative ways. For salmonids, growth hormone gene constructs have been shown to influence growth rate (Du et al. 1992, Devlin et al. 1994, 1995a and b, Pitkanen et al. 1999), smoltification (Devlin et al. 1994, Saunders et al. 1998), appetite and feeding motivation (Abrahams and Sutterlin 1999, Devlin et al. 1999), metabolism and swimming ability (Farrell et al. 1997, Stevens et al. 1998), disease resistance (Jinghan, Iwama, and Devlin, unpublished), developmental rate and larval size (Devlin et al. 1995a and b), cranial morphology (Devlin et al. 1995b, Ostenfeld et al. 1998), muscle structure (Hill et al. 2000), pituitary gland structure (Mori and Devlin 1999), and duration of the life cycle (Devlin et al. 1995a). It is very likely that wild salmon have evolved the optimum growth and metabolic rates and physiological performances to allow maximum survival in nature, but it would be erroneous to assume that all alterations to fitness parameters would be negative and could not have some
impact if introduced into populations.

Transgenic salmonids provide a well-defined genetic alteration that is amenable to scientific experimentation under controlled conditions, but currently, it is very difficult to predict how such changes in phenotype would translate into effects on fitness in natural situations. For example, increased growth rates and feeding motivation, and increased size at hatching, may appear to be competitive advantages. However, further examination may reveal that the metabolic needs for high growth rates cannot be met with available food supplies in nature and viability could be impaired, or increased feeding motivation may yield animals more willing to risk predation than wild fish (Abrahams and Sutterlin 1999, Devlin et al. 1999). Similarly, impairments of swimming ability which would strongly affect the ability of transgenic animals to escape predators, catch prey, or migrate successfully up spawning streams (Farrell et al. 1997, Stevens et al. 1999), or effects on disease resistance, have only been examined at some life history stages. It would be incorrect to assume that such effects accurately forecast effects for all stages and strains, and that effects would occur equally in all environments. This uncertainty represents an important limitation for applying experimental data to risk assessments, but due to the necessity to maintain containment of transgenic animals, information from experiments conducted in secure laboratories still represent the only opportunity to learn about differences in phenotype and fitness between genetically-distinct and wild fish.

Whereas we have no information on the persistence of transgenes in wild fish populations at this time, some information is now available regarding the introgression of domesticated and wild salmonids. In European systems, domesticated Atlantic salmon escaping from aquaculture facilities can return to fresh water systems (Heggberget et al. 1993, Webb et al. 1993, Heggberget et al. 1996, Thorstad et al. 1998), and can successfully breed with conspecifics or closely-related species (Crozier 1993, Youngson et al. 1993, Clifford et al. 1997, Hindar et al. 1998). Domesticated fish in general appear to be inferior spawners and contribute less to subsequent generations than wild fish (Skaala et al. 1990, Fleming and Gross 1992, 1993, Beaudou et al. 1995, Fleming et al. 1996, Clifford et al. 1998, Thompson et al. 1998), but, as juveniles, domestic salmon, and wild/domestic hybrids (with higher growth rates), are more aggressive and tend to dominate wild fish in laboratory and field studies (Einum and Fleming 1997, Fleming and Einum 1997). As is the case with transgenic fish (see above), domesticated salmon are also more risk prone than wild fish (having been selected in environments without significant predation), which may reduce survival in the wild (Einum and Fleming 1997, Fleming and Einum 1997).

A major complication in interpreting laboratory data associated with fitness estimates is that transgenic and most domesticated fish used for experimentation have been reared in culture environments that differ greatly from the wild. Such environmental differences can have very profound effects on phenotype (genotype X environment (GXE) interactions) and consequent estimates of physiological performance or fitness. The expression of a genotype in fish grown in culture vs. the wild will yield different phenotypes and, further, such phenotypes (and hence genotypes) will be under very different selective forces in nature and will tend to be directed to a condition that maximizes survival and reproduction. Whereas such selection could either improve or decrease the ability of a transgene (or domestic gene complex) to survive in populations, at this point, such effects are not possible to accurately predict.

Effects on population genetic structure are also difficult to predict: A transgene with a very large selective advantage that rapidly sweeps through a population could reduce genetic variation within the population (and result in reduced ability of the population to respond to selection in the future). The same transgene could also either increase or decrease population sizes by altering viability or reproductive success. Extinction of populations due to transgene introductions could occur if opposing selective forces both drive a transgene rapidly to fixation and then allow a weaker negative impact to reduce population size (Muir and Howard 1999). However, such effects would primarily be anticipated under situations where the selective forces associated with critical phenotypes did
not change in different environments or population densities, and if competing genotypes could not adapt rapidly enough (by selection) to counter such effects. Thus, in addition to the magnitude of the phenotypic change, a second critical feature that will determine the success of a transgene in populations is the variability of the associated phenotype. If both the variance and heritability (the proportion of the variance caused by genetic factors) of the trait are high, then selection may act quickly to alter the phenotype and fitness, and predictions of impact (in both directions) will be difficult. Alternatively, if the trait is phenotypically stable, estimates of impacts will be more robust.

Gene constructs for traits other than growth may also have complex phenotypic effects in transgenic fish: for example, disease resistant strains may disrupt the natural mortality rates needed to balance natural populations in ecosystems, or transgenes designed to extend tolerance to environmental parameters or stressors may cause them to extend their natural biogeographical ranges. Whereas modeling has revealed scenarios where genetic traits are eliminated or fixed in populations, and is useful in identifying critical phenotypic traits, such predictions are highly dependant on reliable estimates of fitness. Unfortunately, even for the case of growth-enhanced transgenic coho salmon (where a very dramatic change in phenotype has occurred), we as yet have insufficient information to reliably predict potential impacts (or lack thereof) that could occur in complex ecosystems. This limitation is not restricted to transgenic fish: All genetically-distinct fish have the potential to have such effects, be they arising from the selective breeding or domestication, from introductions of foreign species, or having been produced by genetic engineering. An improved understanding of genetics and physiology, and phenotype and fitness, is thus urgently required.

**Physical and Biological Containment**

The uncertainties associated with prediction of ecological impacts of transgenic and other genetically-distinct fish could be greatly minimized by adoption of containment procedures whenever possible to ensure reproductive isolation and prevent genetic introgression among different stocks. Such containment measures range from physical barriers where some experience with the strain or species is available (i.e. land-based culture, or closed-bag or very secure net-pen culture systems), to complete reproductive containment with strains or species where experience is limited and prediction of impacts is currently not possible. Reproductive containment includes approaches such as: 1) conditional lethality controlled by metabolic dependencies that can be met in culture but not the wild, 2) induction of sterility by the production of triploid female populations or specialised transgenic strains, or 3) the use of single-sex (all-female) populations to prevent establishment of feral populations in cases where exotic species are being cultured and no reproductive interaction with local species is possible. The reliability of any containment plan requires examination of the efficacy of inducing the containment measure (i.e. triploid or monosex strains) and the magnitude of uncertainty introduced by human error and unpredictable circumstances (Devlin and Donaldson 1992).

**References**


**QUESTION FIVE**

**What Steps Should be Taken to Reduce the Risk of Aquaculture to Wild Salmon?**

**Alternative Approaches to Aquaculture**

*Helgi Thorarensen, Head of Aquaculture*

*Holar Agricultural College*

*551 Saudarkrokur Iceland, helgi@holar.is*

Land-based farms have several advantages over sea cages. Optimum rearing conditions can be maintained constantly in the tanks. The environmental impact of land-based units is much less, since organic material can be removed from the discharge water before it is returned to the ocean. The chances of fish escaping from land-based farms and mixing with wild populations are small and the risk of disease spreading from land-based units can be minimised. Drug treatment of the fish can be contained in the tanks and lower doses are required than in cages.

The disadvantage of land-based fish farms is that they are more expensive and the cost of production is higher than in conventional sea-cage farming. However, this difference is not as large as many assume, and there are examples of successful land-based fish farming.

Currently, the aquaculture industry in Iceland uses predominantly large, land-based rearing tanks. This is due to harsh natural conditions in Iceland with low seawater temperatures and exposed coastlines that preclude cage farming during the winter in most locations. Moreover, geothermal heat is used to heat the rearing water and this is only possible in land-based tanks. This approach to aquaculture is unique and required the development of novel methods for aquaculture. As a result, the growth of the aquaculture industry in Iceland during the last ten years has been slower than in the neighbouring countries. However, it is predicted that the aquaculture production in Iceland will increase significantly in the near future. The main aquaculture species in Iceland are Atlantic salmon, Arctic char and rainbow trout. Production of abalone, halibut and sea bass also shows promise.

The larger land-based salmon farms in Iceland produce each close to 1000 tonnes annually. In these fish farms, seawater is pumped into circular rearing tanks that are up to 2500 m$^3$ in volume with production.
densities between 20 and 40 kg·m⁻³. The seawater is heated with geothermal water, either by heat convection or by mixing directly into the rearing water. Rearing temperatures are kept between 6-9 °C. Good uniform water quality is maintained with injection of commercial oxygen. In recent years much emphasis has been placed on reducing water use in fish farms. Although there are abundant supplies of fresh water, seawater, and geothermal water in Iceland, the cost of pumping water into the tanks is significant. As a result, water use in the fish farms is kept at minimum with oxygen injection and re-use of water. In addition to reducing the cost of pumping, water re-use also allows fish farmers to increase rearing temperature where geothermal water is in short supply. The net water use in Icelandic fish farms is commonly 0.2 L·min⁻¹·kg⁻¹.

The cost of production of salmon in the larger land-based fish farms in Iceland (including smolts and capital cost) is about $CAD 5 per kg, which is somewhat higher than the average cost of production in Norwegian sea cages. However, the difference is small enough for Icelandic salmon producers to be able to compete with the Norwegian and Scottish producers. The cost of constructing land-based units with an annual production of 1000 tonnes is estimated $7.9 CAD million. Both the cost of production and the capital costs are significantly lower than the estimates presented in the Report of the BC Salmon Aquaculture Review.

Several Icelandic fish farms experimented with ocean ranching during the early nineties. Conditions in Iceland appeared to be favourable for ocean ranching with no sea fishery of salmon and earlier small-scale experiments indicated that good returns (up to 10%) of released fish could be expected. Up to 6 million smolts were released each year during this period, which is ten times the total smolt production of Icelandic rivers. However, these large-scale ocean ranching operations proved not to be economical, because of low numbers (2-3%) of fish returning. Currently, there is no fish farm in Iceland in ocean ranching except for stock enhancement purposes.

Dispersal Behaviour of Escaped Farmed Steelhead Trout (*Oncorhynchus mykiss* Walbaum)
C.J. Bridger¹, D. Scruton², R. Booth³ and R.S. McKinley⁴

1. Aquaculture and Seafood Development, Memorial University of Newfoundland, St. John’s, NF Canada
2. Department of Fisheries & Oceans, Science Branch, St. John’s, NF Canada
3. Lotek Marine, St. John’s, NF Canada
4. Dept. of Biology, University of Waterloo, Waterloo, ON Canada N2L 3G1

Abstract
A combined acoustic and radio telemetry system was deployed in Bay d’Espoir, Newfoundland to monitor the dispersal behaviour of cultured steelhead trout (*Oncorhynchus mykiss*) once released from their rearing site. Two release scenarios were employed. The initial scenario mimicked an opening in a net pen, whereas the second scenario examined the fidelity of cultured steelhead released a kilometre from the rearing location. Results from the initial release showed that all tagged individuals remained in the immediate vicinity of the rearing site for up to four weeks. Results of the second release scenario showed that all tagged individuals had returned to the rearing site within four weeks of being released. In both scenarios, fidelity to the rearing location was drastically reduced after six weeks. Results clearly demonstrate the feasibility of using re-capture techniques, *albeit* for a limited time period, for escaped individuals from aquaculture facilities.

Introduction
The threat(s) of escaped farm fish to wild stocks has been widely debated. These concerns have included direct competition for food, spawning habitat and other behavioural interactions with wild stocks (Hansen *et al.* 1991, Hutchinson 1997). Attempts to limit escapes from aquaculture facilities have included the development of novel net designs and increasing net strength. Unfortunately, fish continue to escape from facilities and, as a result, represent a liability to both wild stocks and the aquaculture industry itself.
One approach to minimize escapee interactions with wild stocks has been to re-capture the farmed individuals using gill nets deployed around net pens. Unfortunately, these nets also entangle native species and, therefore, do not represent a highly desirable approach. Nevertheless, refinement of re-capture procedure to include live traps and the targeting of trapping procedures to escaped fish might mitigate interactions with wild stocks. To date, information on escapee behaviour is clearly lacking and, therefore, implementation of a recapture strategy would be difficult to design.

The objective of this study was to determine, using biotelemetry, the dispersal behaviour of steelhead trout from net pens. Dispersal behaviour was also noted for individuals released away from grow-out sites.

Materials and Methods

Adult steelhead trout were provided from grow-out cages located in Bay d’Espoir, Newfoundland. Individuals were triploid females ranging from 1.5 to 2 kg. In total, 240 steelhead trout were fitted with combined acoustic/radio transmitters (CART). Each transmitter had a unique radio and acoustic coded frequency. Each transmitter was cylindrical (16-mm dia. x 75mm long) and weighed 16.6 g. Transmitter battery life was 360 days with a 5s-repetition rate.

Transmitters were surgically implanted following procedures outlined in Anderson et al. (1997). All individuals to be tagged were anaesthetized using a 60ml • L⁻¹ solution of clove oil. Anaesthetized individuals were exposed ventrally on a V-shaped operating table. Throughout the surgical procedure, gills were continuously irrigated with a dilute solution of clove oil (20 ml • L⁻¹). Transmitters were implanted into the body cavity via an incision positioned posteriorly to the pelvic girdle. The antenna exited the body cavity via a second wound (<0.5mm dia) approximately 3 cm from the incision. The incision was closed using three independent silk sutures (2/0). Once fish retained equilibrium, they were released into the net pen. All fish recovered from the surgical procedure.

Experimental approach included two sets of escapee scenarios based on the intentional release of steelhead trout from cages within Bay d’Espoir. The initial scenario involved the release of 68 individuals on July 12, 1998. These fish were released from the holding cage by lowering the cage below the water surface. This release was designed to mimic fish loss through an opening in the net mesh. A second release of 66 steelhead trout occurred on August 10, 1998. Prior to lowering the net pen to permit the release of tagged individuals, the pen was towed approximately one kilometre from the original grow-out area. Immediately following the release, the net pen was towed back to the grow-out site. This release was designed to test the fidelity of farmed individuals to the net pen.

The behaviour of tagged individuals once released was monitored using manual tracking procedures and at fixed listening stations located throughout the bay. Tracking of individuals was conducted on a daily basis over a three-month period.

Results and Discussion

Of the 68 steelhead released from the net pen within the original grow-out site, 75% (51) remained within a 500 m radius of the cage for at least 4 weeks. Fidelity to the net pen drastically decreased after four weeks and fish appeared to be randomly dispersed throughout the bay. Only 6% of tagged individuals remained in the immediate vicinity of the net pen after 6.5 weeks.

Similar results were obtained from the second release designed to test dispersal behaviour from the grow-out site. Seventeen of the 66 steelhead (26%), released one kilometre from the grow-out site, returned to the original net pen location within four hours. At four weeks, 65% of the released individuals were located within the immediate vicinity of the grow-out period. Only 5% of tagged individuals were located in the grow-out area after 6.5 weeks.

Steelhead trout released from a commercial aquaculture site remained nearby or returned to the rearing site even if released one kilometre away. Steelhead clearly demonstrated a level of fidelity to the rearing site rather than to a specific grow-out cage. Previous studies have also found large aggregates of both cultured and wild fish adjacent to net pens but no information on how long individuals, once escaped, will spend in the immediate vicinity (Collins 1971, Loyacano and Smith 1976, Carss 1990). Our results indicated that fish show a high fidelity to the rearing area for at least four weeks. Furthermore, the high degree of fidelity to the rearing site was reinforced by the behaviour of individuals released one kilometre from the rearing site.
Subsequent monitoring of individuals following the initial four weeks showed that the majority of tagged individuals dispersed to an area just downstream of a hatchery. None of the released individuals were located upstream in any of the tributaries entering the bay.

Results of the study suggest that escaped individuals from aquaculture sites are likely to exhibit a high degree of fidelity to the rearing location. Furthermore, results imply that recapture procedures need to be deployed in the immediate vicinity of the rearing area within the first few weeks of an accidental release.

Literature Cited.

What Steps Should be Taken to Reduce the Risk of Aquaculture to Wild Salmon?

Dr. Malcolm Windsor, Secretary, North Atlantic Salmon Conservation Organization, 11 Rutland Square, Edinburgh, Scotland, UK, hq@nasco.org.uk

NASCO is the international inter-governmental body dealing with salmon in the North Atlantic and I am its Secretary. I have been asked to speak today about: What steps should be taken to reduce the risk of aquaculture to wild salmon? This is not a scientific issue but more a question of action. Before I do so, let me make it clear that I have no doubt that steps must be taken. There is already more than enough evidence of adverse impacts from disease and parasites. Here in the Pacific, where Atlantic salmon is being farmed, there is great concern about ecological impacts of escapees. In the Atlantic we
have the additional worry about genetic “pollution”. There are real fears of loss of genetic diversity and a ‘hybridisation’ of the wild stocks. These genetic impacts are not fully proven but it would be extraordinarily foolish to even consider running the risk of irreversible genetic change. Indeed, I would argue that we have no right to do so.

We should only embark on large-scale genetic trials in the ocean involving wild stocks when we have proved that it is safe to do so. It is not acceptable to put it the other way round to continue a risky action until it is proved unsafe. We did not wait for the full evidence of the impacts of car exhaust emissions on human health before requiring all cars to be fitted with a catalytic converter. So my position is that we must act without delay.

However, my belief, and that of NASCO, is that we will gain little from working by confrontation with the aquaculture industry. What we seek is the “win-win” situation where aquaculture can prosper and be recognised and labeled as a sustainable, responsible industry, i.e. a “win” for aquaculture; and a situation where the wild salmon stocks, Pacific and Atlantic, are healthy and not subject to new genetic, disease or other threats, i.e. a “win” for the wild stocks. The stark alternative is “lose-lose”. In this scenario the salmon aquaculture industry becomes associated with environmental damage, hastens the decline of its own gene bank, acquires a poor product image, loses market share and, in the end, is unsustainable. The wild stocks, already in a poor state, are further weakened and lose genetic diversity and some stocks are irrevocably lost. Aquaculture gets the blame and suffers a ‘consumer backlash’. I am convinced that it need not be like that, but we are going to have to move swiftly to ensure that the “lose-lose” scenario is off the agenda. Just imagine the situation if chickens were regularly escaping from farms and inter-breeding with wild birds. It does not take much to picture the impact on sales of broiler chickens. Let me say then, briefly, how I think we might handle the situation for salmon.

First, it may seem obvious, but we must keep wild populations strong. Each country or province needs to ensure that it has the right legislative framework in place to protect the wild stocks. I have no doubt that such a legal framework must not only protect the wild stocks but the environment in which they live. You might expect me to say that, but I believe it is our duty to ensure the future of these species that have been here for at least 10,000 years and probably a great deal longer—and to which future generations have rights. That is a primary obligation. A model legislative framework for wild salmon conservation might include laws and regulations:

- permitting or prohibiting methods, times and places of fishing
- restricting effort by licensing fishermen
- prohibiting the taking of immature salmon
- restricting catch by quota
- ensuring the free passage of fish
- protecting its environment
- placing conditions on trade in salmon
- restricting importations of species which might adversely affect salmon or its habitat
- minimizing the spread of disease and parasites
- dealing with any other relevant aspects.

Moreover, it is quite clear that, where sacrifices are being made in the name of conservation, there has to be burden-sharing. I mean this in the sense of sharing conservation guidelines between commercial fishermen and sports fishermen, and also sharing burdens with other industries. Those dealing with wild stocks cannot just expect others to make sacrifices. It won’t work. It is no use if the wild salmon manager blames the aquaculture industry for all the ills of the wild stocks. That would be ridiculous; there are many factors affecting the abundance of wild stocks. Within NASCO we are addressing a wide range of these and there have already been major sacrifices by those exploiting the resource, including complete closure of fisheries. It would, however, be equally ridiculous for the aquaculture industry to claim that there is no adverse impact from their industry on wild stocks and the environment in which they live. Until recently, in some countries, that has been the case.

Second, I believe that most countries or provinces that have aquaculture wish to encourage and promote it. Aquaculture brings jobs to remote areas, where other forms of employment are hard to come by. So a regulatory framework also needs to be there to ensure
sustainability—which after all means future prosperity—and, unless there are special problems, not to disadvantage the domestic industry as it needs to compete internationally. The problem is that the industry has developed so rapidly that legislation has not been able to keep up. Some aspects are left to the industry to regulate. We must have tough, fair standards. If not, at the end of the day, no one will be safe, not the government, the employee at the fish farm, the consumer, or wild fish if salmon aquaculture is allowed to be conducted in an unsustainable way. To use my car analogy, it might save car manufacturers costs if there were no standards for exhaust emissions, tire and brake quality, etc., but it would not produce a sustainable car industry.

Third, I believe that the international bodies concerned may need to get involved to ensure a level playing field for aquaculture. This is terribly important because salmon farmers work in a very competitive environment. Recently, at a meeting with the industry in London, the Irish salmon farming industry, for example, which is relatively small compared to the Norwegian and Scottish industries, made clear their concerns. If, for example, the Irish authorities made tougher regulations for aquaculture than the Norwegian authorities, then the Irish industry would quickly be priced out of the market. International bodies such as NASCO can provide the forum for international agreements on, for example, the detailed codes of practice for aquaculture, use of sterile fish, use of transgenic fish, and codes for introduction and transfers, etc. In NASCO, we have agreements on all of these issues, which should mean that the errors of the past are not repeated. We must be prepared to deliver a stable and level playing field to the industry, and this can only be done internationally.

Fourth, we need a lot more knowledge on how to conduct aquaculture in a sustainable way. Let me list just a few obvious areas of research and development that will be important:

- improved cage design to ensure 100% containment and ways to monitor performance
- the role of sterile salmon in aquaculture
- the role of transgenic salmon in aquaculture
- improvements to treatments for diseases and parasites.

Others at this meeting have listed a number of other important areas for research.

Fifth, I believe that the two great elements of salmon aquaculture and wild stocks need to overcome their hostilities and make a fresh start. At a recent meeting in London between the two sides from the North Atlantic, we came to the conclusion that, in a sense, we are joined at the hip. After quite a lot of heat and confrontation, we have tried to make a fresh start. What I mean by this is that we have looked into the abyss, decided that there is no future merely in confrontation and have, in fact, agreed in principle to a new declaration of principles governing our relationship. In that declaration the industry recognizes the need to protect the wild stocks and, indeed, agrees to work with us to help to protect them. The wild fish side, if I can call it that, recognizes the importance of aquaculture and the valuable contributions it can make. The declaration lists the governing principles that will guide our new relationship.

The ink is hardly dry on this and NASCO Council has yet to see it and endorse it but I do think it will prove to be a confidence-building measure that augurs well for the future. We went a step further than this and agreed to set up a small group, made up of the aquaculture industry experts and the regulatory authorities, to study the containment issue. They will consider how to develop internationally acceptable guidelines for containment. They will look at the details, at what sort of target we should aim for, at how we can assess whether or not we are hitting this target, i.e. monitoring performance, and so on. If that works well, we will take on other issues such as codes on disease, parasites, etc. So I see a necessity for drawing together these two sides which, although we may not have thought so in the past, are inextricably linked. We need to become much more closely involved, share aspirations and work as a team so that we can achieve our aims: a classic “win-win” scenario. I have to admit to difficulties in the past but I feel somewhat optimistic about a fresh start.

Finally, I want to refer briefly to the Precautionary Approach. It has to be said that most fisheries management has failed. We see many examples of overexploited stocks, changes due to natural causes, loss of habitat, etc. Some of these failures have been
due to a tendency by politicians and others to ignore advice that they do not like. That is no longer sustainable behaviour. The Precautionary Approach is now being introduced into the work of international fisheries bodies. Basically, it starts from the conviction that, in future, lack of scientific evidence shall not be used as an excuse for avoiding action.

In our case, we have also defined some “tests” of whether any action is precautionary, for example:

- Have the needs of future generations been considered?
- Will changes that are potentially irreversible be avoided?
- Have undesirable outcomes and measures that will avoid or correct them been identified?
- Have steps been taken to ensure that corrective measures can be initiated without delay?
- Has priority been given to conserving the productive capacity of the resource?
- Has there been an appropriate placement of the burden of proof?

So you can see that it is a complete change of philosophy. Some might say that the Precautionary Approach is just the use of common sense. I would not disagree, but we have to define common sense. We need to shift the burden of proof. What I mean by this is that it should not just be assumed that a proposal, for example, to make changes in use of the coastal area is safe. It would be precautionary to assume that it is not safe until the burden of proof has been appropriately placed and the necessary experimentation has been done. It would, however, be going too far to ban all activity that carried the slightest risk. Otherwise no one would ever cross the street. What we need is something a little more sophisticated. We need to appreciate the uncertainty surrounding the scientific advice that we get. We then need to consider the risks associated with various possible actions. And when we come to decide on a management action, whether it be for fisheries regulation or regulation of the aquaculture industry, we need to be able to ensure that such action passes the precautionary test. The adoption of this approach will have profound implications for the way we manage wild fish and aquaculture interactions and will involve longer-term thinking, protecting the rights of future generations.

If we get it wrong we will have the shame of being the generation that irreversibly changed existing wild stocks. So there are many challenges here, and not much time. The Atlantic and the Pacific interests can learn much from each other. I have no doubt that it will be difficult and that sacrifices will have to be made. We will have to change our ‘mind-set’. Nevertheless, we have to make a start, and I do hope that, with the kind of steps that I have tried to outline today, we may still be able to achieve the “win-win” that we all want.

The Precautionary Approach Flow Chart

**Presented by Malcolm Windsor following the Think Tank Session**

International bodies have come to the conclusion that they have to use the precautionary approach. We are no different at NASCO. This is the process that we have agreed to. We start by asking the basic question: Is the information on which your conservation and management measures are based uncertain, unreliable or inadequate? Clearly, there are some areas of endeavour which don’t need the precautionary approach; for example, fairly precise physics and chemistry—I imagine you can land a rocket on the moon with pretty good accuracy; you know everything about it; you know the way the atmosphere behaves, the pressure in the gas of the rocket and how much energy it gives you. In nature, it is possible that we might have a situation where we know practically everything; for example, a river where you know how many fish went in and how many fish went out, the environmental conditions, and essentially everything about it. In this case, you don’t need to apply the precautionary approach—you simply do what you need to do to manage it—it is very obvious. However, in most cases the information is uncertain, unreliable or inadequate and if this is the situation then we say that we must err on the side of caution (see Table 7).

There are seven questions which we apply:

1. Have the needs of future generations been considered?
2. Will changes that are not potentially reversible be avoided?
3. Have undesirable outcomes and measures that will avoid or correct them been identified?
4. Can corrective measures be initiated without delay?
5. Will the corrective measures achieve their purpose promptly?
6. Has priority been given to conserving the productive capacity of the resource?
7. Has there been an appropriate placement of the burden of proof?

The message this morning from our group (Think Tank — Genetics Interaction breakout group) says that the burden of proof in aquaculture should be placed on the producers. Our NASCO agreement doesn’t actually say that—instead it says the process should be responsible for the burden of proof—that could mean a combination of the producers, the government, the universities and others. We say that we should be prepared to justify what we do by these questions. If then we are challenged we should be able to say, “Yes we thought about irreversible change and we will take care of it in this way (the precautionary approach).” But this doesn’t mean we can just go home and say “well we have done it”. We would have to gather the relative scientific information. We would want to be landing at the point on the flow chart where we do have reliable information. In terms of the science needed, although some people think it is not required, we (NASCO) think you actually need more of it. The process should require that you continue to gather relevant scientific information and monitor whatever you are doing. Then you are consistent with the precautionary approach.

In NASCO to date, we have agreed to these definitions. What we have not done yet is to get down to the nitty-gritty and determine how to implement this. In the near future we will be trying to sit down with the various countries that belong to NASCO and examine how to apply this approach to fisheries management and what it may mean for aquaculture. In other words we have not yet implemented the approach, but we have agreed on the approach described in Table 7.

---

**Speaking for the Salmon Workshop series supported by**

Continuing Studies in Science at Simon Fraser University  
8888 University Drive, Burnaby, BC V5A 1S6  
Telephone (604) 291-5466  Fax (604) 291-3851  
Website: http://www.sfu.ca/cstudies/science

**Speaking for the Salmon Series include**

- Speaking for the Salmon: Fisheries and Oceans “Wild Salmon Policy” *(May 2000)*
- Speaking for the Salmon: Aquaculture and the Protection of Wild Salmon *(March 2000)*
- Speaking for the Salmon: Pacific Salmon: Status of Stocks and Habitat *(June 1999)*
- Speaking for the Salmon: Stock Selective Salmon Harvesting *(May 1998)*
- Speaking for the Salmon Workshop Proceedings *(January 1998)*
Table 7. Precautionary approach to salmon conservation, management and exploitation

Is the information on which conservation and management measures are to be based uncertain, unreliable or inadequate?

No

Develop measures based on this information. No need to apply a Precautionary Approach

Yes

Apply a Precautionary Approach. Err on the side of caution in developing measures

Have the needs of future generations been considered?

Will changes that are not potentially reversible be avoided?

Have undesirable outcomes and measures that will avoid or correct them been identified?

Can corrective measures be initiated without delay?

Will the corrective measures achieve their purpose promptly?

Has priority been given to conserving the productive capacity of the resource?

Has there been an appropriate placement of the burden of proof?

Measures are consistent with a Precautionary Approach

Monitor implementation and effectiveness of measures

Continue to gather relevant scientific information

Yes

No