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Disease and parasite implications of the coexistence of wild and cultured Atlantic salmon populations

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The practical difficulties in measuring the prevalence, incidence, and pathogenicity of diseases in wild Atlantic salmon populations cause serious problems in determining the possible implications of disease. Limited research has been undertaken on wild salmon disease associated with environmental effects of fish farming, or with the disease implications of possible changes to the genetic make-up of wild salmonid stocks as a consequence of farmed fish escaping. To date, no significant disease problems have been reported linked to these aspects. The greatest disease risk to both farmed and wild stocks is through the introduction of exotic pathogens into areas where local stocks have no innate resistance. National and international legislative controls are in existence to reduce this risk, but these have not afforded total protection. Serious epizootics of furunculosis and *Gyrodactylus salaris* in stocks of salmon indicate the severe consequences of new disease outbreaks linked to movements of live fish for farming or restocking purposes. A wide range of infectious agents has been recorded from wild salmon and some of these (and from other species of wild fish) provide the primary source of infection leading to disease problems in fish farms. Although disease control has markedly improved in fish farms in recent years, problems still remain with some diseases, notably sea lice. It is likely that the lice population and other diseases in farms contribute infection to local wild stocks, but the extent and consequences of this have not been quantified.

Key words: disease, farmed, salmon, trout, wild.

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Introduction

Many of man's activities impact on his surrounding environment. Some effects may be subtle, others more obvious, some may be tolerated, others not. When a fish farm is set up in an area previously without fish farm activity, it is almost inevitable that there will be consequences, possibly involving some or all aspects of the visual, the physical, and the biological characteristics of the locality (Wallace, 1993). Biological aspects may well include disease and it is understandable that the actual and potential consequences of the development of a new activity will be subject to close scrutiny. In relation to disease, the questions raised which are particularly important include: Where do changes occur? Are they significantly damaging? Can they be prevented or avoided? Is the balance between benefit and damage acceptable or unacceptable?

All of these questions are difficult to answer, but it is in the last-mentioned area where the greatest problems lie, particularly as the view of acceptability changes depending on the perspective of who asks the question. Although science may be able to detect and measure some of the changes, it is often a political question as to whether or not these are within acceptable limits. There has been difficulty in addressing these questions with total impartiality, particularly in the fish disease field.

The objective of this paper is to consider the main factors in the relationships between farmed and wild populations of Atlantic salmon (*Salmo salar* L.) which can be identified as possibly leading to changes in the risk from disease. It is necessary to recognize that the causes of diseases, and of variations in the levels of diseases, are typically multifactorial, complex and interactive in nature. Conclusive cause–effect relationships are, therefore, normally difficult to determine. There has been concern for several years about whether diseases associated with fish farming may affect wild salmonid populations, and Hastein and Lindstad (1991) listed the diseases considered to be of most relevance. It is not intended here to reconsider this list, but instead this review will focus on the underlying mechanisms of

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potential or actual interaction, when possible using practical experiences with particular diseases as illustrative examples. An excellent recent review of the interrelationships between disease and fish is provided by Bernoth *et al.* (1997), and although this concentrated on furunculosis, the wider principles relevant to other fish diseases were comprehensively dealt with.

Practical considerations in disease assessment in wild salmonid populations

In fish farms, the occurrence of disease is usually obvious, as sick and dead fish are readily seen and the whole population can be monitored. The effects of disease can be assessed by measuring reduction in growth, loss of condition or, in extreme cases, through an increase in the mortality rate. In contrast, in wild salmonid populations, there are serious practical difficulties both in detecting significant diseases and in measuring any impact of these on the fish population. The occurrence of an infection in an individual fish host or population does not necessarily indicate a disease outbreak and not all infectious agents are considered to be a potentially serious threat. The questions may be asked:

- whether some infections which are easily found are common because they have little effect, persist for a long period, and accumulate with time, or alternatively because the rate of infection is high because the disease is occurring as an epizootic (an epidemic in human terms)?
- whether diseases which are rare are seldom found because infected fish rapidly die or because the rate of infection is low?

Such questions can only be answered through a knowledge of:

- the pathogenicity of the infection (whether or not the normal functioning of the fish is affected and the chances of survival of the fish are reduced),
- the prevalence of the infection (the level of infection found at any time in the population) and
- the incidence of the infection (the rate of new infection over a specified period of time).

Pathogenicity

A direct indication of the pathogenicity of an infection can be obtained from observations on any associated pathology or the behaviour of a pathogen in the fish farm environment or experimental challenges. However, the use of these indices is subject to dangers of misinterpretation unless fully investigated. While farmed Atlantic salmon may die with few pathological signs of disease with some infections such as acute furunculosis (Munro and Hastings, 1993), other infections may cause the destruction of complete organs such as the pancreas in Pancreas Disease, without causing significant mortality levels (McVicar, 1987).

Prevalence

The problems associated with obtaining fully representative samples of diseased and healthy individuals in a wild salmonid population lead to difficulties in collecting accurate data on the prevalence of disease. In contrast to cage or tank situations, sick fish in the natural environment that show any abnormal behaviour are likely to be rapidly removed from the area by predators and any random samples of fish taken will almost inevitably show only healthy animals, those with non-pathogenic infection levels or those with benign types of disease. Sampling even to initially detect significant diseases in wild salmonid populations, should thus be highly targeted on abnormally behaving, moribund, or newly dead fish. Dying and newly dead kelts make good subjects for disease studies as they frequently reflect the indigenous diseases of an area, and some of these diseases may actually contribute to the death of the fish. For the sea phase of the salmon life cycle there are particularly severe difficulties in obtaining suitable samples for population disease analysis.

In exceptional cases, high prevalence levels of diseases may be found during epizootics, but epidemiological studies of diseases in animal populations show that epidemics are normally spectacular and short-lived events (Anderson and May, 1978). High levels of a pathogen may also persist if reservoirs of infection reside outside the susceptible population, for example in another host where pathogenicity is low, or in another population of the same species, such as within a fish farm stock.

Incidence

A measurement of the incidence (or rate of new infection) may be obtained by either frequent sequential sampling of the host population, which is highly resource-demanding, or through the use of a time-dependent marker of a stage in the course of the infection. Not surprisingly, the former has not found much favour, while the latter has not yet been applied to salmon diseases. The latter method was successfully used to calculate the mortality rate due to *Ichthyophonus* infection in a wild population of plaice (*Pleuronectes platessa*) and employed the time taken to develop an antibody response (McVicar, 1990). Such an approach could be applicable to some salmon diseases, such as infestation by sea lice (*Lepeophtheirus salmonis*), where knowledge of the rate of development of different stages can be determined and the relative proportions of these observed within a sampled population.

Determinant factors of variations in salmon disease

Disease seldom has a single cause and multifactorial aetiology is one of the central axioms of modern epidemiology (Smith, 1997a). It is well documented throughout the scientific literature that the occurrence of disease is the result of the interaction of aspects of the environment, the host, and the infectious agent(s). A long stability in the host-infective agent interaction tends to select for a high degree of adaptation between the two organisms in all aspects of their biology and, not surprisingly, it is relatively uncommon for infections in the natural environment to cause serious overt disease. However, the potential exists for some previously benign or innocuous infectious agents to produce disease if there are any alterations to one (or more than one) of the pathogen, host, or environment factors relevant to wild salmon populations. Such changes may be due to natural causes or be man-induced-associated, for example, with the presence of fish farming. The high degree of interaction between all of the disease determinant factors makes it difficult to identify or quantify the contribution being made by any one factor to any occurrence of disease. Complex mathematical models have been constructed for some diseases (including some in fish) to attempt to achieve this (Begg, 1994), but the success of such models depends on an input of high quality data. Much of the information currently available with respect to disease in wild salmon is fragmentary, on individual fish or small numbers of fish, generally not quantified and does not permit such in-depth analysis.

Environment

The occurrence and spread of infectious disease in farmed fish is due largely to the high densities at which fish are held, and the role which environmental quality plays in fish health in aquaculture is significant. Obvious variations in stock performance and health between different fish farm sites, even within the one company management regime, indicate a strong influence of the local environment on disease. The stresses associated with aquaculture practices can predispose the fish to a wide variety of diseases and it is well established that the occurrence and level of diseases in a farm are often closely linked to holding conditions in tanks or cages (Hastein and Lindstad, 1991). Pickering (1997) provided a review of the mechanisms through which stress may operate within fish farms and its role in the occurrence of disease. To promote good health in farm stocks, it is in the self-interest of fish farmers to maintain good environmental conditions in their farms and in the surrounding areas. In recent years, improved management practices, particularly in conjunction with the use of improved vaccines, have led to greatly reduced levels of disease and improved survival in fish farms in all of the main salmon farming areas (Midtyling, 1997).

Similarly, there is considerable evidence that disease levels in wild fish populations are influenced by natural and man-induced alterations in the environment. If adverse environmental conditions extended from a fish farm environment to the surrounding area, it is conceivable that there could be disease implications for wild fish populations. However, detectable environmental effects arising from farm activity are generally limited to the area in the immediate vicinity of the farm (Lumb, 1989). There has been limited research on possible changes in diseases in local salmon populations associated with fish farm effluents. No significant disease effects have been noted but, because of the complexity of the relationship between environmental quality and fish disease, there cannot be much optimism about easily obtaining results in this subject area. However, any pollution from salmon farming is most likely to affect the farmed fish first, and thus become self-limiting (Wallace, 1993).

Host factors

Genetic differences are known to exist in the susceptibility of different salmonid stocks to disease (Mackie *et al.*, 1935). The implications are well enough understood and are sufficiently important for the genetic selection programmes of most fish farming industries to include resistance to important diseases as one of the main desirable characteristics to be selected for (Gjedrem and Aulstad, 1974; Olivier *et al.*, 1988; Gjedrem, 1997). Alterations to the genetic integrity of local wild stocks arising from the escape of farmed fish may have disease implications as there are several examples of different responses to diseases linked to salmon strains. Possibly the best known is the difference in susceptibility of Baltic and North Atlantic races of salmon to *Gyrodactylus salaris*, which has now been well documented and experimentally demonstrated (Bakke and MacKenzie, 1993).

Such differences most probably partly reflect whether or not the infectious agent and pathogen have had a long association together and have evolved a level of tolerance of each other. The absence of studies specifically on disease implications arising from alterations of the genetic make-up of local wild salmonid stocks as a consequence of escaped farmed fish changing local genetic characteristics makes meaningful conclusions impossible. Although there are no recorded cases of serious diseases occurring as a result of genetic changes in local salmon stocks, the potential must be considered to exist. For example, caution should be exercised regarding the possibility of reducing the innate resistance pattern of Baltic salmon to *Gyrodactylus salaris* described by Bakke and MacKenzie (1993) through the introduction of breeding populations of non-Baltic strains of Atlantic salmon into the area.

Disease factors

In relation to the disease implications of the coexistence of wild and cultured populations of salmon, the key questions to be raised from the point of view of wild stocks are:

- What is the natural occurrence of disease in the wild salmon population?
- Which infections cause a significant disease risk?
- Are important new diseases occurring in farmed fish?
- Has the pattern of existing diseases been altered by the presence of fish farming?

Natural occurrence of diseases in wild salmon

Before it can be determined if there are changes to infection and disease in wild populations of salmon due to the presence of fish farming, information is required on their occurrence prior to farm development. Challenge with a wide range of infectious agents is a natural phenomenon for most living organisms and over 80 different infectious conditions have been listed for Atlantic salmon (ICES, 1992), although few comprehensive and systematic disease studies have been undertaken. The apparent patchiness in the distribution of many infections is as likely to be a consequence of the locality in which research has been conducted as it is to be a true difference in the occurrence of infection in salmon stocks. For transmissible diseases with direct life cycles, the distribution of naturally occurring diseases in wild salmon can be expected to represent both the host specificity and transmission ability of the infectious agent within the freshwater and marine environments and also the extent of overlap or mixing of local salmon stocks. The situation becomes more complicated when alternate, intermediate, or transport hosts are involved as the distribution and movement of these will also contribute to the occurrence of infectious organisms. Differences in the pattern of infection have been used to delineate different high seas populations of Pacific salmonids and also to distinguish salmon stocks on a local level (Margolis, 1983). Similar variations have not yet been detected in Atlantic salmon.

Diseases recognized as causing significant risk

While most infectious agents carry the inherent risk that they could cause problems to a host, some show greater potential for causing damage than others. Much has been learned about the mechanisms of pathogenicity with furunculosis (Bernoth *et al.*, 1997), but, in general, for most fish diseases there is an overall lack of good understanding as to why a particular organism may show a high level of pathogenicity and, under the same conditions, another closely related organism may not. It is, therefore, difficult to predict accurately which new infectious agents will be dangerous either to farmed or to wild fish populations. Experience with particular diseases usually determines which infectious agents are listed in control regulations and there is increasingly close agreement being shown among the lists of controlled diseases in the various national and international regulations. The different categories used in these lists are based on several features of the diseases, including their current distribution, their potential pathogenicity/ economic significance to both wild and farmed stocks, and the opportunities open for control.

Introduction of new diseases

There are many examples in human and veterinary medicine where massive epidemics of disease have occurred shortly after first contact was made with an infectious agent that is new to that population (Mims, 1987). Not all newly introduced infective agents are highly pathogenic, naturally occurring host defense reactions against a wide range of pathogens exists and cross-protection may be conferred from exposure to indigenous related organisms. However, mechanisms of resistance or tolerance often only develop through extended exposure to the new pathogen. Until this occurs, serious damage may be inflicted on the host population. Salmon populations, whether in farms or in the wild, are potentially vulnerable and run a high risk of epidemic outbreaks when they first come into contact with a new pathogen. Considerable emphasis is therefore placed on preventing the introduction of important diseases to fish stocks which have had no previous contact with them. Exposure to new pathogens can occur either through the translocation of salmon outside their normal geographic range or through the introduction of exotic pathogens from other areas. The levels of understanding and concerns of the serious problems actually and potentially occurring as a consequence of stock or disease movements have led to the development of national and international codes of practice and legislation.

Movement of salmon outside their normal range

Experiences of disease consequences associated with moving Atlantic salmon outside their normal geographical range illustrate some of the incipient dangers if these diseases were ever introduced into salmon populations. Netpen liver disease in Atlantic salmon reared on the west coast of Canada (Kent, 1990) may cause mortality of up to 65% and is currently believed to be non-infectious in nature and to be caused by an algal toxin accumulating in invertebrates or forage fish in the marine environment. Major losses due to *Piscirickettsis salmonis* infection occur in Atlantic salmon reared in Chile (Lannan and Fryer, 1993), while the protozoan

Paramoeba pemaquidensis causes significant mortalities among Atlantic salmon reared in sea water in Tasmania (Roubal *et al.*, 1989). Atlantic salmon have proved to be particularly vulnerable to these diseases but so far none of these diseases have been detected in the normal range of Atlantic salmon. As indicated above with respect to *Gyrodactylus salaris*, similar risks may be associated with the use of non-local stocks in fish farming or for restocking within the normal range of *Salmo salar*, particularly if there is limited mixing of stocks.

Introduction of exotic pathogens

Probably the greatest danger to wild (and farmed) populations of Atlantic salmon from disease lies in the risk of introducing new pathogens. It is unrealistic, and likely to be impossible under international laws such as the General Agreement on Tarriff and Trade (GATT), EU, and other legislation, to ban all movements of live fish or trade in fresh fish products. A managed level of risk generally has to be accepted. For decisions possibly restricting trade, there is an increasing requirement to use Import Risk Analysis techniques to decide whether or not there is an acceptable risk associated with a particular activity. In such analyses, the risk of a disease agent passing through each step in the chain of events in the importation process should be assessed, the components presenting greatest risk identified (and if possible the individual elements of risk quantified) and the areas identified where there is the best opportunity to influence (reduce) the risks. In the case of fish diseases, the main areas of risk of translocating disease can be identified as being associated with:

- the occurrence and level of the pathogen in the source material (fish population) in the area of origin
- the occurrence and level of the infection in the parts of the commodity being moved
- the survival of the pathogen through the transportation (or processing procedures if appropriate) to reach the new area in a viable and infectious state and in sufficient concentrations to be able to initiate an infection
- the distribution and handling of the commodity after importation and the associated opportunity for the pathogen to reach a susceptible new host or hosts.

Some of these parameters can be directly addressed and, when considered to be necessary, constaints involving legislation and codes of practice may be put into place to significantly reduce the risks. For fish diseases in general, there are inadequate data available with which to construct proper quantitative risk analysis. Accordingly, qualitative risk analysis in one form or another is implemented. This can take into account not only the existing scientific knowledge about the disease but also past experiences with the distribution, spread, and pathogenicity of the disease in the fish farming and wild fish fields.

Potentially important routes of introduction of fish disease include:

- infection with live fish being used for restocking, ornamental, or fish farming purposes
- viable infectious agents on or in imported fish carcasses or parts of fish
- viable infectious agents on inanimate materials.

(a) Disease spread with live fish. It is inevitable that fish populations reflect the range of susceptible infections found in their surrounding environment, and although the majority of fish in a population may frequently show no evidence of the agent, there is a high risk that at least some individuals will harbour a particular type of infection. Excluding the exceptional cases where fish are reared in pathogen-free waters, it can be assumed there is a high probability that sooner or later locally occurring pathogens will be translocated whenever live fish are freely moved from one locality to another. This risk has been well understood since at least the turn of this century. The recognition of high risk of disease spread through the translocation of live fish for fish farming and restocking purposes has led to several national and international codes of practice and legislation, with the control on movements of live fish being a central principle. As regulations which place restrictions on the trade of live fish are in conflict with a general move towards facilitating trade between countries, internationally acceptable testing programmes demonstrating the absence of specified diseases have to be established and maintained by official services.

However, even with control legislation it is difficult to achieve absolute protection from diseases being introduced. In recent years, the greatly improved communication links, the frequency of travel by people who may come into contact with fish diseases, the demands of trade and the relaxation of trade barriers have all contributed to an increased risk of introducing exotic fish diseases. Two examples from Norway when such preventative measures have failed, probably as a result of the movement of live fish for farming or restocking, illustrate some of the dangers. Hastein and Lindstad (1991) summarized information on the spread of furunculosis from 1985 into some 20 Norwegian rivers after the importation of allegedly latent infected Atlantic salmon smolts from Scotland. The appearance and spread of *Gyrodactylus salaris* from 1975 onwards was directly linked to movements of live fish from infected hatcheries (Johnsen and Jensen, 1991). Legislative control of fish disease is not static and improvements designed to further reduce risks are continually sought and taken into policy consideration whenever significant risk areas are identified.

(b) Viable disease on or in imported fish carcasses or parts of fish. Given appropriate conditions of temperature and humidity, many fish pathogens can survive in an infectious state for prolonged periods associated with fish carcasses and fish products. Consequently, when these commodities are moved between areas, there are recognizable associated risks of disease transmission, although the level of these risks is always likely to be considerably less than with live fish trade. A direct link can be established between the level of risk, the location of the infection in relation to the parts of the fish being imported and the amount of waste material being rejected at the receiving area. Evaluation of dangers to local salmonid stocks arising from the importation of salmonid carcasses from continental Europe, particularly from areas infected with the viral diseases Viral Haemorrhagic Septicaemia (VHS) and Infectious Haematopoietic Necrosis (IHN) indicated significant risks associated with ungutted products and legislation was introduced controlling the export of such material into the UK (Council Directive 91/67/EEC). Similarly, the EU recognized the dangers associated with Infectious Salmon Anaemia (ISA) in farmed Norwegian salmon, a disease currently absent from the EU, and introduced regulations (Commission Decision 93/144/EEC) requiring evisceration of farmed Norwegian salmon prior to export to the EU. Similar import risk analyses are being conducted by several countries (such as Australia and New Zealand) addressing dangers associated with the importation of both farmed and wild salmonid products.

(c) Viable disease on inanimate materials. In recognition of the risk of disease transfer on equipment, it is recognized practice for Scottish Office, Agriculture, Environment and Fisheries Department (SOAEFD) Fish Health Inspectors (and others in similar circumstances) to disinfect boots, waterproof clothing and all equipment which have been in contact with water or fish between inspection visits on farms or wild fisheries. When restrictions are put in place, a balance has to be reached between the level of risks involved, the possible consequences from the disease occurring and the feasibility of enforcement. With its isolated geographic position, the fear of introducing a range of new salmon diseases, and its limited number of entry ports to control, Iceland introduced legislation (Freshwater Fisheries Law, 1970) prohibiting the use of fishing equipment which has been used while angling abroad, unless the equipment has been disinfected. Although highly desirable as good practice, such tight restrictions are not generally operated in other salmon fishing countries. It is recognized that particular care should be taken with *Gyrodactylus salaris*. An epidemic may be initiated by a single parasite and the consequences to previously uninfected salmon stocks are devastating (Johnsen and Jensen, 1991). The parasite is a notifiable disease in the UK, subject to controls under the Diseases of Fish Acts, 1937, 1983. In EC legislation, *G. salaris* is currently a List III category disease, but with the EC recognition of GB, Northern Ireland, the Isle of Man, Guernsey and Ireland as being free of the parasite (Commission Decision 96/490/EC), additional restrictions regarding trade in live fish have been introduced to protect salmon stocks in these areas. As the parasite has the ability to survive for several days away from the fish host in damp conditions such as plastic bags, wet angling equipment, and other dead fish (such as bait fish), caution has to be exercised to avoid transfer of live parasites on such equipment. Advisory leaflets have been introduced in both Finland and in Scotland warning fishery owners and anglers of these dangers and providing advice on how to reduce the risk of translocating live parasites. It is hoped that through proper vigilance, further spread of this dangerous parasite in salmon stocks will be avoided.

Alteration of the pattern of existing diseases

It is well established that fish farms using water frequented by wild fish are likely to become infected with locally occurring diseases and that overall this is the major source of disease in salmonid farming industries in the North Atlantic area (Munro and Hastings, 1993). Similarly, diseases occurring in fish farms may be returned to the wild in farm effluent water and with escaped fish. Consequently, there is the potential for a two-way disease interaction between farmed and wild salmonids.

From the wild salmon point of view, the important questions which can be raised regarding occurrence of disease in farm populations are:

- Does the farm disease alter the characteristics of the same disease in wild populations?
- Does the farm provide a focus or enhancement of disease to wild populations?

(a) Disease characteristics. There are obvious differences in the environmental and biological features of the rearing conditions in fish farms compared to those encountered by local wild stocks of fish. The associated different selective pressures can lead to changes in the characteristic of the infectious agents in the farms and probably the most obvious has been the development of widespread resistance of many bacterial pathogens to antibiotics being used on fish farms. This resistance became a serious problem in salmon farms in the 1980s, particularly with the vibrios such as *V. salmonicida* (cold-water vibriosis) in Norway and *Aeromonas salmonicida* (furunculosis) in all salmon farming areas

(Hjeltnes *et al.*, 1987; Aoki, 1997). There is no available data on such in-farm changes to pathogens (or the possibility of other changes such as to pathogenicity) spreading and persisting with significant effect in wild salmon populations. However, this lack of evidence may at least be partly due to the lack of extensive scientific study in this area. Alternatively, it may be speculated that when infectious agents transfer to wild stocks of salmon, the removal of the selective pressures on disease in the farm and the replacement of these by a different set of pressures in the wild, may lead to the reduction or loss of any farm-associated disease traits.

(b) Changes in the local level of disease. Possibly the most controversial topic in considering disease interactions between farmed and wild populations of salmon is the role which disease from farms may have in focusing or enhancing the level of indigenous disease. Undoubtedly, the environment and the crowding of fish within fish farms is conducive to the spread of infectious diseases (Hastein and Lindstad, 1991) and, although it is in the farmers' interests to control this as far as possible, serious epizootics of disease have been a major problem. An example of a disease transmitted from a farm to local wild stocks is the spread of Infectious Pancreatic Necrosis (IPN) virus from a heavily infected freshwater rainbow trout farm into neighbouring stocks of wild fish, including salmon, up to 7 km away (Munro *et al.*, 1976). In this case the local populations of wild salmon parr remained abundant, there was no evidence of clinical disease in infected wild fish caught and the disease subsequently disappeared after the farm closed.

Furunculosis became a severe problem in farmed Atlantic salmon during the latter part of the 1980s. In Scotland, over 40% of smolts introduced into sea farms in 1989 died before harvest, mainly from furunculosis (Munro and Gauld, 1996). Similar events have been noted with salmon farming in Norway and Ireland (Hastein and Lindstad, 1991; Smith, 1997b). It can be concluded that during that period, high levels of *A. salmonicida* were being released into the surrounding environment. It has proved to be almost impossible to isolate *A. salmonicida* from water in fish farms with epizootic furunculosis although there is experimental evidence for lateral transmission of infection through sea water and the persistence of the bacterium after removal of carrier fish (Enger, 1997). With the risk of spread of the bacterium up to a radius of 10 km from cage sites (Turrell and Munro, 1988), it is highly probable that local stocks of wild fish were being regularly exposed to the infection during that period. It may be co-incidental that this period was when sea trout stocks on the west of Scotland and in the west of Ireland were experiencing their greatest population decline (Whelan, 1993; Walker, 1994). Cipriano and Hartwell (1986) showed that mortality due to furunculosis in farms was greater in *Salmo trutta* than in some other salmonids, such as rainbow trout and brook trout, under the same conditions. However, no direct evidence is available of furunculosis epidemics in wild fish in any of the salmon farming areas during the late 1980s. The epidemics described in wild salmonids in the UK in the early part of this century were highly visible events (Mackie *et al.*, 1935), but it is possible that, with an increased tolerance developed since then, such infections may not now be so apparent. *A. salmonicida* is considered to be endemic in British rivers and the occurrence of obvious furunculosis disease in Scottish rivers is currently rare, and normally associated with high stress situations such as low water levels in rivers and high temperatures. Taking into account the difficulty in observing diseased wild fish, particularly in the sea, it is possible that an epidemic could have gone unnoticed in the sea in the mid to late 1980s. McArdle *et al.* (1993) suggested that furunculosis may have had a role in the collapse in sea trout numbers in some rivers in Ireland in 1989 and 1990. However, as was pointed out by Munro and Hastings (1993), the record of the major furunculosis outbreak in the UK in the early part of this century did not suggest that losses were ever sufficient to depress population numbers overall. Currently, with the introduction of efficacious vaccines and other management procedures, the level of this disease has been markedly reduced in all salmon farming areas, with currently over 90% of Scottish farmed salmon surviving to harvest (Munro and Gauld, 1996).

Bacterial kidney disease (BKD), caused by *Renibacterium salmoninarum*, is a serious infection of cultured and wild salmonids occurring wherever wild or cultured salmonids occur (Evelyn, 1993). It is capable of vertical transmission via the egg as well as horizontal transmission from fish to fish. The ability of *R. salmoninarum* to survive and multiply within fish cells is thought to be a principal reason for the difficulty in controlling BKD. Consequently, in serious farm epidemics, it is normal for stocks to be killed and there are strict regulations in force in several countries regarding movement of infected stocks and their use for breeding. All of these factors, combined with the widespread distribution of the disease in wild salmonid populations, probably make this disease a greater risk to farmed populations than vice versa (Hastein and Lindstad, 1991).

The greatest controversy regarding possible disease interactions between farmed and wild fish currently concerns the sea louse (*Lepeophtheirus salmonis*). With the successful control of furunculosis, the major disease of sea farmed salmon of the 1980s, lice are now considered to be the greatest threat to farmed salmon in all parts of the North Atlantic area. Most marine fish farms are liable to infestation, picked up initially from local wild salmonid stocks. Although this source may persist, the greatest problem arises from the re-infection which often occurs within farm stocks. Heavy levels of infection on farmed salmon may result and if not controlled will cause significant tissue damage and death of the salmon. Although chemotherapy is widely used to remove lice from fish, and management techniques, such as fallowing farm sites to break the disease cycles, are employed by many companies, there is a persistent occurrence of infection in many farms. In the late 1980s, it was suggested, particularly in the west of Ireland, and subsequently in the west of Scotland and Norway, that infection of post-smolt sea trout with lice populations derived from fish farms caused serious disease problems leading to death at sea, the early return of post-smolts to fresh water and the serious decline in the size of the sea trout populations in these areas at that time. There has been a considerable amount of research conducted on this topic, particularly in Ireland but also in Scotland and Norway. However, these efforts did not serve to allay the controversy, and considerable polarization of opinion has developed in the interpretation of available information. Recognizing this continued difficulty, ICES convened a Workshop to summarize available information on the interactions between salmon lice and salmonids, assess the effects of salmon lice on salmonid stocks and, if possible, to reach conclusions on cause–effect relationships. The most important conclusions contained in the report arising from this Workshop (ICES, 1997) are summarized below.

With regard to changes occurring in the populations of salmon, the complexity of the patterns of the decline of stocks throughout the North Atlantic in recent years has made it difficult and contentious to formulate general statements describing the overall situation. For sea trout, long-term decreases in stocks were evident in many areas with an overall problem apparent in survival at sea. Only in the west of Ireland and the north-west of Scotland were sea trout stocks shown to have collapsed. The timing of the decline in sea trout abundance in Scotland and Ireland indicated that the observed changes in salmonid stock levels were probably the result of a complex of interacting factors.

Similarly with regard to changes occurring in the populations of lice, the absence of historic data on lice levels in wild salmonid populations make it impossible to compare levels of lice before and after the development of salmonid farming. Currently, extensive infection with lice of migrating post-smolts and returning salmonids occurs in inshore waters, with the highest levels of infection being in sea areas used for salmonid farming in Ireland, Scotland, and Norway. Early returning sea trout were found to have both high and low levels of lice, mainly of juvenile stages, whereas older sea trout were mainly infected with older stages of lice. There were indications that the pattern of lice infection in trout and salmon post-smolts was different, possibly associated with differences in the migration behaviour of the two salmonids. With Atlantic salmon, infection also occurred in the open sea, with the level of infection and lice population structure in larger salmon reflecting that found in salmon migrating inshore. In salmon farms, no clear spatial or long-term temporal variations could be detected from the limited published data on levels of lice. There were noticeable seasonal and environmental factors influencing farm parasite levels but any ‘‘natural’’ patterns were masked by considerable inter-farm and intra-farm variations, the latter largely reflecting management practices and the use of chemotherapy. Although improvements in farm lice control were generally reported, this had not been quantified except for Ireland. Self-re-infection of farms was common in multi-year class sites, which had led to the increased use of fallowing, use of single year-class and single-bay management strategies. Current lice control methods in salmon farms were generally effective in reducing disease outbreaks, but it was considered likely that there would always be a need for control methods in farms because of the reservoir of infection in the natural environment.

Evidence was presented that heavy lice infection (chalimus or mobile stages) may stress host fish and result in altered behaviour in salmonids (including agitation, ‘‘flashing’’ and the early return of sea trout post-smolts to fresh water). In heavy infections, damage occurred immediately following development of lice to the pre-adult stage and most of the gross pathology and mortality to salmonids was caused by pre-adult and adult lice. It was considered probable that the heavy infections of sea trout with chalimus seen in epizootics leading to early return of post-smolts would lead to increased host mortalities (at the time that the lice developed to pre-adults). The pattern of the infection was similar in sea trout, Atlantic salmon, and Arctic charr. Lice could be lost from fish at all stages of their development. Owing to its host-specificity, *Lepeophtheirus salmonis* was considered unlikely to be involved in disease transmission to or from non-salmonids.

For infection to occur, the infective stages of the parasite and a suitable host have to meet. However, the extent and mechanism of the dispersion of the early lice stages is largely unknown. Pulses of the planktonic stages of lice have been found in the water column, these varying with the tide, photoperiod, time of year, and distance from fish farms. A notable pulse of copepodites has been observed in spring, possibly pre-dating the peak in larval production on a neighbouring farm in a study area. Where these lice originate is uncertain as wild salmonids were scarce inshore at that time. There was no evidence that lice were dispersed by non-salmonid fish species or that lice were present on the infrastructure of fish cages or on fouling organisms or that they over-wintered. No direct evidence was presented for fish farms being a main source of lice infection. The possibility was raised of using genetic differences between lice from farmed and wild fish in

UNRESOLVED QUESTIONS

Observation	Possibility 1	Possibility 2
Lice infections occur in wild salmonid populations.	Current levels are higher than pre-fish farming.	Current levels are not different.
Lice levels are higher in the west of Ireland and west of Scotland than in other areas.	Because of the occurrence of lice in the local farmed salmon populations.	Because of naturally higher lice levels in enclosed sea lochs.
Lice from farms will contribute to lice populations on wild salmonids.	As a major source of lice.	As a minor source of lice.
Lice infections are dangerous to salmonids.	Lice infections are a major factor in salmonid population decline.	Lice infections are not important in salmonid population decline.
Sea trout return early to fresh water with heavy lice infections.	Abnormal behaviour which is induced by lice infection.	Natural behaviour of sea trout in sea water.
Moribund sea trout have heavy infections of lice.	Lice are the primary cause of sickness	Lice secondarily attack fish compromised by other problems.

differentiating between sources of lice and to indicate dispersion patterns. There was a similar paucity of data on the behaviour of salmonid post-smolts. There was some evidence that post-smolt sea trout may exhibit a wide range of movement patterns, including rapid return to fresh water, local residence in the immediate vicinity of river mouths, or more rapid dispersal, all of which may influence the pattern of lice infection.

The dangers of directly linking mathematical associations between different sets of numerical data with cause and effect were stressed, as such correlations may also occur by chance or may be due to both data sets being affected by a common external influencing factor(s). For sea trout, it was noted that there was evidence of a statistically significant relationship in data from most years studied in Ireland (and one year in Scotland) between fish-farming areas and the levels of lice infestations in river estuaries. No significant correlation existed when areas closer than 25 km to farms were considered. Similarly, the data indicated that, while it was possible to show high and low mean lice levels on sea trout at sites close to fish farms, high lice levels were never recorded distant from fish farms in Ireland, Scotland, and Norway. Sea trout stock collapses have occurred in areas in the proximity of salmon farms but have not occurred in all areas where intensive salmon farming is carried out. No sea trout stock collapses have occurred outside farming areas. For Atlantic salmon populations, no similar correlations could be shown as no specific trend associated with return rates to the coast and the presence of intensive aquaculture could be detected.

Owing to the general inadequacy of data available, only limited conclusions on cause–effect relationships were proposed by the Workshop namely:

- that the later development stages of salmon lice significantly and detrimentally affect the physiology of post-smolts and can cause subsequent mortality
- that lice infestation can cause the early return of post-smolt sea trout to fresh water
- that data suggest lice emanating from fish farms may transfer to wild trout populations but this as yet cannot be quantified.

Taking a retrospective look at the discussions and conclusions of the Workshop, it is evident that the problems which existed previously were not resolved. This was largely because the quality of available data prevented firm conclusions being reached on the main questions being asked. Deductions had to be made from data which remained open to different interpretations and polarization of views among the participants still existed. It is, therefore, hardly surprising that similar differences in opinions also exist in the non-scientific community. The main unresolved areas of controversy are tabulated above. The options represent the extremes of interpretation of the generally accepted observations on lice infections in salmonids but, as is commonly found in other fish disease studies, it is unlikely that the true situation will be so clear-cut in either direction. It is probable that the reality will lie somewhere between these extremes.

Conclusions

There are many ways in which the activity of fish farming can potentially have an influence on the disease situation in wild Atlantic salmon populations and there are occasions when this has actually had significant detrimental effects on wild populations. The most notable of these is with the spread of *Gyrodactylus salaris* from the Baltic to western Norway and also the more general spread of furunculosis in several countries early this century and more recently. The greatest danger to salmon stocks is probably associated with the introduction of exotic diseases, but with proper attention to preventative measures and through the imposition of appropriate national and international legislation and codes of practice, this risk should be reduced to acceptably low levels. Despite the concentration of farmed salmon in some areas, there are no documented examples of disease implications to wild fish as a consequence of environmental changes associated with fish farms, but research effort on this topic is low. Local wild stocks of salmonids are the main initial source of infection to farmed salmon. Control of disease outbreaks within farms has markedly improved in recent years, thus reducing any risk of farms being a focus or multiplier of locally occurring diseases, but problems still remain with some diseases, particularly sea lice. It is concluded that lice from salmon farms will contribute to lice populations in wild salmonids, but the extent and consequences of this have not been quantified.

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