Briefing Paper

Impacts of salmon aquaculture on native salmonids fisheries and the aquatic environment

Aquaculture has the potential to be a sustainable source of seafood, which could help to alleviate some of the pressures on the world's oceans. However, the sustainability of current stewardship of fish farms is in question. This is firstly due to the impact of the farms on the surrounding environment, including nutrient enrichment, habitat alteration and damage to wild fish populations (Gross, 1998), and secondly the use of wild fish in fish meal to feed farmed carnivorous fish, such as salmon.

In 1980, commercial fisheries harvesting wild stocks produced 99% of salmon consumed worldwide. By 2003, approximately 60% of salmon were produced in fish farms (FAO, 2005). Salmon are now farmed in 24 countries, with Norway, Chile, Scotland and Canada responsible for 71% of global production. The Atlantic salmon (*Salmo salar*) is the most economically important farmed salmon species, representing 89% of salmon production, with the remainder predominately Chinook salmon (*Oncorhynchus tshawytscha*) and Coho salmon (*Oncorhynchus kisutch)* (FAO, 2005).

The industry has become more technologically advanced, and with it full-time employment at farms has decreased. In Chile, 40% fewer people were employed by the industry in 2000 compared with 1998, due to automation of feeding systems and the use of prefabricated PVC cages (Claude and Oporto, 2000).

Salmon, once a food for the wealthy, is now an everyday commodity available to a far wider range of consumers. However, this abundance, deriving from intensive salmon farming in multiple locations, can come at an environmental cost. This paper focuses on the scientific evidence of the impact of current stewardship of salmon farms on the surrounding environment and, in particular, its effects on wild salmon and sea trout (Annex 1: Atlantic salmon biology). An additional paper will be available shortly reviewing the sustainability of using wild fish in fish meal.

Impacts of salmon farming on wild salmon and the surrounding environment

Salmon aquaculture is certainly not the only threat to wild salmonid populations. Wild Atlantic salmon populations have been in decline throughout their natural range since the early 1970's, thought mainly to be due to reduced oceanic feeding opportunities related to climate change (Friedland and Reddin, 1993). However, there is evidence that the salmon aquaculture industry can impact already weakened wild stocks.

The risks to society from aquaculture, identified in the FAO technical paper (2008) '*Understanding and applying risk analysis in aquaculture'* include:

- Environmental risks; pollutions from feeds, drugs, and chemical wastes, and alteration of water currents and flow patterns
- Biological risks; introduction of invasive alien species and pathogens, and genetic impacts on native stocks
- Social risks; displacement of artisanal fishers, and food safety issues.

A study carried out by Butler and Watt (2003) found compelling evidence that salmon farms could have a serious and sustained detrimental impact on the abundance of wild juvenile salmon, as surveys on 230 sites in 35 rivers revealed rivers with fish farms in their sea lochs had 62-82% and 44-62% lower mean abundances of salmon fry and parr, respectively. The study also found severe collapse of adult Atlantic salmon stocks in 50% of the rivers with farms, where only remnant stocks remained. Ford and Myers (2008) compared marine survival of salmonids (Atlantic salmon, sea trout, pink chum and Coho salmon) in areas with and without fish farms in Scotland, Ireland and Canada. The results showed, on average, that fish farms had a significant negative impact on salmonid populations, typically in the order of a 50% reduction in survival or abundance of salmonids.

The threats that salmonid farms and farmed fish pose to wild fish stocks and the environment, include:

Disease and other parasite transfer

Open system aquaculture entails the transfer of unregulated water supply between wild and captive salmonid populations, which can result in exposure to diseases between both. The high density of fish at fish farms can function as a reservoir for pathogens and diseases, potentially providing an ideal breeding ground and facilitating movement into nearby wild populations (McCallum and Dobson, 1995; Daszak *et al*., 2000). Transmission could also be amplified by escaped fish. In turn, diseases could theoretically be transmitted from wild stocks to the large numbers of farmed fish.

For example:

- ISA is a lethal, highly contagious viral disease spread adult-to-adult in freshwater and seawater (Håstein, 1997). ISA was first discovered in 1984 in the Norwegian salmon fishing industry, and quickly spread to over one hundred farms (Thorud and Djupvik, 1988). Mortality rates associated with ISA during this outbreak varied considerably, from low mortality to some farms losing 80% of the fish stock (Hastein *et al*., 1999). By 1999, it had spread to approximately 10% of all Scottish salmon farms. There is some evidence of the ISA virus in disease in wild salmon parr, juvenile brown trout and sea trout, and eel (Raynard, 2000). The virus is thought to be carried in the mucus, urine and faeces of salmon. Therefore, the high densities in farms create contagious areas for nearby wild salmon.
- Furunculosis, caused by the bacterium *Aeromonas salmonicida*, is one of the most serious infectious diseases of wild and farmed salmonids throughout the world (Ellis, 1997). Furunculosis, which is often fatal, is generally associated with crowded conditions. It was thought to be a disease occurring exclusively in salmonids; however several cases of *Aeromonas salmonicida* infections have been reported in non-salmonids, which have had some form of contact with infected salmonid populations (Bernoth, 1997).

Other viral diseases which have had a significant impact on the European aquaculture industry include; inter alia Infectious Pancreatic Necrosis (IPN), Viral Haemorrhagic Septicaemia (VHS), Pancreas Disease (PD) and Ulcerative Dermal Necrosis (UDN). Movements of fish for public and commercial fish farming have also been linked with the movement of pathogens, for example *Gyrodactylus salaris* in Europe, and whirling diseases in the United States (St-Hilaire *et al*., 2002; Murray *et al*., 2002).

Farmed systems are different from the wild, in that diseased, weaker wild fish are constantly being removed by predators (Mesa *et al*., 1998), lowering the number of new infections likely from each infectious individual (Reno, 1998). This is not the case in aquaculture units, when although good husbandry practice supports the routine removal of moribund stock, this is not always achievable.

As aquaculture continues to expand and diversify, new diseases will continue to emerge, affecting wild and farmed stocks alike. Biosecurity programmes, such as improved operational husbandry, could help mitigate this risk (Murray and Peeler, 2005).

Sea lice

The sea louse (*Lepeophtheirus salmonis*) is a marine parasite of salmonids, which grazes the surface of the fish (Pike and Wadsworth, 2000; Costello, 2006). Despite more than 800 sea lice research publications over the last 30 years, it is estimated that, globally, sea lice cost the aquaculture industry US$480 million a year (Costello, 2009a). Sea lice transfer readily between farmed and wild fish populations (Murray and Peeler, 2005). Open cages allow planktonic larvae to disperse from dense agglomerations of adult lice on farmed salmon into the surrounding waters (Costello *et al*., 1996). This can be detrimental to migrating fish populations, either young smolts leaving freshwaters for coastal areas and the open ocean, or mature fish returning to rivers to spawn.

When present in large numbers, pre-adult and adult lice can cause severe damage whilst feeding on hosts (Brandal and Egidius, 1979; Grimnes and Jakobsen, 1996), including ingesting the entire skin layer of the fish and leaving open wounds. In such circumstances, plasma cortisol and plasma glucose rise, killing cells in the process (Mustafa *et al.,* 2000; Easy and Ross, 2009) and impairing the immune response of the fish to the lice (Heuch *et al*. 2005). Sea lice have been shown to significantly affect ion regulation, indicating juvenile salmon are most vulnerable during smoltation (Brauner *et al*., 2009). Salmon survival and spawning success can also be jeopardised by reduced blood circulation and approximately 20% less agility in the water (Wagner *et al*. 2007).

In addition to the lesions and skin erosion caused by the lice, sea trout (*Salmo trutta*) have also been found to prematurely return to freshwater, a behavioural response of the host fish, attributed to excessive sea lice burdens (Tully *et al*., 1993; Birkeland, 1996; Birkeland and Jakobsen, 1997; MacKenzie *et al*., 1998; Bjørn *et al*., 2001: Tully *et al*., 1999). This behaviour, in the short term may improve survival, but growth potential will inevitably be compromised by sacrificing important foraging opportunities (Webster *et al*., 2007). The fish is also exposed to an increased risk of secondary infection through the lesions in freshwater (Wells *et al*., 2007). Furthermore, sea lice themselves may also be vectors for microbial and bacterial diseases (e.g. Infectious salmon anaemia (ISA) (Nylund *et al*., 1993), although this has not yet been proven (Revie *et al*., 2009). In Norway, sea trout post-smolts heavily infected with sea lice have only been captured in areas where salmon are farmed (Birkeland and Jakobsen, 1997: Bjørn *et al*., 2001), and in Ireland the highest sea lice abundances have been recorded on post-smolt sea trout within 20km of salmon farms (Gargan *et al*., 2003). In western Scotland, 14-40% of sea trout were found to carry potentially lethal lice infections in June 1998-2000 (Butler, 2002).

The severity of lice infection on farmed and wild salmon is dependent on a number of factors including; number of lice (infection pressure), transport of lice though currents (Wallace, 1998), behavioural impacts of salinity (sea lice avoid water with less than 20‰ salinity), temperature (Heuch, 1995), infection success and survival (Tucker *et al*., 2000; Johnson and Albright, 1991), and susceptibility and behaviour of hosts (Heuch *et al*., 2005). For individual fish, the impact of infection and vulnerability to sea lice is difficult to define because it is dependent on sea lice density and the developmental stage of the parasite (Grimnes and Jakobsen, 1996), the size of the host (Finstad *et al*., 2000; Glover *et al*., 2001), the hosts physiological and immunological state, and the time of year (Revie *et al*., 2009). Research by Penston and Davis (2009) found a positive relationship between the scale of salmon production and sea lice larval abundance in Loch Torridon, Scotland. Costello (2009b) suggests that, as more farms develop in a given area lice, transmission between farms can compromise the individual farms efforts on lice control.

Laboratory dose-response studies on wild salmon smolts found infection of 0.75 lice per gram of fish weight would cause death (Finstad *et al*., 2000). Post-smolt monitoring of more than 3,000 fish from the Norwegian Sea for lice, revealed no fish carrying more than 10 adult lice were found alive (Holst *et al*., 2003). An experimental study on juvenile Atlantic salmon found attachment of between 30-50 sea lice larvae can cause the death of a 40g post-smolt (Grimme *et al*., 1996). In sea trout, the natural infection intensity with adult female lice in spring is thought to be 0-3 per fish (Heuch *et al*., 2002; Rikardsen, 2004). However, wild sea trout captured from fish farming areas have been recorded in the summer with between 10-20 adult female lice per fish (Bjørn *et al*., 2003). Wells *et al*. (2006) reported 13 mobile sea lice per wild post-smolt sea trout, weighing between 19-70g, resulted in sub-lethal stress responses. In Norway, based on experimental results, specialists recommend less than 10 lice per wild salmonid to ensure no negative effect on wild salmonid populations (Bjørn *et al*., 2008, 2009).

Although salmon farms are stocked with louse-free fish, the lice exist naturally on wild salmonids, which in part provide a source of infection, along with drifting infection from neighbouring farms. The high densities of salmon in farms then provide an ideal environment for lice reproduction (Costello, 2006), meaning the farms boost sea lice production above natural background levels (Tully and Whelan, 1993; Heuch and Mo, 2001). The aquaculture environment can overcome the natural self-regulation of micro-predators such as sea lice. For example, wild salmon infested with sea lice might suffer from reduced foraging efficiency through the resultant infection, thus increasing host mortality. However, in aquaculture, this does not occur and the cycle is therefore not broken (Frazer, 2008). Also, natural migratory life cycles of salmon spatially separate adults from juveniles, therefore protecting juveniles from parasites associated with adult hosts (Krkošek *et al*., 2006). Fish farms prevent the functional role of migration from protecting the juveniles, and expose salmonids to the parasites at an abnormally young age (Krkošek *et al*. 2005). Sea-trout post-smolts generally do not travel far afield but remain year-round in local coastal waters. This may increase exposure to sea-lice and thus help to maintain a local sea louse over-wintering population (Butler, 2002; Rikardsen, 2004).

Studies, from different geographical locations, have linked high levels of sea lice on wild salmon with infestations in salmon farms, nearby or along native salmon migration paths (Tully *et al*., 1993; Finstad *et al*., 1994; Gargan *et al*., 2000). Research from Scotland (Butler and Watt, 2003), Western Ireland (Gargan *et al*., 2003) and Norway (Holst *et al*., 2003; Heuch *et al*., 2005) have shown wild salmon and sea trout numbers declining more significantly in areas with fish farms, than areas without. Studies in Canada on juvenile pink salmon (*Oncorhychus gorbuscha*) and chum salmon (*Oncorhychus keta*) found during the downstream migration the sea lice infection rate was 73 times greater near a fish farm than ambient infection levels (Krkošek *et al*., 2005). A later study in the Broughton Archipelago, Canada, indicated sea lice-induced mortality of pink salmon was commonly over 80%. They calculated that, if outbreaks continue, a 99% collapse in native pink salmon populations is expected in four generations (Krkošek *et al*., 2007).

Research on sea trout has also shown higher sea lice infection rates in areas with intensive fish farming activity (Tully *et al*., 1999; Bjørn *et al*., 2001; Gargan *et al*., 2003). Research from Ireland, Scotland and Canada indicates sea lice may disperse for up to 30 km from one site (Tully *et al*., 1999; Gargan *et al*., 2003: Krkošek *et al*., 2005). A recent study by Penston and Davis (2009) confirmed a significant relationship between the numbers of gravid (egg-bearing) sea lice on farmed salmon in Loch Torridon, Scotland, and densities of the copepodids in the water column. This evidence supports the hypothesis of ‘self seeding’ infections, described in previous reports (Tully, 1989; Bron *et al*., 1993a, b; Jackson *et al*., 1997; Grant and Treasurer, 1993).

In 1997, Norway developed the ‘National Action Plan against Salmon Lice on Salmonids’ (NA), with the goal of reducing the effects of lice on farmed and wild salmonids (Eithun, 2000). The plan included a legal limit of two adult female lice per fish, which was revised to 0.5 adult females per fish in January 2000 (Heuch *et al*., 2005). In 1999, a modelling study by Heuch and Mo (2001), based on the of figure of 2 adult lice per fish, estimated 111 billion lice eggs would have been produced by farmed salmon around the Norwegian coast between April-June, during the wild smolt run. From an ecosystem approach, as the number of salmon in fish farms continues to increase every year, for lice production to remain constant the allowable limit per fish must be lowered every year (Heuch *et al*., 2005).

Climate change is likely to alter the geographical ranges of sea lice and their hosts (Dulvey *et al*., 2008; Marcogliese, 2008). Research already shows temperature variations, between years, can greatly affect sea lice abundances (Hewitt, 1971; Tully, 1992), with sea lice populations shown to thrive in high water temperatures (Deady *et al.* 1995). This supports early studies indicating that parasites' impacts on hosts will be greater due to rising temperatures associated with climate change (Harvell *et al.*, 2002; Poulin and Mouritsen, 2006).

The debate on the impact of lice from farmed salmon on wild populations is fuelled by two uncertainties; 1) the lack of reliable data on sea lice abundances pre-salmon farming (Beamish *et al.*, 2007) and 2) the sample bias as you can only sample fish that have survived infestation (Revie *et al.*, 2009). However, the growing body of evidence showing the detrimental impacts of sea lice from fish farms on nearby wild salmonids provides sufficient evidence to question the economic and political issues underpinning the current aquaculture and fisheries resource management (Costello, 2009b).

Escapee salmon: Interbreeding of wild and escaped salmon

Farmed salmon escape practically everywhere there is aquaculture. Thorstad *et al.*, (2008), on behalf of the Salmon Aquaculture Dialogue which investigated the incidence of farmed Atlantic salmon in the wild, concluded that, internationally, numbers of farmed salmons escaping are large in relation to the abundances of their wild counterparts. In Norway, it is estimated that 1.3 million salmon escape each year (Weber, 1997), although in 2007 the official statistics quote 450,000 cultivated salmon escaped in Norway (Statistics Norway, 2009). In Scotland, official statistics in 2002 show 309,996 Atlantic salmon escaped from fish farms, and figures for 2009 shown 131,971 Atlantic salmon escaped, predominately due to holes in the cage nets (Scottish Government, 2009). There is growing evidence that these escapees are establishing significant populations in the wild. It is estimated that within Norwegian rivers in close proximity to fish farms, up to 80% of the spawning fish in one season were from fish farms (Fiske *et al.*, 2006, referenced in Hindar *et al.*, 2006). In New Brunswick, Canada, within four years of the first fish farms being built in 1979, 5% of the salmon in the nearby Magaguadavic River were shown to be escapees and, by 1995, this had risen to 90% (Weber, 1997). In the North Atlantic, experimental ocean fishing off the Faroe Islands during the mid-1990s found 20-40% of salmon caught was of farmed origin (Hansen *et al.*, 1999).

The replenishment of wild salmon populations with farmed smolts was thought to be a viable and effective solution to declining populations, as reported by McGinnity *et al.* (2003b). However, farmed salmon typically show lower genetic variability than wild salmon (Norris *et al.*, 1999; Skaala *et al.*, 2004). This means that, when captive salmon escape and breed with wild salmon, the gene pool is changed and diluted, potentially compromising the genetic integrity of the wild salmon population and its genetic adaptation to localised habitats (Crozier, 1993, 2000; Fleming *et al.* 2000). The effect of farmed fish will depend upon a number of factors, including genetic origin, rearing conditions, the condition of the wild population, and the number, timing, magnitude and frequency of escapes (Hutchings, 1991). There is also the possibility that escaped salmon could hybridised with native trout (*Salmon trutta*), as hybrids between Atlantic salmon and trout do occur naturally in the wild (Hurrell and Price, 2006).

Farmed salmon differ from wild salmon both morphologically and physiologically, which can affect behaviour, spawning success and competitive ability (Thorstad *et al.*, 2008). Research from Scotland has found that farm escapees can successfully breed in local rivers to the fish farms (Webb *et al.*, 1991; 1993a). A survey in 1991 found 11 of 12 Scottish rivers within fish farming areas had juveniles of farmed parentage (Webb *et al.*, 1993b). McGinnity *et al.*, (2003b) found in experimental studies in the Burrishoole system, in Western Ireland, hybrids (from a two-generation experiment) and farmed fish had lower survival rates than their wild counterparts. Fleming *et al.* (2000) found that the lifetime reproductive success of escaped farmed salmon was only 16% of that of native fish. Farmed salmon can also demonstrate uncharacteristic migratory patterns, such as dispersing into many rivers. This therefore has the potential to impact more than one wild population (Weir and Fleming, 2006).

Genetic changes, through interbreeding, may result in changes to the ecological and behavioural traits of native salmonids (Holm and Dalen, 2003). Clifford *et al.* (1998) found interbreeding between farmed and wild salmon resulted in four of the seven loci examined shifting in the direction of the farmed salmon, resulting in lower overall heterogeneity of allelic frequencies between the two types. McGinnity *et al.* (2003b) found that the interbreeding of typically smaller wild and bigger captive salmon brought about behavioural suppression of the wild stock by intermediately sized hybrid stock. Simulation studies based on a fixed escape rate of 20% of farmed salmon at spawning suggest ‘substantial changes’ will take place to the wild salmon population within ten salmon generations. The report also indicates that, even with lower invasion rates, recovery of the wild population genetic stock is not likely even if no further escapes occur (Hindar *et al*., 2006).

The Scottish Fisheries Research Report, by Middlemas and Steward (2008), found first year salmon smolts significantly larger than two and three year old smolts in the River Balgy, a small catchment dominated by freshwater lochs, which are used for cage rearing salmon smolts. This could suggest that all the first year smolts caught had escaped from the smolt farms. This indicates it is possible for salmon to escape at all life stages, and that juvenile fish, via freshwater smolt rearing facilities, could also pose a problem to native populations (Clifford *et al*., 1998; Carr and Whoriskey, 2006).

Atlantic salmon are in decline throughout their native range. Multiple factors are contributing to this decline, which makes it very difficult to determine the individual impact of each stressor. This confounds attempts to assess the discrete impact of escapees on population size and productivity. However, it is likely that wild populations are more vulnerable to the effects of escaped salmon due to the additional stress from other pressures (Thorstad *et al*., 2008). In order to allow the species as a whole to keep pace with a changing environment, genetic variation between populations must be maintained (McGinnity *et al*. 2003a). The use of sterile fish in farms is a measure supported by scientists to minimise the impact of farmed fish on wild salmon genetics (Hindar *et al*., 1991; Anon, 1994; Hansen and Youngson, 1998). Cotter *et al,* (2000) found reduced return rates of triploid salmon to both estuaries and freshwater, coupled with their inability to produce viable offspring, demonstrated how the farming of triploid fish could reduce the ecological impact of escaped farm fish.

Chemical wastes

A range of chemicals are used in aquaculture, including disinfectants, antifoulants, medicines (including antibiotics), vaccines (Costello *et al*., 2001) and insecticides (including organophosphates and synthetic pyrethroids). These can be toxic to other organisms in the water column, and some chemical wastes can also bioaccumulate and therefore remain in the environment for extensive periods. Chemicals administered in feed or as bath treatments, can both permeate into the wider environment.

Outputs from fish farms are controlled by local and national waste discharge consents (Costello *et al*., 2001). However, the rapid expansion of fish farming in the 1980s and 1990s saw a dramatic rise in the use of antibiotics on farms. Between 1985 and 1987 in Norway, antibiotic use increased from 17 to 48 mt per year, exceeding the combined use by humans and terrestrial animals in the country during the same period (Weber, 1997). By 1998, the Chilean salmon farming industry was using 100 mt of antibiotics (Claude and Oporto, 2000). The profligate use of these antibiotics can lead to the development of antibiotic-resistant strains of bacteria in both wild and farmed populations. Recent anecdotal evidence of increasing sea lice numbers in Norway and British Columbia has heightened concern of resistance to anti-lice treatments.

Elevated levels of zinc, copper and cadmium have been found in fish farm sediments as a result of feed and faecal outputs, and the anti-foulant products used in aquaculture (Brooks and Maknsen, 2003; Schendel *et al*., 2004; Dean *et al*., 2007). A survey of metal concentrations in surface sediments at 70 sites around fish farms in Loch Craignish, on the west coast of Scotland, found maximum concentrations of 921, 805 and 3.5 µg g^{-1} of zinc, copper and cadmium, respectfully (Dean *et al*., 2007). Elevated levels of sediment metals can have a wide range of impacts on the benthos, including altering community structure and reproductive success (Dean *et al*., 2007).

Biological Waste and Nutrient Loading

Biological waste, such as extra food and faeces, can accumulate in the water and sediments surrounding fish farms. Sediments beneath fish cages have been found to be enriched in phosphorus, nitrogen, organic carbon and zinc (Cornel and Whoriskey, 1993; Kelly, 1993; Troell and Berg, 1997). Factors affecting waste production include fish size, water temperature and husbandry practices including feed composition and feeding methods (Podemski and Blanchfield, 2006).

In areas with significant aquaculture production, the accumulation of organic matter can be detrimental to the surrounding environment (Naylor *et al.*, 2000; Beveridge, 2004). Biological wastes can lead to an overabundance of phosphate and nitrogen, which can result in eutrophication (wherein high concentrations of nutrients permit the over-proliferation of algae and other aquatic plants). This can pose a major threat to water quality and environmental integrity (Nijboer and Verdonschot, 2004; Smith and Schindler, 2009) and, in extreme cases, can lead to a completely de-oxygenated (anoxic) environment (Stutter and Lumsdon, 2008). Organic enrichment can lead to decreased species richness and diversity, and an increase in the abundance and dominance of organisms resistant to sedimentation and low oxygen availability (Hynes 1963; Johnson *et al*. 1993; Brooks and Mahnsen, 2003; Brooks *et al*., 2003; Edgar *et al*., 2005). The wastes can also smother animal and plant communities beneath cages (Weber, 1997). Disrupting or altering these benthic communities can impact sediment nutrient cycling, much of which is anyhow mediated by organisms associated with the sediment. The severe effects of biological waste from salmon farming appear to be relatively localised (Brown *et al*., 1987); however less severe environmental effects may be spread over a large area (Carroll *et al*., 2003). Sediment anoxia and the absence of macrofauna have been reported due to salmon farming in the North Atlantic (Hansen *et al*., 1991), the Baltic Sea (Holmer and Kristensen, 1992) and Chile (Soto and Norambuena, 2004). In Chile, research from eight salmon farms located along 300km of coastline showed the salmon farming resulted in at least a 50% reduction in benthic biodiversity due to organic matter, low oxygen levels in the sediment and the deposition of copper as a result of these aquaculture operations (Soto and Norambuena, 2004).

Faecal production and waste feed are difficult to estimate accurately, and so are rarely reported. Research from Canada suggests faecal production ranges from 15% to 30% of applied feed (Costello *et al,*. 1996; Cho and Bureau, 2001; Bureau *et al*., 2003), and waste feed could constitute between 3–40% of feed (Weston *et al*., 1996). Research in southern Chile found significantly higher concentrations of ammonium nitrogen near salmon cages, compared with control areas, and seaweeds exhibiting faster growth rates and tissue nitrogen content when cultured near fish farm cages (Troell *et al*., 1997).

Little data exists on the recovery of sediments following the removal of fish farms. However, in Scottish saline lochs, significant alterations in benthic communities below cage sites were still apparent more than 3 years after the farming in the area had ceased (Doughty and McPhail, 1995). Recovery of lotic systems is thought to be more rapid due to the water flow increasing the dispersion of wastes and allowing re-colonization by invertebrate drift (Doughty and McPhail, 1995). The length of rehabilitation will depend on local topographical conditions (Holm and Dalen, 2003).

Conclusion

Despite some common perceptions to the contrary, the scientific literature demonstrates that, to varying degrees, salmon farms are having a detrimental impact on native salmonid fisheries, the wider environment and the many public benefits associated with it. In order to make aquaculture a viable and sustainable industry, these threats must be addressed as an urgent priority. Furthermore, from an ecosystems perspective, the benefits of farmed fish production under current stewardship may be heavily outweighed by wider impacts on the environment and the many other sectors of society that this affects. We believe that the Precautionary Principle should be enforced to protect wild Atlantic salmon (an EU Habitats Directive protected species), sea tout (a Biodiversity Action Plan species) and the surrounding aquatic environment. This is also implicit under the EU Water Framework Directive (WFD), which requires ‘good ecological status’ and no deterioration in all water bodies.

Reference List:

Anon. (1994). Report of the working group on impacts of salmon aquaculture. NASCO Document CNL (94)28, North Atlantic Salmon Conservation Organisation, Edinburgh, UK: 25.

Beamish, R.J., Neville, C.M., Sweeting, R.M. and Ambers, N. (2007). Response to Dr. Neil Frazer’s comment on “Sea lice on adult Pacific salmon in the coastal waters of British Columbia, Canada”. *Fisheries Research* **85**: 332-333.

Bernoth, E.M. (1997). Furunculosis: the history of the disease and of disease research. In: Bernoth, E.M. and Ellis, A.E. (eds). *Furunculosis, Multidisciplinary Fish Disease Research*.
Beveridge, M.C.M. (2004). Cage Aquaculture, third Edition. Oxford, Blackwell Publishing Ltd.
Birkeland, K. (1996). Consequences of premature return by sea trout (*Salmo trutta*) infested with the salmon lice (*Lepeophtherius salmonis* Krøyer): migration, growth and mortality. *Can. J. Fish. Aquat. Sci.* **53**: 2808-2813.
Birkeland, K. and Jakobsen, P.J. (1997). Salmon lice, *Lepeophtheirus salmonis*, infestation as a causal agent of premature return to rivers and estuaries by sea trout, *Salmo trutta*, juveniles. *Environmental Biology of Fishes* **49**: 129-137.
Bjørn, P.A., Finstad, B., Nilsen, R., Asplin, L., Uglem, I., Skaala, Ø., Boxaspen, K.K. and Øverland, T. (2008). Norwegian national surveillance of salmon lice epidemics on wild Atlantic salmon, sea trout and Arctic char in connection with Norwegian national salmon rivers and fjords. *NINA Rapport* **377**: 1-33.
Bjørn, P.A., Finstad, B., Nilsen, R., Uglem, I., Asplin, L., Skaala, Ø., Boxaspen, K.K. and Øverland, T. (2009). Norwegian national surveillance of salmon lice epidemics on wild Atlantic salmon, sea trout and Arctic char in connection with Norwegian national salmon rivers and fjords. *NINA Rapport* **447**: 1-52.
Bjørn, P.A., Finstad, B. and Kristoffersen, R. (2001). Salmon lice infection of wild sea trout and Arctic charr in marine and freshwaters: the effects of salmon farms. *Aquat. Res.* **32**: 947-962.
Bjørn, PA., Finstad, B. and Kristoffersen, R. (2003).Registreringer av lakeselus pa laks sjøørret of sjørøye i 1999. NINA Oppdragsmedling **789**. Norwegian Institute for Nature Research, Trondheim, Norway.
Brandal, P.O. and Egidius, E. (1979). Treatment of salmon lice (*Lepeophtheirus salmonis* Krøyer, 1838) with Neguvon- description of method and equipment. *Aquaculture* **18**: 183-188.
Brauner, C.J., Sackville, M., Nendick, L., Tang, S., Gardner, M., Grant, A. and Farrell, A.P. (2009). The impact of sea lice on the physiology of wild out-migrating juvenile pink salmon. *Comparative Biochemistry and Physiology, Part A* **153**: 139-144.
Brons, J.E., Sommerville, C., Wootten, R. and Rae, G.H. (1993a). Fallowing of marine Atlantic salmon, Salmo salar L., farms as a method for the control of sea lice, *Lepeophtherius salmonis* (Krøyer 1837). *Journal of Fish Diseases* **16**: 487-493.
Brons, J.E., Sommervillw, C., Wootten, R. and Rae, G.H. (1993b). Influence of treatment with dichlorvos on the epidemiology of *Lepeophtherius salmonis* (Krøyer 1837) and *Caligus elongates* Nordmann, 1832 on Scottish salmon fish. In: Boxshall, G.A. and Defaye, D. (1993). *Pathogens of Wild and Farmed Fish: Sea lice*. Ellis Horwood Ltd, Chichester: 263-274.
Brooks, .K.M, and Mahnken, C.V.W. (2003). Interactions of Atlantic salmon in the Pacific Northwest environment III. Accumulation of zinc and cooper. *Fisheries Research* **62**: 295-305.
Brooks, K.M., Stierns, A.R., Mahnken, C.V.W. and Shields, D. (2003). Chemical and biological remediation of the benthos near Atlantic salmon farms. *Aquaculture* **219**: 355-377.
Brown, J.R., Gowen, R.J. and McLusky, D.S. (1987). The effect of salmon farming on the benthos of a Scottish sea loch. *J. Exp. Mar. Biol. Ecol.* **109**: 39–51.
Bureau, D.P., Gunther, S.J. and Choy, C.Y. (2003). Chemical composition and preliminary theoretical estimates of waste outputs of rainbow trout reared in commercial cage culture operations in Ontario. *N. Am. J. Aquacult.* **65**(1): 33–38.
Butler, J.R. (2002). Wild salmonids and sea louse infestations on the west coast of Scotland: sources of infection and implications for management of marine salmon farms. *Pest. Management Science* **58**: 595-608.
Butler, J.R.A. and Watt, J. (2003). Assessing and Managing the Impacts of Marine Salmon Farms on Wild Atlantic Salmon in Western Scotland: Identifying Priority Rivers for Conservation. Chapter 9. *In:* (Mills D., Ed). (2003). *Salmon at the Edge*. Blackwell: Oxford.
Carr, J.W. and Whoriskey, F.G (2006). The escape of juvenile farmed Atlantic salmon from hatcheries into freshwater streams in New Brunswick, Canada. *ICES Journal of Marine Science* **63**: 1263-1268.
Carroll, M.L., Cochrane, S., Fieler, R., Velvin, R. and White, P. (2003). Organic enrichment of sediments from salmon farming in Norway: environmental factors, management practices, and monitoring techniques. *Aquaculture* **226**: 165-180.
Cho, C.Y. and Bureau, D.P. (2001). A review of diet formulation strategies and feeding systems to reduce excretory and feed wastes in aquaculture. *Aquac. Res.*: **32**(1) 349–360.
Claude, M. and Oporto, J. (Eds). (2000). La ineficiencia de la salmonicultura en Chile. Santiage, Chile: Terram Publications.
Clifford, S.L., McGinnity, P. and Ferguson, A. (1998). Genetic changes in an Atlantic salmon population resulting from escaped juvenile farm salmon. *J. Fish Biol.* **52**: 118-127.
Cornel, G.E. and Whoriskey, F.G. (1993). The effects of rainbow trout (*Oncorhynchus mykiss*) cage culture on the water quality, zooplankton, benthos and sediments of Lac du Passage, Quebec. *Aquaculture* **109**(2): 101–117.
Costello, M.J. (2009a).The global economic cost of sea lice to the salmonid farming industry. *Journal of Fish Diseases* **32**: 115-118.

Costello, M.J. (2009b).How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. *Proc. R. Soc. B.* **276**: 3385-3394.
Costello, M.J. (2006). Ecology of sea lice parasitic on farmed and wild fish. *Trends in Parasitology* **22**: 475-483.
Costello, M.J., Grant, A., Davis, I.M., Cecchini, S., Papoutsoglou, S., Quigley, D. and Saroglia, M. (2001). The control of chemicals used in aquaculture in Europe. *J. Appl. Ichthyol.* **17**: 173-180.
Costello, M.J., Quigley, D.T.G. and Dempsey, S. (1996). Seasonal changes in food conversion ratio as an indicator of fish feeding management. Bull. *Aquac. Assoc. Can.* **96**: 58–60.
Cotter, D., O'Donovan, Maoiléidigh, N.O., Rogan, G., Roche, N. and Wilkins. N.P. (2000). An evaluation of the use of triploid Atlantic salmon (*Salmo salar* L.) in minimising the impact of escaped farmed salmon on wild populations. *Aquaculture* **186**: 61-75.
Crozier, W.W. (1993). Evidence of genetic interaction between escaped farmed salmon and wild salmon (*Salmo salar* L.) in a Northern Irish river. *Aquaculture* **113**: 19-29.
Crozier, W.W. (2000). Escaped farmed salmon, *Salmo salar* L., in the Glenarm River, Northern Ireland: genetic status of the wild population 7 years on. *Fish. Manage. Ecol.* **7**: 437-446.
Daszak, P., Cunningham, A. and Hyatt, A. (2000). Emerging infectious diseases of wildlife: threats to biodiversity and human health. *Science* **287**: 443-449.
Deady, S., Varian, S.J.A. and Fives, J.M. (1995). The use of cleaner-fish to control sea lice on two Irish salmon (*Salmo salar*) farms with particular reference to wrasse behaviour in salmon cages. *Aquaculture* **131**: 73-90.
Dean, R.J., Shimmield, T.M. and Black, K.D. (2007). Copper, zinc and cadmium in marine cage fish farm sediments: An extensive survey. *Environmental Pollution* **145**: 84-95.
Doughty, C.R. and McPhail, C.D. (1995). Monitoring the environmental impacts and consent compliance of freshwater fish farms. *Aquac. Res.* **26**(8): 557–565.
Dulvy, N.K., Roger, S.I., Jenning, S., Stelzenmüller, V., Dye, S.R. and Skjoldal, H.R. (2008). Climate change and deepening of the North Sea Fish assemblage: a biotic indicator of warming seas. *J. Appl. Ecol.* **45**: 1029-1039.
Easy, R.H. and Ross, N.W. (2009). Changes in Atlantic salmon (*Salmo salar*) epidermal mucus protein composition profiles following infection with sea lice (*Lepeophtheirus salmonis*). *Comparative Biochemistry and Physiology*. Part D **4**: 159-167
Edgar, G.J., Macleod, C.K. Mawbey, R.B. and Shield, D. (2005). Broad-scale effects of marine salmonid aquaculture on macrobenthos and the sediment environment in southeastern Tasmania. *Journal of Experimental Marine Biology and Ecology* **327**: 70-90.
Eithum, I. (2000). Measures to control sea lice in Norwegian salmon farms. *Caligus* **6**: 4-5.
Ellis, A.E. (1997). Immunisation with bacterial antigens; furunculosis. *Fish Vaccinology* **89**: 107–116
FAO (United Nations Food and Agriculture) Technical Paper 519 (2008). Understanding and applying risk analysis in aquaculture [Online]. Available from: http://www.fao.org/fishery/publications/technical-papers/en . [Assessed on 18/09/2009].
FAO (United Nations Food and Agriculture). (2005). Yearbook of Fisheries Statistics extracted with Fishstat Version 2.30. Fisheries database: Aquaculture production quantities 1950-2003: aquaculture production values 1984-2003; capture production 1960-2003; Commodities Production and Trade 1976-2002. [Online]. Available from: www.fao.org/fi/statist/FISOFT/FISHPLUS/asp . [Assessed on 18/09/2009].
Finstad, B., Bjørn, P.A., Grimnes, A. and Hvidsten, N.A. (2000). Laboratory and field investigations of salmon lice (*Lepeophtheirus salmonis*, Krøyer) infestation on Atlantic salmon (*Salmo salar* L.) postsmolt. *Aquac. Res.* **31**: 1-9.
Finstad, B., Johnsen, B.O. and Hvidsten, N.A. (1994). Prevalence and men intensity of salmon lice, *Lepeophtheirus salmonis* Krøer, infection on wild Atlantic salmon, *Salmo salar* L., postsmolt. *Aquaculture and Fisheries Management* **25**: 761-764.
Fiske, P., Lund, R.A. and Hansen, L.P. (2006). Relationships between the frequency of farmed Atlantic salmon, *Salmo salar* L., in wild salmon populations and fish farming activity in Norway, 1989-2000. *ICES Journal of Marine Science* **63**: 1234-1247.
Flemming, I.A. Hindar, K. Mjolnerod, I.B. Jonsson, B. Balsta, T. Lamberg, A. (2000). Lifetime success and interactions of farm salmon invading a native population. *Proceeding of the Royal Society of London B.* **267**: 1517-1523.
Ford, J.S. and Myers, R.A. (2008). A global assessment of salmon aquaculture impacts on wild salmonids. *PloS Biol* **6** (2): doi:10.1371/journal.pbio.0060033.
Frazer, N.L. (2008). Sea-Cage Aquaculture, Sea Lice and Declines of Wild Fish. *Conservation Biology* **23**(3): 599-607.
Friedland, K.D. and Reddin, D.G. (1993). Marine survival of Atlantic salmon from indices of post-smolt growth and sea temperature. In: Mills, D. (ed). *Salmon in the sea and new enhancement strategies*. Fishing News Books, Oxford: 119-138.

Gargan, P.G., Tully, O. and Poole, W.R. (2003). The relationship between sea lice infestation, sea lice production and sea trout survival in Ireland, 1992-2001. In: Mills, D.H. (Ed). *Salmon at the Edge*. Blackwell Scientific, Oxford, United Kingdom. Pg: 119-135.

Glover, K.A., Nilsen, F., Skaala, Ø., Taggart, J.B. and Teale, A.J. (2001). Differences in susceptibility to sea lice infection between a sea run and a freshwater resident population of brown trout. *J. Fish. Biology* **59**: 1512-1519.

Grant, A.N. and Treasurer, J.W. (1993). The effects of fallowing on caligid infestations on farmed Atlantic salmon (*Salmo salar* L.,) in Scotland. In: Boxshall, G.A. and Defaye, D. *Pathogens of Wild and Farmed Fish: Sea lice*. Ellis Horwood Ltd, Chichester: 255-260.

Grimnes, A. and Jakobsen, P.J. (1996). The physiological effects of salmon lice infection on post-smolt of Atlantic salmon. *J. Fish. Biol.* **48**: 1179-1194.

Gross, M.R. (1998). One species with two biologies: Atlantic salmon (*Salmo salar*) in the wild and in aquaculture. *Can. J. Fish. Aquat. Sci*. **55** (1): 131–144.

Hansen, L.P., Jacobsen, J.A. and Lund, R.A. (1999). The incidence of escaped farmed Atlantic salmon, *Salmon salar* L, in the Faroese fishery and estimates of catches of wild salmon. *ICES Journal of Marine Science* **56**: 200-206.

Hansen, P.K., Pittman, K. and Ervik, A. (1991). Organic waste from marine fish farms- Effects on the seabed. In: Mäkinen, T. (ed). *Marine Aquaculture and Environment. Nordic Council of Ministers*. Copenhagen: 105-119.

Hansen, L.P. and Youngson, A.F. (1998). Interactions between farmed and wild salmon and options for reducing their impact. In: Youngson, A.F., Hansen, .L.P. and Windsor, M.L. (eds). Interactions between salmon culture and wild stocks of Atlantic salmon: the scientific and management issues. Report by the convenors of an ICES/NASCO symposium, 18-22 April 2007, Bath, England, NINA, Trondheim, Norway: 80-89.

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S. and Samuel, M.D. (2002). Climate warming and disease risks for terrestrial and marine biota. *Science* **296**: 2158-2162.

Håstein, T. (1997). Infectious salmon anaemia (ISA), a historical and epidemiological review of the development of the disease in Norwegian fish farms. Workshop on Infectious Salmon Anaemia St. Andrews, New Brunswick, Nov 26, 1997, pg 5-12.

Håstein, T., Hill, B.J. and Winton, J. (1999). Successful aquatic animal disease emergencies programs. Rev. Sci. Tech. Off. Int. Epic. **18**: 214-227.

Hendry, K. and Cragg-Hine, D. (2003). *Ecology of the Atlantic Salmon*. Conserving Natura 2000 River Ecology Series No.7. English Nature, Peterborough.

Heuch, P.A. (1995). Experimental evidence for aggregation of salmon louse copepodids, *Lepeophtheirus salmonis,* in step salinity gradients. *J. Mar. Biol. Assoc. U.K.* **75**: 927-939.

Heuch, P.A., Knutsen, J.A., Knutsen, H. and Schram, T.A. (2002).Salinity and temperature effects on sea lice (*Lepeophtheirus salmonis* and *Caligus elongatus*) over-wintering on sea trout (*Salmo trutta*) in coastal areas of the Skagerrak. *J. Mar. Biol. Assoc. U.K.* **82**: 887-892.

Heuch, P.A., Bjorn, P.A. Finstad, B. Holst, J.C. Asplin, L. Nilsen, F. (2005). A review of the Norwegian 'National Action Plan Against Salmon Lice on Salmonids': The effect on wild salmonids. *Aquaculture*. **246**: 76-92.

Heuch, P.A. and Mo, T.A. (2001). A model of salmon louse production in Norway: effects of increasing salmon production and public management resources. *Dis. Aquat. Org.* **45**: 145-152.

Hewitt, G. C. (1971). Two species of Caligus (Copepoda, Caligidae) from Australia waters, with a description of some development stages. *Pacific Science* **25**: 145-164.

Hindar, K., Fleming, I.A., McGinnity, P. and Diserud, O. (2006). Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. *ICES Journal of Marine Sciences* **63**: 1234-1247.

Hindar, K., Ryman, N. and Utter, F. (1991). Genetic effects of aquaculture on natural fish population. *Aquaculture* **48**: 945-957.

Holm, M. and Dalen, M. (2003). The environmental status of Norwegian aquaculture. Bellona Report No. 7, Oslo, PDC Tangen: 89.

Holmer, M. and Kristenssen, E. (1992). Impact of fish cage farming on metabolism and sulfate reduction of underlying sediments. *Mar. Ecol. Prog. Ser.* **80**: 191-201.

Holst, J.C., Jacobsen, P., Nilsen, F., Holm, M. and Aure, J. (2003). Mortality of seaward-migrating post-smolts of Atlantic salmon due to salmon lice infection in Norwegian salmon stocks. In: Mills, D.H. (Ed). *Salmon at the Edge*. Blackwell Scientific, Oxford, United Kingdom. Pg: 136-157.

Hurrell, R.H. and Price, D.J. (2006). Natural hybrids between Atlantic salmon, *Salmo salar* L, and trout (*Salmo trutta* L)., in juvenile salmonid population in south-west England. *Journal of Fish Biology* **39**:335-341.

Hutchings, J.A. (1991). The threat of extinction to native populations experiencing spawning intrusions by cultured Atlantic salmon. *Aquaculture* **98**: 119–132.

Hynes, H.B.N. (1963). Imported organic matter and secondary productivity in streams. *Proceedings of the 16th International Congress of Zoology* **4**: 324–329.

Jackson, D., Deady, S., Leahy, Y. and Hassett, D. (1997). Variations in parasitic caligid infestations on farmed salmonids and implications for their management. *ICES Journal of Marine Science* **54**: 1104-1112.

Johnson, R.K., Wiederholm, T. and Rosenberg. D.M. (1993). Freshwater biomonitoring using individual organisms, populations, and species assemblages of benthic macroinvertebrates. In: D.M. Rosenberg, D.M. and Resh, V.H. (*eds*). *Freshwater biomonitoring and benthic macroinvertebrates.* New York: Routledge, Chapman and Hall: 40–158.

Kelly, L.A. (1993). Release rates and biological availability of phosphorus released from sediments receiving aquaculture wastes. *Hydrobiologia* **253**(1–3): 367–372.

Krkošek, M., Ford, J.S., Morton, A., Lele, S., Myers, R.A. and Lewis, M.A., (2007). Declining wild salmon populations in relation to parasites from farm salmon. *Science* **318**: 1772-1775.

Krkošek, M., Lewis, M.A., Morton, A., Frazer, L.N. and Volpe, J.P. (2006).Epizootics of wild fish induced by farm fish. *Proceedings of the National Academy of Sciences of the United States of America* **103**: 15506-15510.

Krkošek, M., Lewis, M.A. and Volpe, J.P. (2005). Transmission dynamics of parasite sea lice from farm to wild salmon. *Proceedings of the Royal Society of London, B-Biological Sciences* **272**: 689-696.

Madsen, S.S. Skovbolling, S. Nielsen, C. Korsgaard, B. (2004). 17-β Estradiol and 4-nonylphenol delay smolt development and downstream migration in Atlantic salmon. *Aquatic Toxicology*. **68**: 109-120

McCallum, H. and Dodson, A.P. (1995). Detecting disease and parasite threats to endangered species and ecosystems. *Trends Ecol. Evol.* **10**: 190-194.

MacKenzie, K., Longshaw, M., Begg, G.S. and McVicar, A.H. (1998). Sea lice (Copepoda: Caligdae) on wild sea trout (*Salmo trutta* L.) in Scotland. *ICES Journal of Marine Science* **55**: 151-162.

Marcogliese, D.J. (2008). The impact of climate change on the parasites and infectious diseases of aquatic animals. Rev. *Scientif. Techniq. L'Off. Internat. Epizootics* **27**: 467-484.

McGinnity, P. Fergusin, A. Baker, N. Cotter, D. Cross, T. Cooke, D. Hynes, R. O'Hea, B. O'Maoileidigh, N.O. Prodohl, P. Rogan, G. (2003a). *A two-generation experiment comparing the fitness and life history traits of native, ranched, non-native, farmed and 'hybrid' Atlantic salmon under natural conditions*. In: Mills, D. (Ed). Salmon at the Edge. Blackwell.

McGinnity, P. Prodohl, P. Ferguson, A. Hynes, R. O'Maoileidigh, N. Baker, N. Cotter, D. O'Hea, B. Cooke, D. Rogan, G. Taggart, J. Cross, T. (2003b). Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. *Proceedings of the Royal Society of London B*. **270**: 2443-2450.

Mesa, M.G., Poe, T.P., Maule, A.G. and Schrek, C.B. (1998). Vulnerability to predation and physiological stress response in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) experimentally infected with *Renibacterium salmoninarum*. *Canadian Journal of Fisheries and Aquatic Science* **55**: 1599-1606.

Middlemas, S.J. and Steward, D.C. (2008). Unusually high incidence of large one- year old salmon smolts trapped on a small west coast Scottish river. Scottish Fisheries Research Report, Number 69 ISSN 0308 8022.

Murray, A.G. and Peeler, E.J. (2005). A framework for understanding the potential for emerging diseases in aquaculture. *Preventive Veterinary Medicine* **67**: 223-235.

Murray, A.G., Smith, R.J. and Stagg, R.M. (2002). Shipping and the spread of infectious salmon anemia in Scottish aquaculture. *Emerg Infect Dis*. **8** (1): 1-5.

Mustafa, A. MacWilliams, C. Fernandez, N. Matchett, K. Conboy, G.A. Burka, J.F. (2000). Effects of sea lice (*Lepeophtheirus salmonis Kroyer*, 1837) infestation on macrophage functions in Atlantic salmon (*Salmon salar* L.). *Fish and Shellfish Immunology*. **10**: 47-59

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubcheneco, J., Mooney, H. and Troell, M. (2000). Effect of aquaculture on the world fish supplies. *Nature* **405**: 1017-1023.

Nijboer R. C. and Verdonschot P. F. M. (2004). Variable selection for modelling effects of eutrophication on stream and river ecosystems. *Ecological Modelling*. **177** (1-2): 17-39.

Norris, A.T., Bradley, D.G and Cunningham, E.P. (1999). Micro-satellite genetic variation between and within farmed and wild Atlantic salmon (*Salmo salar*) populations. *Aquaculture* **180**: 247-264.

Nylund, A., Wallace, C. and Hovland, T. (1993). The possible role of *Lepeophtheirus salmonis (*Krøyer) in the transmission of infectious salmon anemia. In: Boxhall, G.A. and Defaye, D. (eds). *Pathogens of Wild and Farmed Fish: Sea Lice*. Ellis Horwood, Chichester, UK: 367-373.

Penston, M.J. and Davis, I.M. (2009). An assessment of salmon farms and wild salmonids as sources of *Lepeophtheirus salmonis (*Krøyer) copepodids in the water column in Loch Torridon, Scotland. *J. Fish Dis.* **32**: 75-88.

Pike, A.W. and Wadsworth, S.L. (2000). Sealice on salmonids: their biology and control. *Advances in Parasitology* **44**: 234-337.

Podemski, C.L. and Blanchfield, P.J. (2006) Overview of the Environmental Impacts of Canadian Freshwater Aquaculture. In. In: A Scientific Review of the Potential Environmental Effects of Aquaculture in Aquatic Ecosystems, Volume V. Canadian Technical Report of Fisheries and Aquatic Sciences 2450.

Poulin, R. and Mouritsen, K.N. (2006). Climate change, parasitism and the structure of intertidal ecosystems. *J. Helminthol.* **80**: 183-191.

Rikardsen, A.H. (2004). Seasonal occurrence of sea lice *Lepeophtheirus salmonis* on sea trout in two north Norwegian fjords. *J. Fish Biol.* **65**: 711-722.

Raynard, R.S. (2000). A survey of wild fish in Scotland for evidence of infectious salmon anaemia virus: report for the period May 1998- December 1999. Marine Laboratory Aberdeen Report: No.05/00.
Reno, P.W. (1998). Factors involved in the dissemination of disease in fish populations. *Journal of Aquatic Animal Health* **10**: 160-171.
Revie, C., Dill, L., Finstad, B. and Todd, C.D. (2009). "Salmon Aquaculture Dialogue Working Group Report on Sea Lice".[Online] Commissioned by the Salmon Aquaculture Dialogue. Available from: http://www.worldwildlife.org/what/globalmarkets/aquaculture/WWFBinaryitem11790.pdf. [Assessed 16/10/2009].
Schendel, E.K., Nordstrom, S. and Lavkulich, L.M. (2004). Floc and sediment properties and their environmental distribution from a marine fish farm. *Aquaculture Research* **35**: 483-493.
Scottish Government (2009). Confirmed Reported Escapes from Fish Farms in Scotland. [Online]. Available from: http://www.scotland.gov.uk/Topics/Fisheries/Fish-Shellfish/18692/escapeStatistics . [Assessed on the 23/10/2009].
Skaala, Ø., Høyheim, B., Glover, K. and Dahle, G. (2004). Micro- satellite analysis in domesticated and wild salmon Atlantic salmon (*Salmo salar* L.): allele diversity and identification of individuals. *Aquaculture* **240**: 131-143.
Smith V. H., and Schindler C. W. (2009). Eutrophication science: where do we go from here? *Trends in Ecology & Evolution*. **24** (4): 201-207.
Soto, D. and Norambuena, F. (2004). Evaluation of salmon farming effects on marine systems in the inner seas of southern Chile: a large-scale measurative experiment. *Journal of Applied Ichthyology* **20**: 493-501.
Statistics Norway. (2009). Salmon aquaculture escape figures. [Online]. Available from: http://www.ssb.no/fiskeri_havbruk_en/ . [Accessed 11/12/2009].
St-Hilaire, S., Ribble, C.S., Stephen, C., Anderson, E., Kurath, G. and Kent, M. (2002). Epidemiological investigation of infectious hematopoietic necrosis virus in salt water net-pen rearer Atlantic salmon in British Columbia, Canada. *Aquaculture* **212**: 49-67.
Stutter M. I. and Lumsdon D. G. (2008). Interactions of land use and dynamic river conditions on sorption equilibria between benthic sediments and river soluble reactive phosphorus concentrations. *Water Research*. **42**: 4249-4260.
Thorstad, E.B., Fleming, I.A., McGinnity, P., Soto, D., Wennivik, V. and Whoriskey, F. (2008). Incidence and impacts of escaped farmed Atlantic salmon Salmo salar in nature. *NINA Special Report* 36.
Thorpe, J.E. Mangel, M. Metcalfe, N.B. Huntingford, F.A. (1999). Modelling the proximate basis of salmonid life-history variation, with application to Atlantic salmon, *Salmo salar* L. *Evolutionary Ecology.* **12**: 581-599.
Thorud, K.E. and Djupvik, H.O. (1988). Infectious anaemia in Atlantic salmon *Salmo salar* L. *Bulletin of the European Association of Fish Pathologists* **8**: 109-110.
Troell, M. and Berg, H. (1997). Cage fish farming in the tropical Lake Kariba, Zimbabwe: Impact and biogeochemical changes in sediment. *Aquac. Res*. **28**(7): 527–544.
Troell, M., Halling, C., Nilsson, A., Buschmann, A.H., Kautsky, N. and Kautsky, L. (1997). Integrated marine cultivation of *Gracilaria chilnesis* (Gracilariales Rhodophyta) and salmon cages for reduced environmental impact and increased economic output. *Aquaculture* **156**: 46-61.
Tucker, C.S., Sommerville, C. and Wootten, R. (2000). The effect of temperature and salinity on the settlement and survival of copepodids of *Lepeophtheirus salmonis* (Krøyer, 1837) on Atlantic salmon, *Salmo salar* , *J. Fish. Dis*. **23**: 309-320.
Tully, O. (1989). The succession of generations and growth of the caligid copepods *Caligus elongatus* and *Lepeophtheirus salmonis* parasitising farmed Atlantic salmon smolts (*Salmo salar* L.,). *Journal of Marine Biological Association of the United Kingdom* **69**: 279-287.
Tully, O. (1992). Predicting infestation parameters and impacts of sea lice on wild and cultured fish populations. *Invert. Reprod. Develop.* **22**: 91-102.
Tully, O., Gargan, P., Poole, W.R. and Whelan, K.F. (1999). Spatial and temporal variation in the infestation of sea trout (*Salmo trutta* L.) by the caligid copepod *Lepeophtheirus salmonis (*Krøyer) in relation to sources of infection in Ireland. *Parasitology* **119**: 41-51.
Tully, O., Poole, W.R., Whelan, K.F. and Merigoux, S. (1993). Production of nauplii of *Lepeophtheirus salmonis* (KrØyer) infesting sea trout (*Salmo trutta* L.) off the west coast of Ireland. In: Boxshall, G.A. and Defaye, D. (eds). *Pathogens of Wild and Farmed Fish: Sea lice*. Ellis Horwood Ltd, London: 202-213.
Tully, O. and Whelan, K.F. (1993). Production of nauplii *Lepeophtheirus salmonis* (KrØyer) (Copepoda: Caligidae) from farmed and wild salmon and its relation to the infestation of wild sea trout (*Salmo trutta* L.) off the west coast of Ireland in 1991. *Fisheries Research* **17**: 187-200.
Wagner, G. N. Fast, M. D. Johnson, S. C., (2007). Physiology and immunology of *Lepeophtheirus salmonis* infections of Salmonids. *Trends in Parasitology.* **24**: 176-183.
Wallace, C. (1998). Possible causes of salmon lice *Lepeophtheirus salmonis (*Krøyer, 1837) infections on farmed Atlantic salmon, *Salar salmo* L., in a western Norwegian fjord-situated fish farm; implications for the design of regional management strategies. *Cand. Scient. Thesis*. University of Bergen, Norway.

Waring, C.P. and Moore, A. (2004). The effect of atrizine on Atlantic salmon (*Salmo salar*) smolts in fresh water and after sea water transfer. *Aquatic Toxicology*. **66**: 93-104.
Webb, J.H., Hay, D.W., Cunningham, P.D. and Youngson, A.F. (1991). The spawning behaviour of escaped farmed and wild adult Atlantic salmon (*Salmo salar*) in a northern Scottish river. *Aquaculture* **98**: 97-110.
Webb, J.H., McLaren, I.S., Donaghy, M.J. and Youngson, A.F. (1993a). Spawning of escaped farmed Atlantic salmon, *Salmo salar* L., in western and northern Scottish rivers: egg deposition for salmon. *Aquaculture and Fisheries Management* **24**: 663-670.
Webb, J.H., Youngson, A.F., Thompson, C.E., Hay, D.W., Donaghy, M.J. and McLaren, I.S. (1993b). Spawning of farmed Atlantic salmon *Salmo salar* L. in the second year after their escape. *Aquaculture and Fisheries Management* **24**: 557-561
Weber, M. (1997). Farming salmon: A briefing book. San Francisco, CA: The Consultative Group on Biological Diversity.
Webster, S.J, Dill., L.M. and Butterworth, K. (2007). The effect of sea lice infestation on the salinity preference and energetic expenditure of juvenile pink salmon (*Oncorhynchus gorbusha). Canadian Journal of Fisheries and Aquatic Sciences* **64**: 672-680.
Weir, K.L. and Fleming, I.A. (2006) *Behavioural interactions between farm and wild salmon: potential for effects on wild populations.* In: A Scientific Review of the Potential Environmental Effects of Aquaculture in Aquatic Ecosystems, Volume V. Canadian Technical Report of Fisheries and Aquatic Sciences 2450: 1-29.
Wells, A., Grierson, C.E., Marshall, L., MacKenzie, M., Russon, I.J., Reinardy, H., Sivertsgård, R., Bjørn, P.A, Finstad, B., Wenelaar Bonga S.E., Todd, C.D. and Hazon, N. (2007). Physiological consequences of "premaure freshwater return" for wild sea-run brown trout (Salmo trutta) postsmolts infested with sea lice (*Lepeophtheirus salmonis*). *Canadian Journal of Fisheries and Aquatic Science* **64**: 1360-1369.
Wells, A., Grierson, C.E., MacKenzie, M., Russon, I.J., Reinardy, H., Middlemiss, C., Bjørn, P.A, Finstad, B., Wenelaar Bonga S.E., Todd, C.D. and Hazon, N. (2006). Physiological effects of simultaneous, abrupt seawater entry and sea lice (*Lepeophtheirus salmonis*) infestation of for wild, sea-run brown trout (Salmo trutta) smolts. *Canadian Journal of Fisheries and Aquatic Science* **63**: 2809-2821.
Weston, D.P., Phillips, M.J. and Kelly. L.A. (1996). Environmental impacts of salmonid culture. In: Pennell, W. and Barton, B.A. (*eds*.). *Principles of Salmonid Culture. Developments in Aquaculture and Fisheries Science*, vol. **29**. Amsterdam, Elsevier: 1039.

Annex 1:
Atlantic salmon biology

The Atlantic salmon (*Salmo salar*) is found in the temperate and arctic regions of the Northern Hemisphere. Atlantic salmon are anadromous migratory fish, meaning they migrate from the sea into freshwaters to spawn in their native rivers. Spawning time varies between rivers and may be influenced by the water temperature and amount of daylight. Generally, spawning will occur during the period November-December in Great Britain. Approximately 90-95% of all Atlantic salmon die following their first spawning, but some survive to spawn two or three times. The survivors, predominantly female, return to sea to feed between spawnings.

The eggs are laid in depressions called 'redds' excavated by the female fish in the gravel of the river. After the eggs are deposited, they are immediately fertilised by an accompanying male. Hatching usually occurs in early spring and the young fish, known as alevins in this life stage, remain in the redd for a number of weeks, nourished by an attached yolk sac (Thorpe *et al.* 1999). When they emerge from the gravel in April or May, they are about one inch in length. As they grow, the young fish develop prominent 'dirty thumbprint' markings on their sides and are known as parr. The amount of time parr stay in the river is dependent upon the water temperature and the availability of food. Parr then, by improving their hypo-osmoregulatory performance (Waring and Moore, 2004) and developing a flush of silver scales, undergo smoltification (a process transforming parr to smolts). Smolts then have the ability to inhabit saline waters (Madsen *et al*, 2004). Once smolts have left freshwater, they are believed to demonstrate schooling behaviour whilst heading off to oceanic feeding areas, of which the best known are in the Norwegian Sea and the waters off Southwest Greenland. Salmon that remain at sea for more than one winter undertake the longest migrations, whilst grilse, which have only spent one winter at sea before returning to freshwater, tend not to travel beyond the Faroe Islands and the southern Norwegian Sea.

When salmon begin their migration back into freshwater, typically after between 1-4 years at sea (Hendry and Cragg-Hine, 2003), they stop feeding, and live on fat stored in their tissues. This affects the taste of the flesh, and therefore most salmon caught for food are netted at sea, in estuaries or the bottom of river systems.

Salmon aquaculture mimics this lifecycle. Production starts as mature adult salmon are stripped of the eggs and milt in freshwater hatcheries. The subsequent development of the fertilised egg is accelerated by heated water. Once hatched, the fry are reared in high densities in tanks, until they reach smolt size (60-125 grams). After the transition to smolts, which typically takes one year (compared with the average of 2 years in the wild), the fish are moved to ‘grow on’ operations in floating cages or pens in sheltered coastal areas, anchored to the seabed or land. The cages are open to the marine environment to allow water circulation to increase oxygen levels and remove waste materials and surplus food.