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Animal welfare aspects of husbandry systems for farmed Atlantic salmon[1]

Scientific Opinion of the Panel on Animal Health and Welfare

(Question No EFSA-Q-2006-033)

Adopted on 19 June 2008

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PANEL MEMBERS[*]

The Scientific Panel for Animal Health and Welfare (AHAW) of the European Food Safety Authority adopted the current Scientific Opinion on 19 June 2008. The Members of the AHAW Scientific Panel were:

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[*] A minority opinion was expressed from Prof. Donald Broom based on the view that the accepted Report and adopted Opinion are incomplete and that in order to answer the mandate from the European Commission, the introductory chapters on the welfare, biological functioning and farming of fish should be included (Annex II).

SUMMARY

Council Directive 98/58/EC concerning the protection of animals kept for farming purposes lays down minimum standards for the protection of animals bred or kept for farming purposes, including fish. Following a request from the European Commission, the AHAW Panel was asked to deliver a Scientific Opinion on the animal welfare aspects of husbandry systems for farmed Atlantic salmon.. The Scientific Opinion was adopted on 19th June 2008.

From the data presented in the scientific report factors affecting farmed Atlantic salmon welfare were identified which led to conclusions in the Scientific Opinion. These factors are grouped as: environmental conditions (abiotic and biotic factors), feed and feeding, husbandry, genetics and the impact of disease and disease control measures. A risk assessment was carried out to obtain a ranking of risk and compare the production systems. The discussion of the risk assessment is presented in the opinion.

Atlantic salmon behaviour such as feeding, swimming and social behaviour are relevant when considering the welfare impact of farming systems. Genetic selection of salmon should take into account possible consequences for their welfare of any changes.

The main factors affecting Atlantic salmon welfare were considered to be those discussed below.

Water quality is essential for good welfare in fish and several damaging effects of poor water quality on fish health were recognised. Water quality effects relate not only to the absolute levels but also to the rate of its change and interactions with other factors. Tolerance levels were indicated when available. For instance it was recommended that oxygen saturation should be maintained above 70% to maintain full appetite and growth but subsequent research on the impact on fish welfare may show that higher levels are required. Carbon dioxide concentration (CO_2) can be an important factor especially in systems where oxygen supplementation is used. Optimal photoperiod and light intensity are also key factors and different positive and negative effects according to the life stage were identified.

Stocking density was considered a major factor affecting salmon welfare. Its effects interact with those of many other factors and make it difficult to establish a maximum and minimum values or optimum stocking densities that would safeguard welfare. The monitoring of the conditions of the fish, such as fin damage, other injuries, growth rate, and behaviours expressed and overall health, was recommended to set appropriate levels of stocking density.

Atlantic salmon diet contains a high proportion of marine fish meal and oil, to meet size and life cycle specific requirements for macro- and micronutrients but the increased demand for marine feed components has placed a focus on alternative resources. Introduction of novel non-marine feed components can lead to specific problems although there is evidence for their potential to partly replace high quality fish meal in diets.

Grading (sorting by body size) is an important part of husbandry. Grading systems should be set up to minimise the time fish are out of the tanks or cages, to ensure sufficient water quality is maintained and to minimise stress. Monitoring of the environment, fish size, fish health status and fish behaviour was recommended.

Saprolegnia infection, winter ulcer disease, IPN and sea lice are examples of diseases that cause poor welfare, and require control. Availability of veterinary medical products approved for Atlantic salmon is limited and this constitutes an important risk. Vaccines have made a significant contribution to controlling serious infectious diseases and to the significant reduction of the use antibiotics/chemotherapeutics. However several risks were identified. Future research on non invasive effective vaccination methods and new types of adjuvant is necessary.

A risk assessment approach was used to compile a risk ranking for these groups of factors, estimate which hazards are more important for each life stage and enable a comparison of the different production systems. Due to the limited amount of quantitative data related to production systems and effects of potential hazards on Atlantic salmon welfare, the risk assessment was mainly based on expert opinion.

In the risk assessment no major differences were found concerning overall welfare risk among the different production systems used for each life stage. Production systems can differ in their risk score for different categories of hazards, since they can have specific risks. Measures to improve welfare should be adapted to different production systems taking into consideration the specific requirements of each life stage.

A minority opinion was received based on the view that the accepted Report and adopted Opinion are incomplete and that in order to answer the mandate from the European Commission, the general chapters on the welfare, biological functioning and farming of fish should be included.

Key words: **Atlantic salmon, welfare, risk assessment, fish-farming, stocking density, water quality, feeding, disease.**

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BACKGROUND AS PROVIDED BY THE EUROPEAN COMMISSION

Council Directive 98/58/EC concerning the protection of animals kept for farming purposes lays down minimum standards for the protection of animals bred or kept for farming purposes, including fish.

In recent years growing scientific evidence has accumulated on the sentience of fish and the Council of Europe has in 2005 issued a recommendation on the welfare of farmed fish[2]. Upon requests from the Commission, EFSA has already issued scientific opinions which consider the transport[3] and stunning-killing[4] of farmed fish.

TERMS OF REFERENCE AS PROVIDED BY THE EUROPEAN COMMISSION

In view of this and in order to receive an overview of the latest scientific developments in this area the Commission requests EFSA to issue a scientific opinion on the animal welfare aspects of husbandry systems for farmed fish. Where relevant, animal health and food safety aspects should also be taken into account. This scientific opinion should consider the main fish species farmed in the EU, including Atlantic salmon, gilthead sea bream, sea bass, rainbow trout, carp and European eel and aspects of husbandry systems such as water quality, stocking density, feeding, environmental structure and social behaviour.

Due to the great diversity of species it was proposed that separate reports and scientific opinions on species or sets of similar species would be more adequate and effective.

It was agreed to subdivide the initial mandate into 5 different questions.

Question 1

- In relation to Atlantic salmon

Question 2

- In relation to trout species

Question 3

- In relation to carp species.

Question 4

- In relation to sea bass and gilthead sea bream

Question 5

- In relation to European eel

This opinion will refer only to question 1 as referenced above.

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[2] Recommendation concerning farmed fish adopted by the Standing Committee of the European Convention for the protection of animals kept for farming purposes on 5 December 2005

[3] Opinion adopted by the AHAW Panel related to the welfare of animals during transport -30 March 2004

[4] Opinion of the AHAW Panel related to welfare aspects of the main systems of stunning and killing the main commercial species of animals- 15 June 2004

ACKNOWLEDGEMENTS

The European Food Safety Authority wishes to thank the members of the Working Group, chaired by the panel member Donald M. Broom, for the preparation of the Scientific Report, which has been used as the basis of this Scientific Opinion: Ron Roberts, Christine Müller-Graf, Geir L. Taranger, Børge Damsgård, Sunil Kadri, Tore Hastein, Lynn U Sneddon and Toby Carter.

The scientific co-ordination for this Scientific Report has been undertaken by the EFSA AHAW Panel Scientific Officers Ana Afonso, Tomasz Grudnik and Denise Candiani.

CONCLUSIONS AND RECOMMENDATIONS

1. OUTCOMES FROM THE DATA PRESENTED IN THE SCIENTIFIC REPORT

1.1. Atlantic salmon Life History

RECOMMENDATION

- The evaluation of the needs of salmon, and consequently of salmon welfare, should take into consideration the functioning of the fish during each different life stage.

1.2. Atlantic salmon farming

CONCLUSIONS

- There are relatively few hatcheries compared with the number of ongrowing farms. The most common farming systems are flow-through freshwater tanks up to the smolt stage and sea cages up to time of slaughter. Broodstock are normally transferred back to freshwater tanks prior to spawning.
- The ongrowing stage in sea cages represents normally 50-70% of the life cycle.

RECOMMENDATION

- Data on Atlantic salmon farming production systems used and key production indicators such as stocking densities, mortality, feed consumption and water quality indicators should be collected at European level in order to better evaluate the impact on welfare.

1.3. Biology of salmon

1.3.1. Feeding behaviour

CONCLUSIONS

- Feeding behaviour in wild salmon changes markedly between the freshwater and sea-water stages. The extent to which this is reflected in farmed salmon and the effect on their welfare is not precisely known.
- Salmon show a variety of different feeding patterns, including a daily rhythm of feeding. Feeding level changes substantially during maturation and ceases before spawning.
- The salmon is quite aggressive at the parr stage, and periods of food absence are one of the factors that can lead to fin-biting or other damage.

RECOMMENDATION FOR FUTURE RESEARCH

- Studies of the relevance of feeding behaviour in the wild to the welfare of farmed fish are needed.

1.3.2. *Swimming behaviour*

CONCLUSIONS

- Available space as well as water currents and life stage can affect swimming speed and swimming behaviour, and it is believed that larger rearing units can stimulate or allow higher swimming speed.

- Moderate increase in swimming speed may reduce agonistic behaviour and stress responses during the freshwater stages.

- Schooling behaviour depends on group size. With normal farming group sizes in sea cages, salmon swim in a structured school provided that there is sufficient light for visual contact. It is believed that schooling behaviour may reduce agonistic behaviour in salmon.

1.3.3. *Alertness and Exploration*

CONCLUSIONS

- Predation avoidance is an important part of the behavioural and physiological repertoire of salmon as they are very vulnerable to predation, especially when young. As a consequence, the fear system and other predator avoidance mechanisms are well-developed. Humans can elicit anti-predator responses or positive responses with possible effects on salmon welfare.

- The presence of shelters in juvenile salmon rearing systems is associated with indicators of reduced stress.

- Farmed salmon show exploratory behaviour in relation to several functions including food-finding, predator avoidance and aggression avoidance but the effect on their welfare is not precisely known.

1.3.4. *Social behaviour*

CONCLUSIONS

- Husbandry systems of whatever type, remove many of the circumstances that affect the behaviour of wild salmon.

- Aggression has genetic and environmental components. Although feed ration is the most studied factor, sub-optimal conditions can also include poor feed management, low water current speed, and low fish stocking density.

- The consequences of harmful behaviour in farmed salmon are indicators that there has been, or that there still is poor welfare. Such indicators include major injuries, bitten or otherwise damaged fins, and increased mortality. Where observations of behaviour are possible, measures also include observations of biting and the presence of subordinate fish that are unable to obtain sufficient resources.

- The importance of aggression as a decisive factor in social hierarchies has been demonstrated by superior performance of the most aggressive fish. The formation of such hierarchies in the sea water stage is not well established, also in realistic farming situations in fresh water stages such hierarchies may be suppressed with moderately high stocking density and sufficient feeding.

- Salmon are predators and will occasionally damage smaller members of their own species. They can also be aggressive to co specifics of similar size, in particular during the fresh water stages, including sexual maturation; this can be minimised by appropriate management.
- Sexual maturation occurs when there is a period of high feed intake and is associated with increased aggressiveness. A small percentage of fish reach sexual maturation during the normal farm production cycle.

1.4. Factors affecting Farmed Atlantic salmon welfare

1.4.1. Environmental conditions Abiotic Factors

CONCLUSIONS

- Water quality is essential for good welfare in fish and several damaging effects of poor water quality on fish health were recognised.
- All aquatic organisms have certain tolerance limits with regard to water quality where they are able to maintain homeostasis but limits for good welfare may be narrower and more difficult to determine.
- The threat to fish welfare from water quality relates not only to the absolute levels but also to the rate of its change and interactions with other factors.

RECOMMENDATION

- Care should be taken when keeping salmon of all ages to monitor water quality and to minimise exposure to adverse water quality conditions or changes in water quality to which the fish cannot easily adapt.

1.4.1.1. pH

CONCLUSIONS

- Safe levels of water pH depend on adaptive ability and the interaction with a range of other water quality parameters, especially aluminium (Al) and ammonia and are different for different life stages. Alevins are particularly sensitive to extreme pH.
- Although some farms operate successfully at pH levels of 5.4 to 6, because of the various interacting factors problems are more likely to occur unless there is a pH range for salmon of 6.0-8.5 in fresh water and 7.0-8.5 in sea water.
- Low oxygen levels, low pH, and high labile aluminium and other toxic metal concentrations are factors that interact and can harm eggs and alevins and result in mortalities and developmental disorders.

RECOMMENDATION

- In the water in which salmon live, pH should be monitored closely, and according to the other environmental conditions, maintained above 5.4 and preferably within a range of 6.0-8.5 in fresh water and preferably above 7.0 in sea-water. Rapid changes and extreme values of acidity or alkalinity should be avoided.

1.4.1.2. Water temperature

CONCLUSIONS

- Temperature tolerance is highly dependent on acclimation and in general salmon seem to be able to adapt to temperatures in the range of 0-20 C provided the fish are supplied with water saturated with oxygen. However, most life-stages: eggs, alevins, fry, smolts and sexually mature fish, have limited temperature tolerance for normal development.
- The water temperature affects the development and loss of sea-water tolerance, and hence the time window for transfer to sea-water, for salmon smolts.
- Temperatures at which salmon egg hatching is successful vary in the industry up to 11C or more. However some experimental studies indicate a correlation between high temperatures (above 8C) and deformities. Hence there is uncertainty about the effects of higher temperatures.
- Rapid changes of temperature can lead to severe stress in salmon at all life stages.

RECOMMENDATION

- Rapid changes in temperature and extreme temperatures should be avoided particularly in the early life stages.

1.4.1.3. Salinity

CONCLUSIONS

- The ability to tolerate salinity above 10ppt increases with increasing body size, but full osmoregulatory capacity in full strength sea water (>30ppt) is only achieved after a proper smoltification (parr-smolt transformation).
- The early transfer of salmon pre-smolts to full strength sea water leads to a large risk of poor welfare.
- Sexually mature fish lose their ability to maintain hydro mineral balance in sea water as they approach spawning.

RECOMMENDATIONS

- When salmon are to be transferred to sea water, appropriate photoperiod, salinity and temperature conditions for effective smoltification should be provided to allow complete physiological change before transfer. Appropriate tests should be applied to verify the smolt status.
- Salmon broodstock should be kept in freshwater or brackish water with salinity below 10ppt prior to and after spawning.

1.4.1.4. Oxygen

CONCLUSIONS

- All life stages of salmon have a high demand for oxygen. The relative oxygen consumption (mg O_2/kg fish/min) of the salmon increases with temperature, activity, feed consumption and stress level, while it decreases with increasing body size.
- The available dissolved oxygen (mg/l) in water depends on temperature, salinity and the partial pressure of oxygen in the air that is in contact with the water.
- Dissolved oxygen is normally a limiting factor in flow-through tanks, unless extra oxygen is added and low oxygen level due to low water flow in combination with high stocking biomass is a major hazard.
- There are indications of impaired growth and appetite below 80% saturation. Mortality starts to occur at around 40%.
- Reduced growth, increased stress levels and increased susceptibility to viral diseases following use of hyper oxygenated water (>150% in inlet water) on pre smolts have been reported.
- The concentration of oxygen available to fish varies across different production systems and for different life stages. There is a welfare issue related to the oxygen available to the fish, including the security of the supply where extra oxygen is supplied. In all systems a reduction in the oxygen saturation will cause welfare problems and can lead to mortality.

RECOMMENDATION

- The oxygen saturation as a guideline should be maintained above 70% to maintain full appetite and growth but subsequent research on the impact on fish welfare may show that higher levels are required.
- Sitting, cage design, cage orientation, bio fouling control and stocking density should be optimised to maintain adequate oxygen levels in cages.

1.4.1.5. Carbon dioxide

CONCLUSION

- Carbon dioxide concentration (CO_2) can be an important factor affecting salmon welfare. Carbon dioxide concentration and its effects depend on water quality factors such as pH, temperature, water flow and stocking density.

RECOMMENDATION FOR FUTURE RESEARCH

- Further studies are needed for determining the lowest observed effect of the concentration of CO_2 in interaction with other water quality factors and its effects on the various life-stages of farmed salmon.

1.4.1.6. Super saturation

CONCLUSION

- Super saturation is an uncommon but serious cause of mortality in farmed salmon. Salmon are particularly vulnerable to super saturation, during the early life stages. However, maximum values for safe super saturation are not known.

RECOMMENDATION

- Care should be taken to avoid super saturation of dissolved gases that might harm salmon for example by effective monitoring and equipment maintenance.

RECOMMENDATION FOR FUTURE RESEARCH

- The level of gas super saturation capable of inducing sub-lethal effects and the nature of these effects need to be further investigated.

1.4.1.7. Ammonia

CONCLUSIONS

- Ammonia, a fish waste product, is present in ionised and un-ionised forms. The level of the more toxic form, the un-ionised ammonia is dependent on total ammonia level, pH, temperature and salinity.
- Sub-lethal concentrations of ammonia can damage the gills and also impair immune function leading to increased susceptibility to infectious disease.
- High stocking densities and insufficient water flow result in build up of ammonia in the water.
- Concentrations of un-ionized ammonia higher than 0.02 mg/l for all stages have been shown to cause tissue damage resulting in poor welfare.

RECOMMENDATION

- To maintain good welfare the maximum level of un-ionised ammonia (NH_3) should not exceed 0.02 mg/l for all stages.

1.4.1.8. Nitrite

CONCLUSION

- High levels of nitrite have toxic effects on freshwater life stages of Atlantic salmon.

RECOMMENDATION

- Nitrite concentrations that are harmful to salmon should be avoided.

RECOMMENDATION FOR FUTURE RESEARCH

- The nitrite concentrations capable of inducing sub-lethal effects and the nature of these effects need to be further investigated.

1.4.1.9. Aluminium

CONCLUSION

- Poor welfare and increased likelihood of mortality result when there are significant concentrations of aluminium in low pH conditions, Salmon are particularly vulnerable during smoltification to levels of labile Al above 20 µg/l. Water treatment methods are available to reduce the problem.

RECOMMENDATION

- Salmon should not be exposed to aluminium concentrations that result in poor welfare, for example, concentration of labile Al above 20µg/l should not be present during smoltification.

1.4.1.10. Other metals

CONCLUSIONS

- Environmental conditions such as pH, oxygen concentration, temperature, hardness, salinity and presence of other metals may modify metal toxicity to fish. Hypoxic conditions, temperature increase, and acidification usually render the fish more susceptible to toxic effects of metals.

RECOMMENDATION

- Salmon should not be exposed to concentrations of metals such as copper, iron, zinc and cadmium that result in poor welfare. Water supplies should be monitored for the levels of such metals, and equipment in direct contact with the water should not result in metal contamination that harms fish.

RECOMMENDATION FOR FUTURE RESEARCH

- Research on the effects of metals in water and diet in the welfare of farmed salmon is needed.

1.4.1.11. Suspended solids

CONCLUSIONS

- High content of suspended solids can sometimes injure gills and other tissues of salmon, and lead to panic reactions.

- The total amount and physical characteristics of suspended particles in water are relevant to the possible impact on Atlantic salmon.

1.4.1.12. Water flow

CONCLUSIONS

- Parr prefer high water flow rates whereas fry prefer areas of low flow within rivers and these life stage requirements are normally taken into account in fish farms.

- Water flow is important for water renewal and for the water current itself. Where water flow is insufficient for the fish stocking density, there can be an accumulation of harmful metabolites in the water as well as depletion of dissolved oxygen.

RECOMMENDATION

- Salmon should have sufficient water flow for removal of waste products and uneaten food and for oxygen provision if not otherwise provided, but the flow should not be too great for the young fish to maintain station without excessive energy usage.

1.4.1.13. Water depth

CONCLUSIONS

- Water depth will affect available space, gradients in hydrostatic pressure and light, as well as time for feed to sink through the water column, all factors that can affect salmon welfare.
- The water depth also affects the ability of the farmer to inspect and monitor the behaviour of the fish, such as feeding behaviour, panic behaviour, or behaviour indicative of diseases.
- Salmon need to be able to go to the surface to fill the swim bladder, and therefore require contact with air at the water surface to maintain neutral buoyancy in the water column. Whilst they appear to be able to adapt to periods of submersion without contact with the surface, it is not clear how difficult it is for the fish to adapt to this situation.
- The swimming depth (i.e. the vertical positioning) in sea cages depends on environmental gradients of light, temperature and salinity and is modulated by feeding motivation and health status. Salmon appear to choose micro environments in the sea cages based on these gradients, this can lead to unequal usage of the water column affecting fish density and thereby the oxygen consumption at certain depths.
- During the alevin stage and until shortly after first feeding, salmon need a bottom substratum for vertical support such as gravel, dense vegetation or artificial grass. Lack of such support will reduce survival, first feeding success and growth and may lead to deformities.

RECOMMENDATION

- Where water depth does not allow for the direct observation of fish other methods (eg. underwater cameras) should be used for effective monitoring.
- All salmon alevins should have an appropriate bottom substratum such as gravel, dense vegetation or artificial grass for vertical support.

1.4.1.14. Light

CONCLUSIONS

- Optimal photoperiod and light intensity are key factors in the development of Atlantic salmon but have different effects according to the life stage.
- Exposure to light during egg and alevin stage is negative since light stimulates physical activity which results in poorer yolk sac conversion into somatic growth.

- From first feeding onwards light is considered as a positive factor and long days or continuous light stimulate growth and rapid development. Low light intensity (less than 10 lux) at the parr stage can have negative effects on growth, whereas intensities between 30 and 1000 lux did not have adverse effects on growth.

- Appropriate photoperiods (circadian periods of darkness and light) are needed for proper timing and completion of events such as smoltification and sexual maturation.

- Photoperiod treatments (continuous light regimen) reduce precocious sexual maturation in salmon parr in freshwater with positive effects on fish welfare.

- Continuous light during winter and spring stimulates somatic growth in salmon post-smolts and can reduce the proportion of sexually maturing fish with positive effects on fish welfare.

- Photoperiod treatments can be employed to advance or delay the spawning time. Improper combinations of photoperiod and temperature may result in failed spawning in salmon broodstock.

- Artificial light can be used as a tool to control salmon swimming depth in cages, and indirectly the actual fish density by leading to a homogeneous fish distribution.

- Use of light to accelerate growth and stimulate early out-of-season smoltification has been associated with lowered skeletal mineralisation and bone strength under given conditions.

RECOMMENDATION

- Eggs and alevins should be kept in darkness. Other life stages should be provided with light and appropriate photoperiod signals to ensure proper timing of events such as smoltification and sexual maturation and maintenance of homeostasis.

RECOMMENDATION FOR FUTURE RESEARCH

- Further research is needed to determine welfare implications of photoperiod and light manipulations at the various life-stages of salmon.

1.4.2. Environmental conditions Biotic Factors

1.4.2.1. Predation

CONCLUSIONS

- Predators cause mortalities, inflict damage on fish and are responsible for distress and feeding interruptions.

RECOMMENDATION

- Salmon should be managed in such a way that harmful aggression and predation are minimised. Protective measures, such as ropes or netting to prevent or deter predator entry, should be used in particular on cage systems.

1.4.2.2. Species that may invade sea cages

CONCLUSION

- Poor welfare risks due to invasive species such as algae or jelly fish in open water systems can be very severe although rare and unpredictable.

RECOMMENDATION

- Consideration should be given to the development of contingency plans to protect the salmon from episodic exposure to invasive species such as jellyfish and toxic algae.

1.4.2.3. Stocking Density

CONCLUSIONS

- Stocking density is a major factor affecting salmon welfare. Its effects derive from interaction with many other factors that make it difficult to establish maximum and minimum values or optimum stocking densities that would safeguard welfare. Although high densities may lead to a reduction in the quality of the rearing environment and subsequently welfare problems, both low and high densities can result in increased of intra-specific aggression.
- The optimum stocking density for salmon has not been determined to the extent that an equation for space requirements of salmon can be provided in this report.
- Although the welfare of cage salmon has been observed to vary widely (from poor to good) at densities between 10 and 30 kg/m^3, there are indications that above some higher stocking densities, e.g. 22-23 kg/m^3, the risks of poor welfare increase.

RECOMMENDATIONS

- Stocking density per se should not be used as an indicator for good welfare.
- As it is difficult to set appropriate levels of stocking density the monitoring of the conditions of the fish (such as fin damage, other injuries, growth rate, behaviours expressed and overall health) should be used.

RECOMMENDATION FOR FUTURE RESEARCH

- The effects of stocking density on the welfare of fish in various conditions should be investigated.

1.4.3. Feed and Feeding

CONCLUSIONS

- Farmed salmon are fed exclusively on proprietary diets formulated to meet the size and life stage requirements. Current commercial diets generally are well formulated, based on research and industry experience. However, there are uncommon instances where welfare problems have occurred as a result of nutritional deficiencies arising from improperly formulated diets.

- Atlantic salmon diet contains a high proportion of marine fish meal and oil, to meet size and life cycle specific requirements for macro- and micronutrients but the increased demand for marine feed components has placed a focus on alternative resources. Introduction of novel non-marine feed components can introduce problems due to their inherent nutritional deficiencies e.g. essential amino acids, PUFAs and presence of anti-nutrient factors, although there is recent evidence for their potential to partly replace high quality fish meal in diets.

- Feed delivery methods are of primary importance to the success of feeding but different approaches generally ensure that salmon populations are fed daily according to their needs at a population level, and hence, lack of food is not, on the whole, considered as a welfare issue although some individual fishes may receive insufficient food.

- Short-term periods of feed restriction are commonly used in salmon production, for welfare reasons, e.g. before handling or transporting fish, there is no published data on negative impact of these practices on welfare.

RECOMMENDATIONS

- Farmed salmon should have daily access to sufficient feed with appropriate composition in order to provide nutrients for normal activity, growth and homeostasis, to minimise size variability and potentially to reduce competition and associated stress or body damage. This is particularly important for parr, that may show fin-biting and other injurious behaviour and for smolt during the first period after sea water transfer when energy reserves are limited.

- The accessibility to feed should be appropriate in relation to: feeding regime and dose, pellet size, distribution and sinking velocity, stocking density, fish distribution, schooling behaviour and level of competition. Larger salmon usually have more energy reserves and can tolerate somewhat longer periods of feed deprivation.

- Nutritional requirements of salmon are generally well known and should be properly addressed especially in terms of micronutrient bioavailability and absence of anti-nutritional factors, when novel feed ingredients, such as vegetable proteins and lipids are introduced, or as a result of dietary adjustments for compliance with new regulatory requirement or environmental concerns.

- Feeding systems and protocols in sea-cages should ensure that there is sufficient feed availability for all individuals in the cage.

1.4.4. Husbandry and Management

CONCLUSION

- There is little published information on the impact on welfare of husbandry and management procedures in Atlantic salmon farming.

1.4.4.1. Handling

CONCLUSIONS

- Various handling procedures can lead to injury, stress and increased disease incidence in salmon. Handling is however essential during several procedures such as grading and vaccination that contribute to good welfare for farmed salmon.

- The alevins are fragile regarding handling, especially in the period just after hatching when the yolk sac is still large.

- Smolts are a very vulnerable stage in the salmon life cycle, both due to physiological and morphological changes.

- Poor physiological adaptation to the sea water, poor water quality during smoltification and rough handling or transportation may lead to impaired welfare, increased mortality and increased susceptibility to diseases following transfer to sea water.

- Broodstock at the final stages of sexual maturation are very susceptible to handling damage and secondary infections.

- Single stripping followed by slaughter is better for welfare than multiple usage and handling of males.

RECOMMENDATIONS

- Handling of salmon should be minimised and proper equipment and handling protocols used to avoid stress and physical damage associated with handling procedures. In many cases anaesthetics are needed to minimise stress and physical damage.

- Alevins should only be handled close to first feeding, when most of the yolk sac is resorbed

- Broodstock should be handled with the greatest care under anaesthesia in order to minimise physical damage and stress

- Single stripping followed by slaughter should be used to avoid multiple usage and handling of males.

1.4.4.2. Crowding

CONCLUSION

- Crowding to very high densities, associated with pre-slaughter levels (>200 kg/m³) has been identified as causing an increase in stress indicators such as cortisol concentration in adult salmon

RECOMMENDATION

- Appropriate crowding systems and tank design should be used to minimise the adverse effects of crowding.

1.4.4.3. Grading

CONCLUSION

- Grading (sorting by body size) is an important part of husbandry as it prevents aggression and in smaller fish, cannibalism. Grading may cause stress if the fish are removed from water or if damage to scales, skin or other tissues occurs.

- Grading of parr is especially important before the initiation of smoltification. The wider the size range at sea water transfer, the more likely it is that a number of individuals within the population will be unable to osmoregulate properly.

RECOMMENDATIONS

- Grading systems should be set up to minimise the time fish are out of the tanks or cages, to ensure sufficient water quality is maintained and to minimise physical stress on the fish.

- Large size variation in salmon smolt populations transferred to sea water should be avoided

1.4.4.4. Monitoring

RECOMMENDATIONS

- There should be proper monitoring of the environment, fish size, fish health status and fish behaviour in order to take appropriate actions to ensure good welfare during the production cycle, including various prophylactic measures. This includes effective and repeated monitoring of key environmental factors such as oxygen and temperature, pH, CO2, ammonia, salinity, nitrate, turbidity and light. A monitoring system should also include regular monitoring of biomass, fish numbers and size, feed consumption and appetite control. Monitoring of fish condition and behaviour as potential welfare indicators is also essential.

- There should be appropriate treatment protocols and emergency plans, including those for emergency killing and removal of dead fish.

1.4.4.5. Smoltification testing

CONCLUSION

- The monitoring of smoltification is essential to determine timing for transfer to sea water. Several testing methods are used by the industry to monitor sea water tolerance in smolt batches

RECOMMENDATION

- Methods for testing for smoltification with reduced welfare risk, such as measurement of ATPase activity in gill tissues, should be used.

1.4.5. Genetics

CONCLUSIONS

- Farmed salmon have been subject to selective breeding for less than ten generations and are morphologically indistinguishable from wild fish

- Genetic selection in Atlantic salmon has been for rapid growth, late sexual maturation, improved harvest quality and resistance to diseases.

- Increasing genetic resistance to endemic diseases greatly improves welfare. Selection for resistance to a certain type of disease may compromise resistance towards other disease or affect other life history traits.

RECOMMENDATION

- Genetic selection of salmon should take into account possible consequences for their welfare of any changes.

RECOMMENDATIONS FOR FUTURE RESEARCH

- Research is needed on the possible effects in genetic variability and consequences of breeding programmes.

- Further research on triploid salmon production and all female production is desirable, taking account of welfare and environmental perspectives.

1.4.6. Impact of disease on welfare in Atlantic salmon

1.4.6.1. Furunculosis

CONCLUSION

- Furunculosis is a systemic bacterial disease in all life stages of Atlantic salmon. Effective oil-adjuvanted vaccines are available and are widely used in Atlantic salmon farming for prevention and control of furunculosis but such vaccines produce adverse effects that from a welfare point of view are undesirable.

RECOMMENDATION FOR FUTURE RESEARCH

- Research should be initiated into methods of stimulating immunity to Aeromonas salmonicida which do not require aggressive inflammatory response to ensure efficacy.

1.4.6.2. Winter ulcer disease

CONCLUSION

- Winter ulcer disease is a bacterial disease of Atlantic salmon in sea-water. Sub-optimal conditions such as high fish density, poor water exchange, low water temperatures, previous infections with salmon lice and inadequate nutrition may play a role in the development of disease. Antibiotic therapy, vaccination and supportive husbandry methods are of some value against winter ulcer disease.

RECOMMENDATION FOR FUTURE RESEARCH

- More effective vaccines for winter ulcer disease should be developed.

1.4.6.3. *Saprolegnia* infection

CONCLUSION

- *Saprolegnia* is a particular problem in freshwater in particular to sensitive life stages such as smolt and broodstock. Poor handling and hygiene constitute predisposing factors. Since the removal of Malachite Green from the available treatments for *Saprolegnia*, there is no adequate alternative. The only approved treatment in Europe is less effective.

RECOMMENDATION

- A suitable alternative treatment for fungal infections which is both efficacious and environmentally acceptable should be developed.

1.4.6.4. Infectious pancreatic necrosis (IPN)

CONCLUSION

- IPN is a serious disease with profound welfare significance particularly in the fry and smolt stages. Vaccines are becoming available but cannot deal with IPN in fry. Even when the immune system is properly developed, vaccination is still not normally an option for salmon parr until the fish are 30g or more as there are few reliable delivery systems to allow oral or in tank application of vaccines to such fish which are too small for vaccination by injection.Genetic selection and improved biosecurity are likely to be the area where greatest benefits will accrue.

RECOMMENDATIONS

- Eggs should be from SPF tested sources and from strains with a IPN resistance selection programme.
- All farms should have a verifiable and audited integrated biosecurity programme for viral pathogen management.

1.4.6.5. Sea lice

CONCLUSIONS

- The ectoparasitic copepod sea-lice, principally *Lepeophtheirus salmonis*, can cause severe tissue damage on the surface of the bodies of salmon in sea cages. Sea-lice can cause very poor welfare and severe economic loss.
- Treatment for sea lice can be administered via feed but most treatments require that the fish is held in a small volume of water and subjected to a relatively high concentration of chemical. The restriction in itself involves poor welfare.

RECOMMENDATION

- Salmon with significant infestations of sea-lice should be treated to avoid serious risk of poor welfare

- All marine farms should maintain a sea-lice strategy to minimise infestation from wild fish, involving stocking arrangements, monitoring and strategic treatment using appropriate chemicals. It is important that such strategies are developed in agreement with neighbouring farms and wild fish interests.

RECOMMENDATION FOR FUTURE RESEARCH

- Research is necessary on genetic resistance of Atlantic salmon to sea lice, more efficacious treatments and improved husbandry to prevent treatment resistance in sea lice as well as development of vaccination and attractants.

1.4.6.6. Pathology resulting from jellyfish strikes

CONCLUSION

- Jellyfish can be extremely serious welfare risks. They are however spasmodic and unpredictable in their occurrence.

1.4.6.7. Eye-lesions

CONCLUSION

- Eye lesions are multi factorial and often consequences of inadequate husbandry. In particular, cataracts leading to blindness and failure to feed have been frequently associated with dietary imbalance and are a serious welfare problem.

RECOMMENDATION

- Feedstuffs that cover the nutritional needs of Atlantic salmon and optimised management procedures should be used to avoid stress and mechanical damage, thus reducing the risk of eye-lesions and secondary infections.

1.4.6.8. Effect of poor welfare on disease

CONCLUSION

- Intensification of production systems adds to the stress levels and consequent risk of disease. Intensive systems therefore require the highest standards of management and monitoring.

RECOMMENDATION

- Salmon should be managed in such a way to avoid poor welfare and consequent immune system function suppression and increase of vulnerability to disease.

1.4.7. Disease Control Measures

1.4.7.1. Medical control measures

CONCLUSION

- Availability of veterinary medicinal products approved for Atlantic salmon is limited and this constitutes an important risk for poor welfare caused by diseases.

RECOMMENDATIONS

- Measures should be taken to facilitate rapid and beneficial release of efficacious veterinary medicinal products for use in fish farming.
- Approval procedures for veterinary medicinal products for aquatic animals should take into account animal welfare consequences.
- In the case of severe diseases to which therapeutic measures are inadequate or not available, killing in the interests of welfare is recommended.
- Organic certification systems in relation with the use of necessary treatments for salmon diseases should be reviewed taking into account animal welfare consequences.
- The usage of antimicrobials and other medical products should be monitored as well as resistance pattern in significant pathogens. Such a monitoring should also include the use of vaccines.

1.4.7.2. Vaccination of fish

CONCLUSIONS

- Vaccines have made a significant contribution to controlling serious infectious diseases and to the significant reduction of the use antibiotics/chemotherapeutics.
- Presently the benefits of higher immunogenicity and longer effect of injectable adjuvanted vaccines are considered more than the associated welfare risks.
- Vaccination of fish may be by immersion, feeding or ingestion although most is by injection.
- Adjuvants are widely used, some causing a chronic inflammatory response in the peritoneum, which seems a necessary component of its mode of action.
- Vaccination can involve handling stress, growth retardation, deformities and injuries such as peritoneal adhesions, all of which are welfare issues. These effects are long lasting and can affect all the individuals in the population.

RECOMMENDATION

- All methods of vaccination of fish should minimise any poor welfare that they cause

RECOMMENDATIONS FOR FUTURE RESEARCH

- Future research on non invasive effective vaccination methods is necessary
- Further research on scientifically acceptable levels and distribution of lesions or effects should be developed to determine thresholds of acceptability of all injectable immunological preparations.
- Future research on new types of adjuvants, such as double phase adjuvants, without losing vaccine efficacy is necessary.

1.4.8. Biosecurity

CONCLUSION

- Individual farm biosecurity strategies with mandatory protocols are a major advantage in controlling the spread of serious infectious disease and hence poor welfare.

RECOMMENDATION

- Farms should operate to agreed biosecurity plans subject to veterinary audit

1.4.9. Mortality

CONCLUSIONS

- A farm annual health plan that is subject to regular veterinary audit allows monitoring of fish health and mortalities and is a major means of detecting health status problems and instituting therapeutic or husbandry modifications which will limit their welfare effects in a timely and economic fashion.
- There is often a high level of un-accounted mortality or loss in salmon farming in sea cages.

RECOMMENDATIONS

- All salmon farms should operate veterinary audits encompassing mortality recording and annual audit.
- Any increased mortality level should be investigated.
- Fish should be accurately counted when entering the cage, and dead fish should be accounted for, and rapidly removed to avoid spread of diseases and to indicate situations where there is poor welfare.

2. RISK ASSESSMENT

2.1.1. Discussion risk assessment

The risk scores based on expert advice were used to compile a risk ranking by category such as abiotic or biotic to obtain an idea which hazards are the more important for each life stage in the various production systems considered, and also to enable the comparison of the different production systems.

2.1.1.1. Welfare risks associated with eggs incubation

Only hazards belonging to the abiotic factors category were assessed. Welfare impact on subsequent life stages was considered. The adverse effect considered was the development of deformities which would lead to life long poor welfare consequences. The ranking by order of the highest risk scores is summarized in (Table 1).The combined uncertainty scores were high for all abiotic factors.

No considerable differences between the 2 production systems, cylinders and trays, were found with regards to potential risks to welfare.

Table 1. Welfare risk ranking - Eggs

	Trays	**Cylinders**
Abiotic	Rapid change of water temperature Too high water temperature Too high water flow	Rapid change of water temperature Too high water temperature Too high water flow

2.1.1.2. Welfare risks associated with farming of alevins

Only hazards belonging to the diseases, husbandry and abiotic factors categories were assessed in a single system, trays. The ranking by order of the highest risk scores is summarized in Table 2. The diseases considered for this life stage constituted a high risk for poor welfare since death is usually preceded by severe pathological alterations. Absence of suitable substrate for the alevins support was considered an important risk for alevins in trays and although a low exposure was assessed, its adverse effects were considered severe as it could affect the entire life of the salmon. The combined uncertainty scores were high for all abiotic factors moderate for husbandry and low for diseases.

Table 2. **Welfare risks ranking - Alevins**

	Trays
Disease	*Saprolegnia* IPN
Abiotic	Environmental complexity (lack of vertical support) Rapid change of water temperature Too high water temperature
Husbandry	Lack of biosecurity /lack of staff training

2.1.1.3. Welfare risks associated with farming of Fry

The welfare risks associated with diseases constituted high risk for poor welfare in particular conditions such as eye lesions which adverse effects may continue in subsequent life stages .For the abiotic hazards category, water oxygen content constituted the most important welfare risk but in recirculated tanks high CO_2 was assessed as the limiting factor. The adverse effects of stocking density were found to be high as well as interspecific interaction (aggression). High stocking density is closely linked with deterioration of water quality but the aspects of interaction are difficult to disentangle. For the feeding, an unbalanced diet and lack of food over long periods were the higher score hazards. Lack of biosecurity and insufficient grading as well as lack of staff training were ranked highest in the husbandry factors category. The combined uncertainty scores were low for both diseases and husbandry factors. The ranking by order of the highest risk scores is summarized in Table 3.

Two production systems were considered; flow-through tanks and tanks with recirculation. For the fry, recirculated tanks showed overall a smaller risk score due to the higher level of biosecurity and reduced risk of disease introduction. However abiotic factors could constitute a greater risk for welfare than in flow-through tanks.

Table 3. **Welfare risks ranking - Fry**

	Tanks flow through	Tanks recirculated
Diseases	Eye lesions Furunculosis	Eye lesions Furunculosis
Husbandry	Lack of biosecurity Lack of grading Lack of staff training	Lack of grading Lack of biosecurity Lack of staff training
Abiotic	Too low water oxygen content Too low water flow Too high water temperature	Too high carbon dioxide content Too low water oxygen content Too low water flow/ Too high ammonium content (pH dependant)
Feed	Unbalanced diet Feed deprivation (long term)	Unbalanced diet Feed deprivation (long term)
Biotic	Aggression / High stocking density	Aggression / High stocking density

2.1.1.4. Welfare risks associated with farming of Parr

The welfare risks associated with chronic diseases such as eye lesions but also IPN infection were important hazards. For the abiotic hazards category, reduced water oxygen content, low water flow and too high a temperature were ranked highly, as for parr. High carbon dioxide levels and high ammonia content were assessed as a risk in recirculated tanks. For cages inadequate light period and rapid changes in water temperature were more of a risk than for the tanks. High stocking density was an important risk as well as aggression but also low stocking played a more important role than for fry. An unbalanced diet, lack of food over long periods and nutrient deficiency were the highest hazards in the category of feed and feeding. Lack of biosecurity, insufficient sorting, lack of staff training and impact of lack of monitoring were the top hazards for the management issues for all production systems. The ranking by order of the highest risk scores is summarized in Table 4.

Three production systems were considered, tanks flow-through, tanks with recirculation and fresh water cages. Flow-through tanks and cages showed a higher risk due to lower biosecurity and increased risk of disease introduction. Fresh water cages can also be exposed to predators and compared with tanks there is less control of water quality. Cage culture of parr has also particular problems in relation to husbandry practices, handling and fungus control.

Table 4. **Welfare risks ranking - Parr**

	Tanks flow through	**Tanks recirculated**	**Fresh water cages**
Diseases	IPN	Eye lesions	Eye lesions / IPN
	Furunculosis /Eye lesions	IPN	*Saprolegnia*
Husbandry	Lack of biosecurity	Lack of grading	Lack of biosecurity
	Lack of grading	Lack of biosecurity	Lack of grading
	Lack of staff training	Lack of staff training	Lack of staff training
Abiotic	Too low water oxygen content	High carbon dioxide content	Too low water flow
	Too low water flow	Too low water oxygen content	Too low water oxygen content
	Too high water temperature	Too low water flow	Water temperature rapid change
Feed	Unbalanced diet	Unbalanced diet	Unbalanced diet
	Feed deprivation (long term)	Feed deprivation (long term)	Feed deprivation (long term)
Biotic	Aggression / High stocking density	Aggression / High stocking density	Aggression / High stocking density

2.1.1.5. Welfare risks associated with farming of smolts

For smolts the high ranking abiotic hazards were: too low water oxygen content, reduced water flow and wrong light signals. In recirculated tanks high carbon dioxide content and ammonia content were the high ranking hazards. High stocking density and aggression were the top hazards in the biotic category, for the tanks low stocking density was also a significant risk. Lack of food over a long period of time and a deficiency in nutrients were at the top of the feeding hazards. Lack of biosecurity and lack of staff training and monitoring was also important for smolt. Lack of biosecurity was a more serious hazard in the cages than in the tanks. IPN and furunculosis but also *Saprolegnia* infections and eye lesions constituted a high risk. The ranking by order of the highest risk scores is summarized in Table 5.

Three production systems were considered, tanks flow-through, tanks recirculated and fresh water cages. Overall risk score of the three systems did not differ, except for increased management risks in the freshwater cages. Cages can also be exposed to predators and compared with tanks there is less control of water quality

Table 5. **Welfare risks ranking - Smolts**

	Tanks flow through	**Tanks recirculated**	**Freshwater cages**
Diseases	IPN	Eye lesions	*Saprolegnia*
	Furunculosis	IPN	Furunculosis
Husbandry	Lack of biosecurity	Lack of staff training	Lack of biosecurity
	Lack of staff training	Lack of biosecurity	Lack of staff training
Abiotic	Too low water oxygen content	High carbon dioxide content / Too low water oxygen content	Too low water oxygen content
	Too low water flow / Light period	Too high Ammonium / water flow	Too low water flow/ Light period
Feed	Feed deprivation (long term)	Feed deprivation (long term)	Feed deprivation (long term)
	Deficiency of nutrients	Deficiency of nutrients	Deficiency of nutrients
Biotic	High stocking density	High stocking density	High stocking density
	Aggression	Aggression	Aggression

2.1.1.6. Welfare risks associated with farming of ongrowing Atlantic salmon

Only seawater cages were considered as a production system for Atlantic salmon ongrowing. Eye lesions and sea-lice infection were the most important welfare risk factors in the disease category for ongrowing Atlantic salmon welfare. Low water oxygen content and low water flow were the top of the list of the hazards for abiotic factors. Sea-cages are exposed to natural non-controllable water quality so site selection and cage design characteristics are of utmost importance in determining the exposure to these hazards. Too high a stocking density and intra specific interaction (aggression) were followed by mixing fish from different origins in the category of biotic factors. Predators were not considered as an important risk since anti-predator control measures are usually in place. An unbalanced diet and protein replacement (vegetable protein) were top hazards for the feeding category but were less importance than for earlier life stages. Lack of biosecurity and lack of staff training were the highest risks score for the husbandry hazards category.

Table 6. **Welfare risks ranking – Ongrowing**

	Seawater cages
Diseases	Eye lesions
	Sea lice
Husbandry	Lack of biosecurity
	Lack of staff training

Biotic	High stocking density Aggression
Abiotic	Too low water oxygen content Too low water flow
Feed and feeding	Unbalanced diet / Vegetable proteins

2.1.1.7. Welfare risks associated with farming of Atlantic salmon broodstock

Atlantic salmon broodstock can be kept in tanks or cages, the final stages of maturation, prior to spawning can only be achieved in fresh water. Only a small % of the population is designated as broodstock (at their last year of life) and held to become mature. The broodstock may be held for only one year or for two depending on whether they are early or late spawners, in addition some farms use a single stripping while others reuse their male population. For the purpose of this RA the duration of this life stage duration was considered the same than ongrowing.

Lack of biosecurity was the most important hazard, especially for sea cages. Several hazards on the disease category were assessed in seawater cages but not considered relevant for tanks. Handling was the second highest hazard in the husbandry category. In the biotic category intra-specific interactions (aggression), stocking density (both too low and too high) was listed, but the risk of poor welfare from a low stocking density was considered more important than from too high. Water oxygen content and water flow were the highest abiotic hazards and more relevant for tanks than for sea cages. For sea cages, the water salinity and the correct light period were important risks. The highest risk for welfare at this life stage from feed and feeding was from an unbalanced diet. The ranking by order of the highest risk scores is summarized in Table 7.

Table 7. **Welfare risks ranking – broodstock**

	Tanks	**Sea cages**
Disease	Eye lesions *Saprolegnia*	Sea lice Eye lesions
Husbandry	Lack of biosecurity Handling	Lack of biosecurity Handling
Biotic	Aggression Low stocking density High stocking density	Aggression Low stocking density High stocking density
Abiotic	Too low water oxygen content / too low water flow Tank shape/ Light period	Water salinity Too low water oxygen content Too low water flow/ Light period

Feeding	Unbalanced diet Feed deprivation (long term)	Unbalanced diet Feed deprivation (long term)

2.1.1.8. Risk associated with production systems

Overall the production system within life stages seemed not to differ very much. There were higher scores for sea cages than for the other production systems, mainly related to problems with disease. For broodstock sea and brackish cages had higher risk scores with regards to disease. Flow-through tanks had more problems with disease than recirculating tanks for abiotic factors. Overall the highest risk scores were found for disease across all life stages. Inadequate management followed as a risk, but with considerably lower risk scores. Biotic factors were more a risk for broodstock, and abiotic hazards i.e. mainly water quality which was a concern for all life stages.

2.1.2. Conclusions and recommendations - risk assessment

CONCLUSIONS

- No major differences concerning overall welfare risk between the different production systems used for each life stage were found.
- Production systems can differ in their risk score for different categories of hazards, since they all can have specific risks: for example re-circulated tanks can show an overall smaller risk score with regards to disease, but a higher risk score with regards to abiotic factors than flow-through tanks. Sea cages have more of a problem with biosecurity than the other systems.
- Different production systems require different measures to control the welfare risks for farmed Atlantic salmon.
- The uncertainty is still high indicating the need for well-documented and peer-reviewed data for some of the hazards.
- Risk ranking is possible for the different life stages but uncertainty is high and interaction between factors renders the assessment difficult.

RECOMMENDATIONS

- Measures to improve welfare should be adapted to different production systems and should take into consideration the specific requirements of each life stage.
- More and detailed data about the existing production systems at European level are necessary.
- Disease was assessed as an important risk factor for the welfare of farmed Atlantic salmon however prevalence data of salmon disease in aquaculture need to be collected and published for a thorough assessment.
- More research needs to be carried out and published on the abiotic hazards in farming systems.

The EFSA Journal (2008) 736- Annex II , 1-19

Animal welfare aspects of husbandry systems for farmed Atlantic salmon[1]

MINORITY OPINION

This minority opinion from Prof. Donald M. Broom is based on the view that the accepted Report and adopted Opinion are incomplete and that in order to answer the mandate from the European Commission, the introductory chapters on the welfare, biological functioning and farming of fish should be included.

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[1] For citation purposes: Scientific Opinion of the Panel on Animal Health and Welfare on a request from the European Commission on Animal welfare aspects of husbandry systems for farmed Atlantic salmon. *The EFSA Journal* (2008)736- Annex II, 1-31

SUMMARY

Fish are very diverse in their body form and have a wide range of sensory systems, some of which, such as electroreceptors and the lateral line system, are not shared by birds and mammals. As vertebrates, fish, birds and mammals share a similar general brain structure. Over and above this, however, comparative neuroanatomy highlights many differences among vertebrate groups; it also highlights differences in brain structure among species of fish. On the other hand, studies of brain function suggest a number of parallels between fish and other groups. Fish have nociceptors and these look like and have a similar response profile to those of birds and mammals. The question of whether fish experience the input of these receptors as pain remains controversial but experiments have shown the brain is active during such stimulation and that painkillers reduce prolonged behavioural and physiological responses. It is clear that the responses given by fish to nociceptive stimulation are more complex than simple reflexes, including significant shifts in behavioural priorities and the performance of anomalous behaviour. In this context, our working position is that juvenile and adult fish have the capacity to perceive painful stimuli and experience at least some of the adverse affective states that we associate with pain in mammals. Data suggest that the affective state of fear sometimes motivates behaviour in fish. The systems in mammals and birds that result in the production of adrenaline and cortisol have close anatomical and functional parallels in fish. Fish show physiologically and behaviourally similar freeze and flight responses and prolonged cortisol production is associated with immunosuppression.

WELFARE CONCEPTS

Attitudes to animal welfare encompass three aspects: what animals feel or experience; how animals are functioning; and how the subject animals compare with their 'natural' wild counterparts (Fraser, 1999) and these influence how animal welfare is understood. Feelings and experiences are part of animal functioning and have effects that may be assessed. However, observations on animals in the wild are not involved in welfare assessment, but give a guide as to their likely functioning when removed from the environment in which they have evolved.

Welfare is a characteristic of an individual animal and is concerned with the effects of all aspects of its genotype and environment on the individual (Duncan 1981). Broom (1986) defines welfare as follows: "the welfare of an animal is its state as regards its attempts to cope with its environment". According to this definition, an animal's welfare depends on the ease or difficulty of coping and also the extent of any failure to cope, which may lead to disease and injury. Furthermore, welfare also includes pleasurable mental states and unpleasant states such as pain, fear and frustration (Duncan 1996, Fraser and Duncan 1998). Such feelings cannot be measured directly but may be inferred from measurements of physiology and behaviour and are a component of coping systems (Cabanac 1979, Broom 1998, Panksepp 1998).

Whenever animals are overtaxed by environmental impacts, welfare is poor to some degree and aspect of animal welfare (MacIntyre et al., 2008).

When considering fish, application of these welfare concepts appear more difficult to develop and require specific consideration. There are several reasons for this. First, there is less knowledge of basic biology particularly of brain functioning in relation to awareness of pain and fear then for mammals or birds (Rose, 2002).._Fish are poikilothermic animals which live in an aquatic environment. Environmental factors have a major impact on fish biology and coping with environmental changes is a major task for fish. There are many publications, on the impact of external factors on fish physiology and behaviour: Such biological knowledge is a valuable source of information when assessing fish welfare (Iwama, 2007). In this context, the concept of 'needs' is central to discussions of animal welfareThe needs can be fulfilled by physiological changes and by carrying out certain behaviours. Such behavioural requirements are more difficult to evaluate as sophisticated experimental evidence is required to determine their strength (Hughes & Duncan 1988, Jensen & Toates 1993, Broom and Johnson 1993, Vestergaard 1996). Such experiments have rarely been conducted in fish even though a failure to meet such needs in some way may contribute to poor welfare.

Where welfare or health are referred to as good in this report, these words imply a state that is positive for an individual and by implication for the population as a whole, Where welfare or health are referred to as poor, a negative state is implied. The following sections will deal with the major recognisable adverse states in the fish species being studied with a review of the available scientific data and its interpretation.

CONCLUSION

The concept of welfare is relevant to all farmed animals, including farmed fish, and some aspects of fish welfare can be scientifically assessed. However, although the same methodology is relevant in studying the welfare of fish, birds and mammals, much less research has been carried out on fish.

WELFARE ASSESSMENT IN FISH

The scientific assessment of welfare is discussed by Huntingford *et al.*(2006) and and FSBI (2002).. Welfare assessment may be based upon a list of needs, for example measuring the hazards associated with the non-fulfilment of these needs. It may be assessed in various ways. Poor welfare can be assessed by how far an individual animal has deviated from what is normal for animals in a good environment (Morton and Griffiths, 1985), i.e. one that meets all of their needs. Normality is not necessarily that which is natural for wild fish and an assessment of deviation from normality must be based upon baseline studies of farmed fish in a satisfactory environment., taking into account their previous experiences e.g. (specific) rearing environment. To understand, compare and develop actions to improve fish welfare, defined protocols of welfare measures or indicators are needed.

Some welfare research involves measuring direct indicators of poor or good welfare while other research evaluates what is important to animals by studies demonstrating positive preferences and motivation (Dawkins 1990) and also aversion i.e. negative preferences and how hard an animal will work to avoid, as opposed to access, an environmental variable. Some such work on preferences and motivation has been conducted with fish, but there is not a large amount of data on these issues. Measures of physiological functioning, productivity, health and pathology and behaviour all form the basis of welfare assessment. As an example, measuring disease resistance or the functioning of the immune system offers one way of estimating the welfare "cost" of certain aquaculture conditions. Compromised immune performance can lead to disease outbreaks with associated direct negative welfare consequences. Moreover, lowered disease resistance is generally believed to be a consequence of maladaptive physiological stress, and disease challenge testing may therefore also be an indirect measure of such stress conditions.

Due to the complex causal relationships among the various needs of farmed fish and their behavioural and physiological consequences, it is impossible to find one single measurement or welfare indicator that will cover all possible welfare relevant effects of all possible rearing systems, farmed species and potential situations. Some of the methods used and evaluation of the results will be species and system specific. When the welfare of fish or other animals is assessed, sets of measures can be used, which might be physiological (Oliveira *et al.*, 1999, Ellis *et al.*, 2004), behavioural or pathological (see Huntingford *et al.*, 2006). Whilst a single measure could indicate poor welfare, a range of measures will usually provide a more accurate assessment of welfare because of the variety of coping mechanisms used by the animals (Koolhaas *et al.*, 1999, Huntingford and Adams 2005) and the various effects of the environment on individuals. Useful welfare indicators must to be valid reflections of welfare and repeatable. In addition to measures, which are the outputs of good husbandry, farm practices that help to ensure good welfare provide important indirect welfare indicators, independent of the condition of the fish. Such indicators of welfare through good practice include staff training, good husbandry protocols, monitoring and biosecurity systems, health plans and contingency plans. These complement measures of welfare outcomes by indicating ways by which poor welfare can be avoided.

Indicators that do not necessarily give information about individual fish are commonly used by fish farmers to assess changes at a population level. Indeed, many fish farms have strategies for real-time monitoring of such indicators, which include feed intake, growth rate and mortality. In the case of feed intake, the indicator is not the feed intake per se, but the deviation from an expected feed intake based on biomass and water temperature. Production variables of this kind have a place in welfare assessment and a failure of fish to feed and grow often indicates poor welfare. However, high performance levels (e.g. high feed intake and good growth) do not necessarily indicate good welfare. At a population level, changes in rate of mortality may be a useful indicator of poor welfare.

Indicators at the individual level cover all measurements of individual fish in a system, either by non-invasive monitoring in free-swimming fish, or with targeted sub-sampling of fish. Examples of individual measures are fin condition and parasite load. Representative sub-samplings are difficult in large farm systems, but can work well in smaller systems. The individual indicators commonly relate to the ability of the fish to maintain a normal physiological (and possibly behavioural) state, including the ability to mount effective immune responses.

INTRODUCTION TO THE BIOLOGY AND FUNCTIONING OF FARMED FISH SPECIES

1.1. Diversity of teleost fish forms and environmental adaptations

The three major groups of fish are: Agnatha (hagfish, lampreys), Chondrichthyes (sharks, rays, sturgeons) and Actinopterygii (bony fish with teleosts being the most prevalent). Most aquaculture finfish species are teleostean fish (Evans *et al.*, 2005). There are more than twenty thousand living species of teleosts that have been evolving over 500 million years, representing every aquatic environment and a vast range of physiological and behavioural traits.

Each species has developed a set of tolerance limits for each environmental factor, and within such ranges ecological interactions are further limiting the natural distribution and habitat selection (Randall *et al.*, 2002, Helfman *et al.*, 1997). The tolerance ranges are species specific and may be wide or narrow, developing the species into opportunistic generalists or specialists designed for long-lasting natural ecological niches. Individual fish have abilities to to cope with a changing environment, including large annual changes in e.g. water temperature and food availability. As a result of such plasticity, fish have been able to inhabit every conceivable aquatic environment, from a Tibetan lake at an altitude of 5,250m to the pacific depth at –8,370m. They are also extraordinary diverse in terms of numbers of species, body forms, life-styles and physiologies. Fish genomes are more varied and plastic in comparison with other vertebrates, owing to frequent genomic changes (Cossins and Crawford, 2005).

Teleost fish share many common morphological and physiological adaptations with other vertebrates, including many components of the neural and endocrine systems, immune system and the physiological stress cascade. However, some key systems such as the respiratory- and osmoregulatory systems differ markedly form land-living vertebrates due to the particular challenges imposed by living in water. Respiration (i.e. exchange of gases such as oxygen and carbon dioxide) takes mainly place over the gills (except in the early larval stages). The gills are also involved in uptake and excretion of ions and maintenance of osmoregulatory balance. The intimate physiological contact of all body fluid compartments and tissues through gills, skin and gastro-intestinal system with the external environment is a situation that can lead to major physiological challenges. Variations in water conditions (including oxygen levels, temperature, pathogen, salinity and water-borne pollutants) can have a direct and unavoidable impact on susceptible cells, tissues and organs. This close physiological contact is more easily defined and its impact more readily studied than in terrestrial species. Fish are sensitive sentinels of environmental challenge particularly pollution (Cossins & Crawford 2005).

Some fish species go through marked metamorphosis or habitat changes such as transfer from freshwater to sea-water that often represent critical periods with reduced capacity to withstand stressors or infectious diseases. The intimate contact with the water, including pathogens, represents a challenge in terms of barrier functions as a part of the disease defence. Breakdown of the integrity of these barriers, e.g. due to various forms of stress, may lead to increased susceptibility to infectious diseases. The development of acquired immune function often takes place after the metamorphosis from larval to juvenile form which represents a challenge on vaccination, in particular in marine farmed fish species that are exposed to a suite of pathogens from early life stages.

Fish in a natural habitat display complex swimming, feeding, anti-predator and reproductive behaviours, and such behavioural traits are linked to genotypical differences between species and individual animals, and are modified by phenotypical development and learning. In addition, several fish species undergo ontogenetic niche shifts during their lifespan, and consequent changes in behaviour, e.g. change in salmon from a territorial parr in the river to a schooling fish which migrates from freshwater to sea-water, and years later to a mature fish which migrates back to the river prior to spawning **(**McCormick *et al.*, 1998).

1.2. Environmental factors and fish physiology.

The main environmental factors which control spatio-temporal distribution of fish are temperature, salinity, light, oxygen, food, pollutants, hydrodynamics and substratum. Moreover, the physiological processes of fish are carried out under environmental conditions harsher and more restrictive in many ways than those experienced by terrrestrial animals (Wedemeyer, 1997). For example, the concentrations of the gases in the aquatic environment are highly variable compared with those in air. Oxygen depletion in water is not unusual and at times respiration can be difficult. All these reasons explain why coping with changes in environmental factors is a major ability for fish species that is relevant when considering fish welfare.

During the last 40 years, considerable research effort has been devoted to the effects of environmental factors on fish physiology-(Somero and Surarez, 2005).

Scientific information on the effects of environmental factors on physiological functions in fish, including development, growth, reproduction, excretion, osmoregulation, respiration and immunity are summarised in several text books on fish ecophysiology (Evans 1993, Rankin 1994, Bruslé and Guignard 2004). Teleost fish share with other vertebrates many common developmental pathways, physiological mechanisms and organ systems. The challenge imposed by aquatic life leads to major physiological roles for exchanging epithelia such as gills. This is not only related to the major physiological functions (i.e. respiration, osmoregulation, excretion, acid-base balance regulation) carried by the gill which then play a central role in a suite of physiological responses to environmental and internal changes but also to the huge surface exchange built up by the gill which are a major entry for many biotic or abiotic water compounds (Evans, 2005). An example of fish ecophysiologyis the study of the effect of xenoestrogen on sex differentiation on trout reared in cages (Jobling et al., 1998) which led to literature on the effect of endocrine disruptors (Sumpter and Johnson, 2005).

Literature on fish behaviour and analysis of behavioural responses exhibited by fish exposed to stressors are mostly devoted to fish in their natural environment (Schreck, Olla and davis, 1997). Fewer studies have looked at fish behaviour in production systems. Feeding behaviour (Volkoff and Peter, 2006), social interaction and hierarchies (Gilmour et al., 2005) are important in fish aquaculture.

CONCLUSION

Fish live in the aquatic environment and respond to harmful chemicals and many other stressors at intensity levels frequently far below those that can be perceived by terrestrial animals

1.3. Sensory systems in fish

Both conservation and innovation in the organisation of sensory systems occur across vertebrates. Fish perceive optical, positional, chemical, tactile, mechanosensory and electrosensory (lateral line), acoustic, and magnetic stimuli by receptors innervated by particular brain regions (Hodos & Butler 1997). Some basic patterns of sensory innervation are common to all vertebrates for the relay of sensory inputs from putative stressors in the environment to the brain, directly impacting on the fish’s welfare.

The optical characteristics of water affect illumination intensity and spectral quality. This has led to evolution of the fish eye to cope with these challenges. Fish eye adaptations allow the efficient collection of light (Warrant & Lockett 2004) and other specialisations (Siebeck & Marshall 2001). They do not have eyelids or nictitating membranes and the large choroidal complexes are subject to pressure changes and to gaseous embolism. Thus the fish eye is particularly vulnerable to a variety of husbandry effects leading to poor welfare (Roberts 2001).

Sound and vibrations travel well in water and fish are highly responsive to and potentially easily disturbed by exposure to such systems. However, it is not clear whether or not salmonid fish are disturbed by such stimuli (Wysocki *et al*. 2007).

The ear of bony fish comprises three semi-circular canals, a utricle and a sacculae and lagena. The auditory receptors comprise a very variable set of sensory organs that perceive sound from the environment. The ascending auditory pathways in mammals and fish are similar. The vestibular system of vertebrates detects position and motion of the head and is important for equilibrium or balance and coordination of head, eye and body movements.

Fish have highly elaborate chemosensory detection of information from the environment including other fish. Chemicals detected by the fish and conveyed to the brain via cranial nerve I are involved in olfaction. Structural organisation of the peripheral olfactory organ is variable throughout fish species, although the ultrastructural organisation of the olfactory sensory epithelium is extremely consistent (Hara 1994). Olfactory signals such as those involved in reproduction and feeding may be processed independently through two distinct subsystems (Laberge & Hara 2001, Nikonov *et al.*, 2005). The neuronal components are similar to the olfactory systems of mammals except that there is no connection between respiratory structures and the olfactory system in fish. Chemical pollution and chemical signals such as alarm pheromones may often cause poor welfare in fish so consideration of the impact of olfactorily important chemicals in the fish environment can improve welfare.

The taste buds of vertebrates are the receptors of the gustatory or taste organ that may occur in the oropharyngeal cavity and elsewhere on the body surface (Hara 1994).

The lateral line system detects mechanosensory information and is found in all fishes and some amphibians but has been lost in reptiles, birds and mammals. The sensory organ consists of hair cells called neuromasts located in the lateral line canals or on the head and body. The lateral line system allows fishes to respond to water movements and other movements relatively close to the fish. This system alerts fish to prey, predators, school neighbours, water flow from environmental obstacles, and in salmon reproductive vibrations (Satou *et al.*, 1994) that facilitates orientation behaviour (Montgomery *et al.*, 1997).

Magnetoreceptors have not been identified with certainty in any animal, and the mode of transduction for the magnetic sense remains unknown. However, magnetite particles embedded in specific cells in the basal lamina within the olfactory lamellae of rainbow trout, *Oncorhynchus mykiss*, have been identified (Walker *et al.*, 1997). All fish can use their lateral line to detect local movement and electroreception is widespread in fish, including farmed species. The implications for welfare are starting to be considered (Spiess *et al.*, pers. comm.).

CONCLUSION:

Fish have a wide range of sensory systems, some of which, such as electroreceptors and the lateral line system are not shared by birds and mammals.

1.4. Comparative Brain Structure

As in all vertebrate brains, the fish brain consists of forebrain (i.e. telencephalon and diencephalon), midbrain (mesencephalon), and hindbrain (rhombencephalon). The pallium constitutes the exterior surface of the telencephalon, in mammals the neocortex is a greatly expanded part of the pallium. Thus, the general anatomy of the teleost (bony fish) brain is similar to that of other vertebrate brain, however, the fish brain is smaller relative to body size and less complex in structure than that of higher vertebrates (Kotrschal *et al.*, 1998). Moreover, among fish there is a marked inter species variation in brain anatomy, often reflecting sensory specialization, fundamental differences in embryonic development, and the degree of cell migration and proliferation and intraspecific variation in brain structure is evident (Butler 2000).

The fish brain grows continuously throughout life and appears to be highly responsive to the environmental conditions that the fish experiences as it develops (Ramage-Healey & Bass 2007, Dunlap *et al.*, 2006, Kihslinger & Nevitt 2006, Kihslinger *et al.*, 2006, Lema 2006).

In vertebrates specific brain structures have been associated with emotions and motivated behaviour. It is now indicated that the same function can be served by different structures in different groups of animals (e.g. cognitive functions in birds and mammals, Jarvis *et al.*, 2005) and structures that seem to be different may be more homologous than had previously been thought. Comparative anatomical studies have shed some light on the potential functional role of fish brain structures in relation to motivational and affective states. The issues are complex and there is considerable disagreement among specialists about the extent of commonality of brain function within the vertebrates. Fish do not have the extensive analytical cortex that mammals have and sensory processing is carried out in different regions of the brain according to the adaptations of the particular group of fishes. Fish do not have the extensive cerebral cortex that mammals have, this being smaller relative to body size and without the characteristic folded and layered appearance of the mammalian cortex. Additionally, sensory processing is carried out in different regions of the brain according to adaptations of the particular group of fishes (Rose 2002, Vogt 2003).

The possibility cannot be excluded that parts of the brain other than the cerebral cortex have evolved the capacity for generating negative emotional states in fish (Huntingford *et al*., 2006). The concept of pain in vertebrates revolves around the perceived noxiousness of certain stimuli, and may have been conserved through evolution as a protective strategy.

At the level of the telencephalon, fish lack the higher cortical centres that have been demonstrated as necessary for full processing and experience of pain in mammals (Rose 2002). Extensive interconnections exist between the telencephalon, diencephalon and mesencephalon in fish (Rink & Wullimann 2004). Neural pathways that connect to various forebrain structures are of fundamental importance to consciousness and the perception of pain and fear in mammals (Willis & Westlund 1997). The pallium (the grey matter that covers the telencephalon) has thickened to various extents in different classes of vertebrates, and in mammals it consists of a laminated structure, the cerebral cortex (Striedter 1997). Unlike mammals, in the majority of modern fish species, the pallium is unlaminated (Vogt 2003), however there is evidence to suggest it has developed into a highly differentiated structure with respect to the processing of sensory information (Bradford 1995, Butler 2000). The telencephalon in fish contains several brain structures that are thought to be functionally homologous to those associated with pain and fear in higher vertebrates (Bradford 1995, Chandroo *et al.,* 2004, Portavella *et al.*, 2004), and this is known to be active during a potentially painful event (Dunlop and Laming 2004). Therefore, information about noxious stimuli, such as those resulting from tissue damage, in fish may be processed in a functionally homologous way, not yet fully characterised, to that involved in processing noxious stimuli in mammals. In mammals, the hippocampus, a telencephalic structure, is involved in memory and learning of spatial relationships whereas the amygdala, a structure which is also telencephalic, has long been known to be important in arousal and emotions, particularly fear responses (Carter 1996, Maren 2001). Recent studies have identified structures in the teleost telencephalon that appear to be homologous to the mammalian amygdala and hippocampus with alterations in fear, spatial learning and memory retrieval when these areas are lesioned (Portavella *et al.,* 2002). Another important structure in the fish brain, the hypothalamus, is thought to perform functions similar to those of the hypothalamus in other vertebrates. The hypothalamus is involved in various functions, including sexual and other social behavior, and is also responsible for the integration of both internal and external signals including those originating from those telencephalic areas that have been implicated in fear responses (Fox *et al.,* 1997, Portavella *et al.,* 2002, Chandroo *et al.,* 2004).

CONCLUSION

Our understanding of the extent to which brain structure and function in fish are comparable with other vertebrate groups is limited. As vertebrates, fish, birds and mammals share a similar general brain structure. Over and above this, however, comparative neuroanatomy highlights many differences among vertebrate groups; it also highlights differences in brain structure among species of fish. On the other hand, studies of brain function suggest a number of parallels between fish and other groups.

1.5. Sentience

Sentience refers, among other properties, to the ability to experience pleasurable and adverse states, a key issue when considering the welfare of any animal and a focus of public concern and there are discussions of this matter in relation to fish (Broom 2006, 2007, Yue *et al.* 2008).

Animals that have some cognitive ability at a certain stage of their development, start development without such ability. Hence it is relevant to consider at what time, during the life of a fish, their perceptual and cognitive abilities develop. It is likely that fish develop some cognitive ability only when they are able to perceive external stimuli. While little is known about the development of cognitive ability, we have some evidence concerning the stage of life at which the development of responsiveness to external stimuli starts (EFSA, 2005).

1.6. Pain

Pain is defined as an aversive sensation associated with tissue damage. As non-human animals are unable to communicate the experience of pain directly, a number of criteria have been defined to provide a guide as to whether an animal might be capable of experiencing pain (Bateson 1991, Broom 2001a, b, Sneddon 2004). These criteria include: (i) the existence of functional nociceptors (ii) the presence and action of endogenous opioids and opioid receptors (iii) the activation of brain structures involved in pain processing (iv) the existence of pathways leading to higher brain structures (v) the action of analgesics in reducing nociceptive responses vi) the occurrence of avoidance learning vii) the suspension of normal behaviour associated with a noxious stimulus.

Each of these areas will be considered in turn to assess how well fish fulfil these criteria and how their functioning compares to the nociception and pain systems of higher vertebrates.

Nociception is the detection of a noxious stimulus and is usually accompanied by a reflex withdrawal response away from that stimulus immediately upon detection. Noxious stimuli are those that can or potentially could cause tissue damage so stimuli such as high mechanical pressure, extremes of temperature and chemicals, such as acids, venoms, prostaglandins and so on, excite nociceptive nerve fibres. Martin & Wickelgren (1971) and Mathews & Wickelgren (1978) identified sensory neurones in the skin and mouth of a lamprey (*Petromyzon marinus*) during heavy pressure, puncture, pinching or burning, and found that the output was like that which would be recorded in a mammalian nociceptor when responding to a painful stimuli. Studies of the rainbow trout (*Oncoryhnchus mykiss*) have shown that nociceptors are present on the trout face and are innervated by the trigeminal nerve (Sneddon 2002, 2003a). These studies on nociceptor anatomy and physiology strongly support the hypothesis that the rainbow trout has the sensory equipment for detecting potentially painful stimuli. Studies of nerve responses, nerve and other tissue regeneration, behavioural responses and effects of analgesics indicate nociceptive function in the fins of salmonid and other fish (Becerra et al 1983, Geraudie and Singer 1985, Turnbull et al 1996, Chervova 1997).

Fish have the necessary brain areas for nociceptive processing to occur (e.g. pons, medulla, thalamus; Sneddon 2004).The functional possibility for high level processing, such as that carried out in the cortex in humans, is crucial in terms of pain perception. In term of anatomy the fish brain is far smaller relative to body size and simpler in structure than of a human. Moerover, fish lack cortical structure such the neocortex, which plays a key role in the subjective experience of pain in humans (FSBI 2002; Rose 2002). However, it is not impossible that parts of the brain other than the cerebral cortex have evolved the capacity of generating negative emotional states in fish (Huntingford et al. 2006).

In fish as in other vertebrates, nociceptive information is relayed to the brain from the periphery via two major tracts. The trigeminal tract conveys information from the head while the spinothalamic tract conveys information from the rest of the body. In fish the trigeminal has been shown to project to the thalamus as it does in other vertebrates (Goehler & Finger 1996, Finger 2000). The elasmobranch (Ebbesson & Hodde 1981) and teleost (Goehler & Finger 1996, Finger 2000) groups both have the same basic components of ascending spinal projections as higher vertebrates.

The possession of opioid receptors, endogenous opioids and enkephalins is one of the requirements to determine whether nociception can occur in an animal (Bateson 1991, Broom 2001a, b). These substances are involved in analgesia in the mammalian central nervous system and are produced in order to reduce pain internally. Met-enkephalin and leu-enkephalin are present in all vertebrates which have been tested and there are at least six opioid receptors described for teleost fish (Dores and Joss 1988, Dores *et al.*, 1989, Dores and Gorbman 1990, McDonald and Dores, 1991). Opioids elicit antinociception or analgesia through three distinct types of receptors in mammals (Newman *et al.*, 2000) and these have been identified in the zebrafish, *Danio rerio* (Stevens 2004). When goldfish are subjected to stressful conditions, there is an elevation of pro-opiomelanocortin, the precursor of the enkephalins and endorphins, just as there would be in humans (Denzer and Laudien, 1987). Goldfish which are given electric shock show agitated swimming but the threshold for this response is increased if morphine is injected and naloxone blocks the morphine effect (Jansen and Greene 1970). Work by Ehrensing *et al.*, (1982) showed that the endogenous opioid antagonist MIFI down-regulates sensitivity to opioids in both goldfish and rats. Opiate receptors and enkephalin like substances have also been found in various brain areas of goldfish, *Carassius auratus* (Finger 1981, Schulman *et al.*, 1981) and rainbow trout, *O. mykiss* (Vecino *et al.*, 1991). The distribution of enkephalins in the fish brain shows a similar pattern to that seen in higher vertebrates (Simantov *et al.*, 1977, Vecino *et al.*, 1992). In general it is clear that there are very many similarities amongst all vertebrates in their opioid systems.

A simple reflex response to a noxious stimulus can indicate nociceptive function, however, adverse affects on an animal’s normal behaviour beyond a simple reflex may indicate a psychological component that is indicative of suffering, and suggests that the animal may be perceiving pain. Reflex responses occur instantaneously and within a few minutes but some of the responses of fish may be prolonged.(Sneddon 2006). A recent study investigated the behavioural response of rainbow trout that had been given subcutaneous injections of acetic acid and bee venom (algesics) to the lips (Sneddon *et al.*, 2003a). These fish showed an enhanced respiration rate for approximately 3 hours, did not feed within this period, and showed anomalous behaviours such as rubbing of the affected area on the aquarium substratum and glass and rocking from side to side on either pectoral fin (Sneddon 2003b, Sneddon *et al.*, 2003a). These, therefore, appear to represent changes in behaviour over a prolonged period as a result of nociceptive stimulation.

The ability of analgesics to modulate nociceptive responses is also indicative of pain perception since the selectively act on this system. The adverse behavioural responses seen in the rainbow trout, *O mykiss,* were quantified and when morphine was administered to fish injected with acid, there was a dramatic reduction in this rubbing behaviour as well as rocking behaviour and the enhanced respiration rate was also ameliorated (Sneddon 2003b, Sneddon *et al.*, 2003a). Further to this, acid injected fish did not show an appropriate fear response to a novel challenge supporting the idea that this painful stimulus dominates the fish attention (Sneddon *et al.*, 2003b). Studies have shown that goldfish are able to learn to avoid noxious, potentially painful stimuli such as electric shock (Portavella *et al.,* 2002, 2004). Learned avoidance of a stimulus associated with a noxious experience has also been observed in other fish species (Overmier & Hollis 1983, 1990) including common carp, and pike, avoiding hooks in angling trials (Beukema 1970a, b).

There are strong debates on the question of pain in fish with opposing views (Rose 2002, Derbyshire *et al.,* 2007, Sneddon 2004, 2006). For example, Derbyshire *et al.,* (2007) argue that the results from Sneddon's studies presented above can be interpreted as showing a remarkable capacity of trout to withstand oral trauma which would be expected as trout normally feed on potentially injurious prey such as crayfish, crabs and spiny fish. They also suggest that there is an important difference between knowledge about sensation and sentience (Derbyshire *et al.,* 2007). Rose (2002) argues that there are major neurobehavioral differences between fish and humans, particularly at the level of brain regions responsible for pain awareness in humans. In fish, in which the cerebral hemispheres were removed, leaving the brainstem and spinal cord intact, ome behaviour was still possible(Overmier and Hollis, 1983). Because the experience of fear and pain depends on cerebral cortical structures in mammals and these are absent in fish brains, Rose (2002) concluded that awareness of fear and pain is impossible in fish. However, evidence of an active nociceptor system in fish associated with effects of administration of noxious substances on normal behavioural repertoire has led to the inference that fish potentially have the capacity for long-term suffering (Chandroo et al. 2004, Sneddon 2006, Braithwaite and Boulcott 2007).

CONCLUSION

It has been convincingly demonstrated that fish have nociceptors and that these look like and have a similar response profile to those of birds and mammals. The question of whether fish experience the input of these receptors as pain remains controversial but experiments have shown the brain is active during this stimulation and that painkillers reduce prolonged behavioural and physiological responses. It is clear that the responses given by fish to nociceptive stimulation are more complex than simple reflexes, including significant shifts in behavioural priorities and the performance of anomalous behaviour. In this context, our working position is that juvenile and adult fish have the capacity to perceive painful stimuli and experience at least some of the adverse affective states that we associate with pain in mammals.

1.7. Fear

Fear serves a function that is fundamental to survival and is the activation of a defensive behavioural system that protects animals against actual or potentially dangerous environmental threats. In higher vertebrates, fear involves mainly the amygdaloid and hippocampal regions of the brain although other areas are also implicated. Studies in fish have shown that these responses also appear to be dependent upon cognitive mechanisms and homologous limbic brain regions in the telencephalon. The dorsomedial (Dm) telecephalon in fish has been implicated in emotional learning and is thought to be homologous to the amygdala in mammals (Bradford 1995, Butler 2000, Portavella *et al.,* 2004). In mammals the hippocampus is involved in memory and learning of spatial relationships and it is the dorsolateral (Dl) telencephalon in fish that is thought to be functionally homologous to the hippocampus. Dm lesions impaired acquisition of an avoidance response but had no effect on performance in a spatial learning task, while Dl lesions affected spatial learning but did not impair the acquisition of the avoidance response (Portavella *et al.*, 2002). Therefore Dm and Dl areas of the fish telencephalon share functional similarities with the amygdala and hippocampus, respectively, in mammals.

Studies on fear conditioning in mammals measure levels of freezing and startle behaviour (Fendt & Fanselow 1999). In fish, a number of different behavioural responses to potentially threatening stimuli have been described and include escape responses such as fast starts (Chandroo *et al.*, 2004, Domenici & Blake 1997, Yue *et al.*, 2004) or erratic movement (Cantalupo *et al.*, 1995, Bisazza *et al.*, 1998), as well as freezing and sinking in the water (Berejikian *et al.*, 1999, 2003). Such behaviours may serve to protect the individual from the threat and a number of studies have illustrated that these behaviours can be shown in response to conditioning. Many fish species also release chemical alarm substances when injured. These are thought to act as warning signals, as conspecifics show a behavioural fright response to these chemicals (Smith 1992, Lebedeva *et al.*, 1994, Brown & Smith 1997, Berejikian *et al.*, 1999). These alarm behaviours include dashing movements, vigorous movements in the aquarium substratum, and fast swimming towards hiding places, remaining there for an extended period. These behaviours are thought to be associated with predator evasion (Hamdani *et al.*, 2000).

Learned avoidance studies not only show that a consistent suite of behaviours are produced in response to fearful stimuli in fish but they also provide evidence that the displayed behaviour is not merely a reflex response. Learning to avoid an aversive stimulus in the future implies a cognitive process of recognising that the behavioural response will lead to the desired effect of avoidance (Yue *et al.*, 2004). This may support the suggestion that an affective state such as fear may serve to motivate behaviour in fish.

Learning is thought to be mediated in part by receptors in the brain that are activated by N-methyl-D-aspartic acid (NMDA). Administration of selective antagonists of NMDA receptors impair learning mechanisms such as associative learning and conditioned fear in mammals (Miserendino *et al.*, 1990, Sanger & Joly 1991, Kim *et al.*, 1991, Maren 2001). Experiments with goldfish have shown that intracranial administration of MK-801, an NMDA receptor antagonist, blocks specific aspects of Pavlovian fear conditioning in fish (Xu & Davis 1992, Xu 1997).

CONCLUSION

Fear often depends on cognitive and learning ability and fear responses by fish are described for various situations, suggesting that the affective state of fear sometimes motivates fish.

1.8. Stress responses

Selye (1973) defined stress as “the nonspecific response of the body to any demand made upon it”. Following a period of controversial debates about the definition of stress and stressors, all recent reviews on stress in teleost fish define this term as a condition in which the homeostasis is threatened or disturbed as a result of the actions of intrinsic or extrinsic stimuli commonly defined as stressors (Wendelaar Bonga 1997, Iwama *et al.*, 1997, Barton 2002, Chrousos 1998, Wendemeyer *et al.*, 1990). The problems associated with Selye’s concept of stress are discussed by Broom and Johnson (2000) and there is debate about whether or not the concept should be limited to that which is detrimental to the fish. The response to stressors is often an adaptative mechanism that allows the fish to cope with stressors in order to maintain homeostasis. If the intensity of the stressors is overly severe or long lasting, physiological response mechanisms can become detrimental to fish welfare or maladaptative (Barton 2002, FSBI, 2002, Wendelaar Bonga 1997).

During the last 20 years, there has been extensive research devoted to the biology of stress in fish. Physiological and behavioural responses to a large variety of physical, chemical and biological stressors including those seen in aquaculture have been measured (for review see Wendelaar-Bonga 1997, Iwama *et al.,* 1997, Barton 2002, FBSI 2002, Conte 2004, Ashley 2007). Hypothalamic-pituitary-interenal (HPI) axis responses are generally considered as an adaptive strategy to cope with a perceived acute threat to homeostasis, for example poor water quality. Although fish are able to tolerate acute adverse water quality conditions, when they become too challenging or prolonged, fish cannot maintain homeostasis and experience chronic stress which in the long term can impair immune function, growth and reproductive function. Furthermore, chemicals may have toxic effects at the level of cell and tissue but, in addition, elicit an integrated stress response which may be specific to the toxicant.

The stress physiology of fish is directly comparable to that of higher vertebrates. Stress physiology is manifested by primary, secondary and eventually tertiary stress responses (see review Wedemeyer *et al.*, 1990, Wendelaar Bonga 1997, FSBI 2002, Ashley 2007). The primary stress response to short term potentially harmful situations involves, amongst other things, the release of catecholamines (adrenaline and noradrenaline) from the chromaffin cells into the circulating system. Simultaneously, activation of the hypothalamic-pituitary-interenal (HPI) axis is observed. The corticotrophin releasing factor (CRF) is released from the hypothalamus and acts on the pituitary resulting in the synthesis and release of adrenocorticotrophic hormone (ACTH) which in turn stimulates the synthesis and mobilisation of glucocorticoid hormones (cortisol) from the interrenal cells. Released catecholamines and cortisol will result in an activation of various physiological and behavioural mechanisms that constitute the secondary and possibly tertiary stress responses. The secondary changes include alteration of secretion of other pituitary hormones and thyroid hormones, changes in turn-over of brain neurotransmitters, mobilisation of energy by breakdown of carbohydrate and lipid reserve and by oxidation of muscle protein, improvement of respiratory capacity via increased heart stroke volume and increase blood flow to gills. As a consequence of this last effect, disruption of the hydromineral or osmoregulatory balance can be observed.

Primary and secondary stress responses are short-term effects of acute, short-lived challenges. When these responses are prolonged or repeated and fish has no way to avoiding or escape the challenge, a series of tertiary effects become apparent, including changes in immune function and disease resistance (Pickering 1992, Balm 1997), in growth (Barton *et al.*, 1987, Pickering *et al.*, 1991) and in reproduction (Pankhust and vander Kraak 1997, McCormick 1998, Schreck *et al.*, 2001).

Behavioural responses are often shown early in defence against adverse environmental changes, often triggered by the same stimuli that initiate the primary physiological stress responses. The exact behavioural response depends on the stressor in action. For example, the response to an approaching potential predator might be escape, whereas the response to an approaching competitor might be attack. The behavioural response to abiotic environmental stressors, such as inappropriate water temperature, oxygen or water current, includes a range of responses in movement pattern, spatial choice and social interactions, but these responses are poorly described in most fish species. In addition, individuals of the same species may differ in the nature and magnitude of their behavioural responses to various stressors. Such behavioural differences, together with the physiological variation with which they are associated, are referred to as coping strategies. Some individuals adopt what is called a proactive coping strategy, showing adrenaline-based fright and flight responses, while others adopt a reactive coping strategy, showing cortisol based “freeze” and hide responses (Korte *et al.,* 2005).

However it is not clear to what extent these are general strategies. These differences are correlated with variation in brain serotoninergic activity (Schjolden and Winberg 2007) and are also affected by the extent of exposure to stressors.

Chronic stress is a major factor in the health of fish (Conte, 2004). As in mammals, there is a clear link between stress and immune status arising mostly through the effects of cortisol which can suppress many aspects of the immune system (Wendelaar Bonga 1997). However, the relationship between stress and immune system goes in two directions since components of the immune system can influence stress responses through modification of the secretion of hormones (Ottaviani *et al.*, 1996, Balm 1997). While disease is not always connected to poor environmental conditions (Huntingford *et al.*, 2006), aquaculture practice presents many situations where stress and physical injury can increase susceptibility to naturally occuring pathogens (Ashley, 2007). For example, diseases associated with low temperatures over winter period have been described in a number of different species (Tort 1998b). Fin erosion is also an important problem in aquaculture which often occurs as results of aggressive interactions. Fin erosion may increase susceptibility to infections (Turnbull *et al.*, 1996). One example of the strong interaction between environmental stress and a serious infectious disease is the case of furunculosis. Many fish may carry the causative pathogen but clinical outbreaks occur normally after stressful events such as grading or transportation of fish. So predictable is the response that a predictive test for identifying carrier populations is the ‘furunculosis stress test’ where samples of healthy fish are injected with cortisone to identify individuals which might become clinical cases if stressed (Hiney *et al.*, 1994).

An acute stress response does not necessarily imply any harmful consequence as such a response may be important to the maintenance of homeostasis. However, mid- and long-term exposure to stressors generally leads to maladaptative effects and sometimes to chronic stress, which are associated with decreased welfare. Such effects have been described with chronic effects on growth, reproduction or immune function and disease resistance. So, while studies on stress responses do not necessarily give us a complete view of welfare in fish, deleterious effects of several components of the stress response observed after chronic exposure to stressors are indicative of poor welfare (Huntingford *et al.*, 2006, Ashley *et al.* 2007).

Measurements of the levels of both glucose and lactate in the plasma may sometimes be biomarkers of stress in fish (e.g. Arends *et al.*, 1999; Acerete *et al.*, 2004). Measures of the expression of stress related genes might also provide useful markers (e.g. Gornati *et al.*, 2004). Chronic stress has been also studied and exerts a strong effect on haematology (Montero *et al.*, 2001), metabolism (Mommsen *et al.*, 1999), neuroendocrine function (Dibastistta *et al.*, 2005b), and osmoregulation (Wendelaar Bonga, 1997). However, reliable indicators of chronic stress are still under investigation and will probably rely on a range of measurements.

Avoidance of the maladaptative consequences of prolonged stress is a central concern in aquaculture and assessments of potential methods to reduce stress responses is an active area of research (Ashley 2007). Thus, fish have been selectively bred for reduced emergency responses: High responding (HR) and low responding (LR) lines of rainbow trout have been generated by selection for consistently high or low cortisol response to a standard confinement test (Pottinger and Carrick 1999). In addition, these two strains of rainbow trout also show a divergence in sympathetic reactivity as a response to confinement (Schjolden and Winberg 2007). However, all testing was conducted under controlled laboratory conditions and the welfare and productivity of LR strains have not yet been compared under commercial conditions. Manipulation of fish diet has been also shown to play an important role in inter-renal sensitivity: For example, vitamin E added in the diet has been shown in sea bream to slow down elevation of plasma cortisol levels in response to a stressor and to increase survival rate

(Montero *et al.*, 2001). In African catfish (*Clarias gariepinus*), vitamin C fed during early development induced lower inter-renal gland activity (Merchie *et al.*, 1997).

Although much research has been devoted to stress biology in fish, major questions concern the development of new techniques for non-lethal and non-invasive sampling of physiology and behaviour of fishes which would allow measurement of stress outside a controlled laboratory environment (Scott and Ellis 2007), including meat quality measurements (Skjervold *et al* 1999). Cumulative stress responses at different life stages and methods for evaluating stress in relationship to fish performance have not been much studied.

If stressors and failure to cope persist, the final consequence is death. Mortality rate is therefore a useful welfare indicator as mentioned in Chapter 5. In fish species, there is variation amongst species in the mortality rate in the wild. Amongst salmonids, the egg is large so mortality in alevins and fry is lower than in some species with less food reserve available. When considering the mortality rate, that which occurs in the wild is not directly relevant as farmed fish should be cared for and protected from starvation, predation and avoidable disease. Taking into account the biological functioning of the fish species, mortality rate can give information about the extent of stress and poor welfare.

CONCLUSION

In common with all vertebrates, fish possess a suite of adaptative behavioural and physiological strategies that have evolved to cope with stressors. The systems in mammals and birds that result in the production of adrenaline and cortisol have close anatomical and functional parallels in fish except that the adrenaline and cortisol production are from the more diffuse chromaffin and inter-renal tissue rather than from a discrete adrenal gland. Fish show physiologically and behaviourally similar freeze and flight responses and prolonged cortisol production is associated with immunosuppression.

NEEDS OF FISH

A need is a requirement on the part of an animal to obtain a particular resource or to respond to a particular environmental or bodily stimulus. The exact set of needs for any given species is a consequence of its biology. In general needs are associated with all of the major biological functions of the animal. In aquaculture, the fish experience only a part of the range of natural variation in environmental factors. Some factors may be less variable than in the wild, e.g. food availability, while other factors vary more than in nature, e.g. oxygen concentration. In addition, while fish in nature may swim away from adverse or sub-optimal conditions, the farmed fish spatial and temporal environment, gives few options for individual preference. Nevertheless all farmed animals have needs and good welfare depends upon these being met to a greater or lesser degree.

However, there is variation in the importance of the various needs for the welfare of the individual. Needs range from resources whose absence results in rapid death to those whose presence improves welfare for a period, but lack of which would never result in death

The following list of needs is not in order of importance and reflects current knowledge. Some needs require being satisfied only at intervals of some hours or only when fish are at certain life stage, young or adult. The causes of some problems of fish are multifactorial and may be related to more than one need. The welfare risk assessment refers to hazards that are linked to the known needs of a particular species. Those hazards or factors have been identified for each species.

1 Need for adequate physical and chemical environmental conditions:

1A. To have access to appropriate oxygen concentration

All fish need oxygen of a certain partial pressure, the actual value varying according to species.

1B. To avoid harmful substances or environmental conditions in water

All fish need an appropriate aquatic environment. Inappropriate water conditions, for example too high salinity or carbon dioxide concentration, too much ammonia or other toxic chemicals, or suboptimal pH can harm fish.

1C. To have appropriate visual, olfactory and other environmental conditions

It may be that problems are caused to fish of particular species by inappropriate light, vibration, chemical stimuli, pressure changes, or electrical changes.

1D. To avoid extreme temperatures

Although fish are poikilotherms, adverse temperature conditions can harm fish for various reasons including impact on oxygen availability and demand, so they need to avoid them if possible. Body temperature modification in most fish, where it can occur at all, is behavioural.

1E. To osmoregulate

Fish need to maintain relative stability in the ionic composition and osmotic strength of their body fluids, for example when exposed to inappropriate salinity.

1F. To have space for movement

Fish require space to carry out various functions, such as food searching, social interactions and responses to threats, and crowding can lead to problems. The fish species vary greatly in what space they need.

2 Need to have appropriate social interactions

Some fish species shoal for much of their lives and good welfare may depend upon such behaviour. Other species are social for part of their lives or for none of their lives. Some fish need to avoid attacks by conspecifics.

3 Need to avoid predation

Many fish living in natural conditions are very vulnerable to predation. The biological functioning fish of most species is strongly adapted to maximise the chance of recognition of danger from predators and escape from it.

4 Need to feed for maintenance and growth

A variety of nutrients are needed by fish. Fish also need to avoid feed containing dietary toxins and anti-nutrients.

5 Need to maintain good health condition

Fish use various behaviours, anatomical adaptations, physiological responses and immune responses to combat pathogens. They need to avoid any physical or chemical impact that causes tissue damage.

RECOMMENDATION

Since there is evidence in fish for the range of abilities and functions associated with learning and cognition and with affective states such as pain and fear, the welfare of fish should be considered during all aspects of their husbandry.

Fish farming in Europe

World aquaculture has significantly increased during the last fifty years from a production of less than a million tonnes in the early 1950s to 59.4 million tonnes by 2004. Consumption of farmed fish is about 45.5 million metric tons whereas around 60 million tons are wild caught fish from both fresh and sea-water. The 70% of the total aquaculture production comes from the Chinese aquaculture, 22% from the Asian and the Pacific region whereas Europe contributed to approximately 4% of world farmed fish production (FAO;

http://www.fao.org/newsroom/en/news/2006/1000383/index.html).

Nevertheless Europe has the largest production of some species like Atlantic salmon, European sea bass and gilthead sea bream. Currently, Norway is the top producer in Europe, with an annual salmon production of more than 580,000 tonnes representing a 41% of increase in the production rate from 1998 to 2003. Other major producing countries of farmed fish in EEA are Spain, France and Italy. United Kingdom and Greece are also centres of fish farming activity and smaller quantities are produced in several other European countries (Table 1).

Table 1**. Finfish aquaculture production in EEA countries in 2005**

Country	2005	% growth 1995 - 2005
Norway	652306	135.30
United Kingdom	143012	64.50
Greece	80136	268.36
Spain	57346	100.74
France	50352	-23.11
Italy	47642	-27.49
Denmark	38732	-13.41
Poland	36607	45.78
Germany	35130	-22.02

Czech Republic	20455	9.51
Ireland	15384	15.68
Finland	14355	-17.24
Hungary	13661	45.95
Netherlands	8675	213.63
Iceland	8246	136.61
Romania	7284	-63.27
Sweden	4805	-20.20
Portugal	4115	137.31
Bulgaria	2971	-31.70
Austria	2420	-17.07
Cyprus	2315	419.06
Lithuania	2013	17.44
Slovenia	1335	72.04
Switzerland	1214	4.57
Belgium	1200	41.84
Slovakia	955	-40.94
Malta	736	-18.58
Estonia	553	75.56
Latvia	542	3.24
Total	1253283	63.29

(Source: Eurostat, 2008)

European finfish aquaculture species comprises a range of teleosts including salmonids like Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*) and arctic charr (*Salvelinus alpinus*), sea basses (mainly European sea bass *Dicentrarchus labrax*), sea breams (mainly gilthead sea bream *Sparus aurata*), carps (e.g. common carp, crucian carp, grass carp and silver carp), flatfish like turbot (*Psetta maxima*), halibut (*Hippoglossus hippoglossus*) and sole (*Solea vulgaris vulgaris or Solea solea*), European eel (*Anguilla anguilla*), catfish (*Clarius sp.*) and gadoids like Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) (Table 2).

***Table 2.** Yearly production of the main farmed fish species in EEA in tonnes*

Species	1995	2000	2005
Atlantic salmon	347 861	589 606	733 332
Rainbow trout	258 168	286 629	261 805
Gilthead seabream	17 487	58 747	71 475

Common carp	75 000	72 178	69 557
European seabass	17 000	40 869	49 202
European eel	6 819	10 658	8 202
Atlantic cod	317	169	8 115
Turbot	2 978	4 785	6 838
Catfish	1 482	3 640	6 674
Silver carp	8 851	4 909	2 568
Atlantic halibut	-	35	1 445
Grass carp	1 334	1 526	1 090
Arctic charr	531	1 028	905
Haddock			72
Sole	30	23	11

*catfish (Clarius Spp. and Silurius spp)

Source: Eurostat, 2007

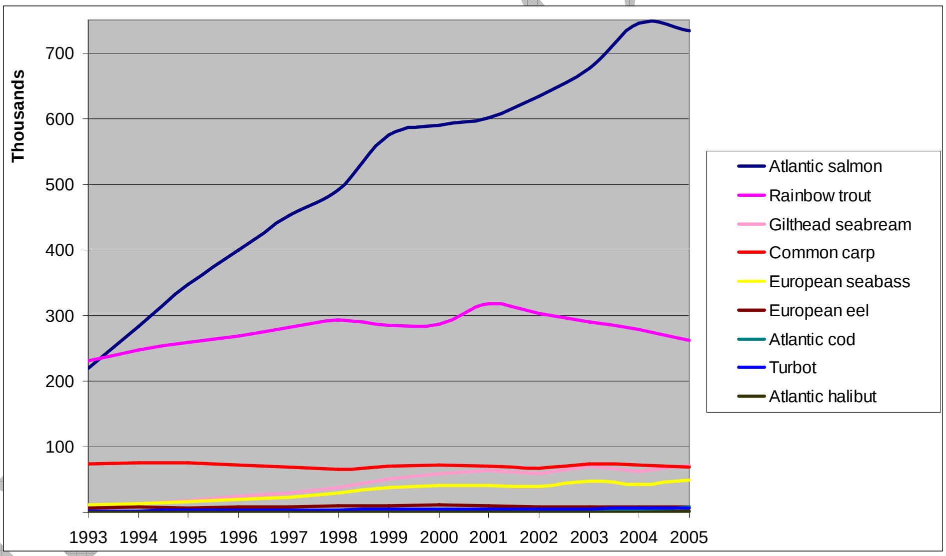

Figure 1: *Yearly production (thousands of tons) of the main farmed finfish species in EEA* (Source: Eurostat, 2007).

Annex I to the EFSA Journal (2008) 736, 1-122

Scientific Report on animal welfare aspects of husbandry systems for farmed Atlantic salmon

(Question No EFSA-Q-2006-033)

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PANEL MEMBERS

This scientific report was peer reviewed by the Members of the Scientific Panel for Animal Health and Welfare (AHAW) of the European Food Safety Authority. The scientific report was used as the basis for the scientific opinion adopted on 19th June 2008. The members of the AHAW Scientific Panel were:

Bo Algers, Harry J. Blokhuis, Donald M. Broom, Patrizia Costa, Mariano Domingo, Mathias Greiner, Daniel Guemene, Jörg Hartung, Frank Koenen, Christine Müller-Graf, David B. Morton, Albert Osterhaus, Dirk U. Pfeiffer, Ron Roberts, Moez Sanaa, Mo Salman, J. Michael Sharp, Philippe Vannier, Martin Wierup, Marion Wooldridge.

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BACKGROUND AS PROVIDED BY THE EUROPEAN COMMISSION

Council Directive 98/58/EC concerning the protection of animals kept for farming purposes lays down minimum standards for the protection of animals bred or kept for farming purposes, including fish.

In recent years growing scientific evidence has accumulated on the sentience of fish and the Council of Europe has in 2005 issued a recommendation on the welfare of farmed fish1. Upon requests from the Commission, EFSA has already issued scientific opinions which consider the transport2 and stunning-killing3 of farmed fish.

TERMS OF REFERENCE AS PROVIDED BY THE EUROPEAN COMMISSION

In view of this and in order to receive an overview of the latest scientific developments in this area the Commission requests EFSA to issue a scientific opinion on the animal welfare aspects of husbandry systems for farmed fish. Where relevant, animal health and food safety aspects should also be taken into account. This scientific opinion should consider the main fish species farmed in the EU, including Atlantic salmon, gilthead sea bream, sea bass, rainbow trout, carp and European eel and aspects of husbandry systems such as water quality, stocking density, feeding, environmental structure and social behaviour.

Due to the great diversity of species it was proposed that separate reports and scientific opinions on species or sets of similar species would be more adequate and effective.

It was agreed to subdivide the initial mandate into 5 different questions.

Question 1

- In relation to Atlantic salmon

Question 2

- In relation to trout species

Question 3

- In relation to carp species.

Question 4

- In relation to sea bass and gilthead sea bream

Question 5

- In relation to European eel

This report will refer only to question 1 as referenced above.

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1 Recommendation concerning farmed fish adopted by the Standing Committee of the European Convention for the protection of animals kept for farming purposes on 5 December 2005

[2] Opinion adopted by the AHAW Panel related to the welfare of animals during transport -30 March 2004

[3] Opinion of the AHAW Panel related to welfare aspects of the main systems of stunning and killing the main commercial species of animals- 15 June 2004

ASSESSMENT

1. Scope and objectives of the report

As a consequence of the diversity of farmed fish species, it was decided that the main species should be considered in separate reports The Atlantic Salmon fish farming industry and production systems is described in Chapter 4. Chapters 3 and 5 concern aspects related to the biology of salmon describing both farmed and wild Atlantic salmon behaviour when relevant. Chapter 6 provides evidence concerning major factors affecting the welfare of salmon.

A Risk Assessment approach was followed to describe possible welfare risks. The risk assessment methodology is explained in Chapter 7. The information about potential hazards forms the basis for the hazard identification in the assessment of risks associated with particular husbandry conditions for salmon. Aspects of salmon welfare were not only described qualitatively but also a semi-quantitative risk assessment based on expert opinion was carried out. This risk assessment had three objectives: i) to make the assessment of the salmon welfare more transparent, ii) to allow a ranking of the most important hazards to salmon welfare and iii) to attempt a comparison of the different production systems for each life stage.

2. Atlantic salmon taxonomy

In Europe the only 'salmon' farmed is the native species of the Atlantic coasts of Europe and North America, the Atlantic salmon: *Salmo salar* Linaeus 1758.

Salmo salar and the brown trout, *Salmo trutta* Linaeus 1758, which shares its range, are the only two members of the Family Salmonidae of the Order Salmoniformes.

3. Atlantic salmon life history

The table below describes the life stages (in bold) of farmed Atlantic salmon, with reference to their wild counterparts. There is considerable evidence of the behavioural differences between domesticated and wild populations of Atlantic salmon (Huntingford, 2004). However information exists on the behaviour and physiology of wild salmon which may be relevant to this report. Table 1 should be regarded as a table for comparison when using scientific data stemming from wild populations.

Table 1. **Farmed and wild Atlantic salmon life stages**

Farmed Salmon	**Wild Salmon**
Stripped **Eggs** are fertilised and placed in hatching containers. Unfertilised **Eggs** are removed. On hatching **Alevins** are kept in a variety of systems until they move up into the water column, at which point 'first feeding' occurs and the fish are transferred to tanks, as '**First Feeding Fry**'.	**Eggs** are laid in the gravel of a redd, in well-aerated clean water. On hatching, **Alevins** reside within the gravel until absorption of the yolk sac when they migrate up into the river flow to commence exogenous feeding.
After first feeding the fry are termed parr and are maintained in tanks under a variety of systems through the **Parr** to the **Smolt** stages Timing of **Smoltification** can be modified with the use of manipulated environmental regimes.	**Fry** start to feed within the drift and, as **Parr**, move away from the redd. After a year or more, depending upon various factors such as food availability and temperature, the **Parr** will undergo **Smoltification** to become **Smolts** and are ready to migrate to sea.
Following smoltification the **Ongrowing Salmon** are transferred to sea cages to grow for up to 2 years, until slaughtering at around 3 – 4 kg weight. Fish maturing after one winter in sea cages are often referred to as **Grilse**.	**Smolts** are adapted for sea-water survival and migrate to the sea. At sea the fish grow for one or more years until maturity, at which point they will migrate back to freshwater to spawn. Maturing fishes returning after one winter at sea are called **Grilse,** after more than one winter at sea they are referred to as multi-sea winter salmon.
Maturing **Broodstock** are maintained in separate sea cages or lands based tanks for several years, or are caught from the wild. They are usually moved to freshwater tanks about 2 months prior to spawning at which point the **Eggs** will be stripped and fertilised with milt. Wild broodstock are usually stripped for restocking purposes and may be held post stripping with a view to release as 'well-mended kelts:	Adult **Salmon** may enter a river up to one year before spawning, residing within pools in the river and then finally migrating upstream to the spawning site. Salmon typically spawn between October and January in the Northern hemisphere. Any fish which survive spawning return to sea as **Kelts**.

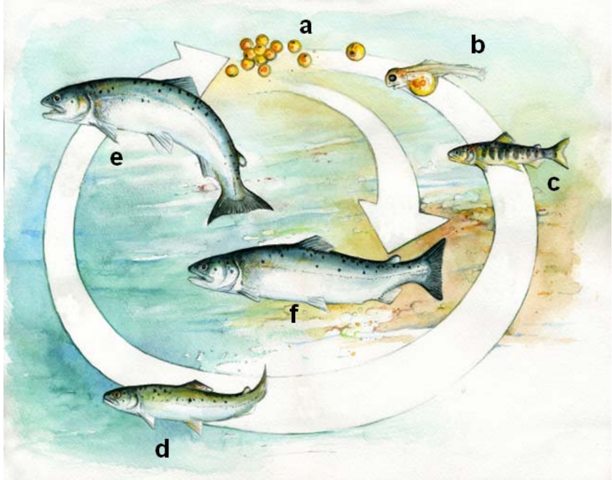

Figure 1. **Atlantic salmon (*S. salar*) lifecycle.**

Illustration showing eggs (a), alevins (b), parr (c), smolts (d), adults salmon (e) at sea and spawning salmon (f) upon return to river. (Drawing courtesy of Dr. Stein Mortensen, Institute of Marine Research, Norway).

4. Atlantic salmon farming

Eggs and milt are normally manually stripped or surgically removed after lethal anaesthesia from broodstock held in freshwater tanks or ponds. Female broodstock are usually killed after one usage mainly because there is a need to collect kidney or other tissue samples for disease-free certification. Males can be repeatedly stripped but they are often slaughtered at the end of the spawning season. Anaesthetics can be used under veterinary prescription.

Following manual fertilisation, eggs are usually disinfected in isotonic iodophor solutions prior to water hardening. The disinfection procedure is used to prevent vertical transmission of diseases. Eggs are subsequently rinsed in clean fresh water to remove surplus disinfectant, milt and ovarian fluid. The eggs are then hydrated or water hardened in freshwater for up to one hour and then transferred to flat-screen incubators or containers for incubation. The eggs are very fragile between 8 and 220 degree days post-fertilisation (known as green eggs), during which time all handling and movement may cause later damage. After 220 degree days the embryo eyes are clearly visible, and the eggs are known as eyed eggs. Between 250 and 370 degree days the eggs are manually shocked, usually by pouring from one incubator unit to another, which causes all non viable or non-fertilised eggs to absorb water and turn white. These eggs are removed by manual or automatic sorting methods.

Hatching will normally take place between 490 and 510 degree days post-fertilisation. Immediately prior to hatching the eyed eggs are transferred into shallow layers in the hatching system so that is possible to remove dead eggs and alevins easily. Following hatching, **alevins** (free embryos) will remain in shallow water (up to 10 cm) on a suitable substratum that allows vertical position with limited movement required, until the yolk sac is absorbed and the alevins require artificial feed. The ideal substratum needs to: i) provide support to alevins; ii) prevent crowding; iii) allow efficient oxygen transfer; iv) disinfection; and v) convenient access for mortality removal. The stage for first feeding, known as point of feed, usually occurs between 780 and 810 degree days post-fertilisation. At this point, the fry are usually transferred into shallow tanks or raceways where suitable water flows can be provided to allow normal swimming activity, even distribution of food, and removal of waste products. Eggs and alevins are normally kept in near darkness until first feeding, when extended daylength up to 24h daylight period is recommended to encourage feeding response and early growth.

Incubation temperatures will range according to site location and production system, but generally temperature up to 8 °C between fertilisation and hatching is commonly used by the industry. To produce early smolts (S0), post-hatch alevins may be exposed to heated water up to 10 °C, increasing to 12 °C from first feeding.

First feeding takes place in freshwater tanks at depths typically between 300 and 900mm, until the fry are free swimming and able to keep position within the tank and supplied with formulated dry feed. Once the majority of the population are clear of the bottom of the tank, known as swimming up, the water depths may be increased to normal operating levels to maximise available space. Once the population feeding response is established, parr may be ongrown either in tanks or raceways with flowthrough or recirculated water, or transferred to cages in freshwater lakes. Temperatures at first feeding can be critical to subsequent size and timing of transfer of smolts. When temperatures at first feeding are too low, bimodality (see section 5.2) of the population may occur. Salmon in freshwater are termed **fry** up to 1g, then parr during the freshwater growth phase up to a size where the first smoltification signals may be observed known as pre-smolts. This is typically a mean weight of around 15g or a length of 85mm. Artificial photoperiod regimes may be used to control growth and developmental stages during the freshwater phase. Usually, extended daylength is used from point of feed to discourage bimodal populations and to maximise growth.

Cage production of **parr** relies on ambient temperature and oxygen levels, and typically operates at much lower stocking densities than landbased systems. Stocking densities used vary considerably between sites. Artificial lighting can be used in cages by providing a 24h daylight period to encourage final stages of smoltification. Production in freshwater tanks may use ambient flowthrough, but in most commercial operations, supplementary oxygenation is used to permit higher densities, improve feed efficiencies and improve growth. In the industry the level of supplementary oxygen is determined by monitoring oxygen saturation in the effluent either by using manual meters or by automatic systems, and the rate of oxygen addition to the incoming water is adjusted accordingly. Modern intensive systems incorporate automatic controls to maintain stable oxygen levels throughout the day. Partial water reuse systems may be used up to 40% without any water treatment however this usually constitutes an emergency measures for water shortage periods or specific inflow problems. Freshwater tanks with recirculation are becoming an increasingly important production system. Recirculation consists of reusing up to 95% of effluent water by a process of particle filtration to remove suspended solids, biofiltration to remove ammonia, degassing to remove carbon dioxide, and reoxygenation.

Feeding in freshwater is usually done by automatic feeders, designed to ensure wide distribution of feed particles, on timer control to provide frequent meals throughout the feeding period. Supplementary hand feeding is often used to determine appetence.

The parr-**smolt** transformation, smoltification, comprises a range of morphological, physiological and behaviour changes that pre-adapt the smolts to a marine life (i.e. from fresh to sea-water). This process normally takes place in the spring (typically April to June depending on water temperature) under ambient light conditions when the salmon is either 1.5 or 2.5 years old (from fertilisation). If salmon smolts are prevented from entry or transfer to sea-water when the smoltification process is completed, they will start to reverse into a freshwater adapted fish again in a process termed desmoltification. Desmoltified salmon are not able to grow and live in full strenght sea-water. Farmed Atlantic salmon moltify using similar mechanisms to those in nature, but the onset of the process is largely controlled by photoperiod manipulation, enabling the production of smolts outside the natural smolt window during spring (Berge et al., 1995).

Various signals are used on pre-smolts to achieve smoltification, using a combination of photoperiod regimes and or specific manipulation of mineral balances in the water and feed. In wild fish, smoltification is initiated by the natural changes in daylength; this being a winter signal where a period of short day length is followed by a spring signal, extended daylight. In farming conditions these signals are artificially administered to induce smoltification out of normal season. Regimes of extended daylight and temperatures above 6 to 8 ºC coupled with grading are used to guarantee that the large majority of the population reaches the minimum size to respond to the smoltification signs. Fish can either be maintained on ambient temperature and light regimes to produce "S1" smolts in the spring of the year following hatch, or light and temperature regimes can be manipulated artificially to induce early smoltification “S0” (Figure 2). The production of S0 is based on early season eggs and first feeding starts earlier at higher temperatures.

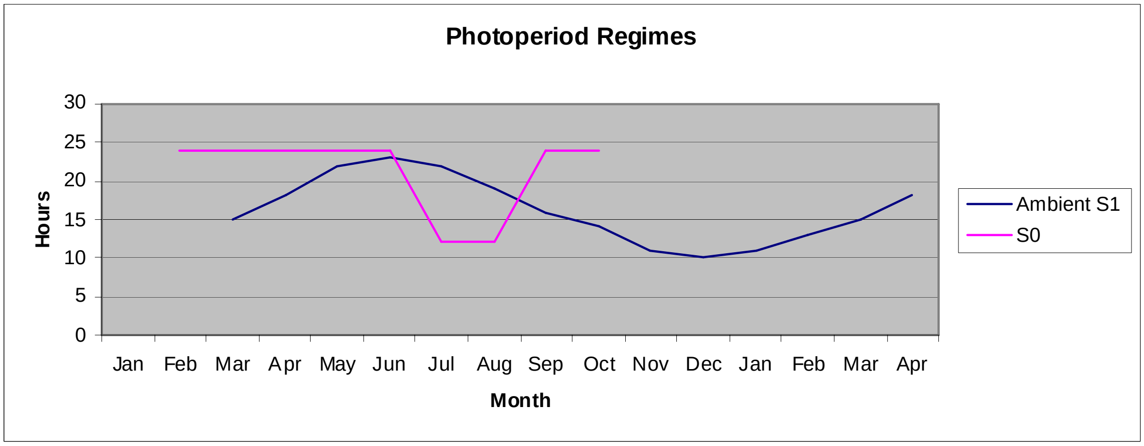

Figure 2. **Photoperiod regime for S0 and S1 production**

The evaluation of smoltification is estimated by various methods from visual inspection to sea-water challenges on a small sample of the fish population. Nowadays the most common system being used is gill ATPase measurements, which do not involve exposure to potentially lethal salinity levels. The quality of the smolts is also determined by body condition factor, fin and opercular condition and health status. The correct timing for sea-water transfer for a given batch is central for growth and survival in sea-water.In order to optimise growth and survival after transfer to sea temperature and lighting differentials between freshwater and sea-water should be kept as low as possible. For out of season smolts (S0), artificial lighting in sea cages can be used to maintain the extended day-length (18-24h) light regime following transfer until ambient day length starts to increase.

Ongrowing constitutes the largest part of the production life cycle with fish being slaughtered between 10 and 24 months post-transfer. The length of grow out stage depends on temperature, day length, fish strain and production regime. On-growth in sea-water normally takes place in sea cages, mainly located in protected inshore areas although use of offshore sites are becoming more frequent due to increased environmental protection regulations and the need to increase unit size to improve production efficiency. Cage types vary from rigid square cages of timber, steel or plastic construction from 9-20 m sides to flexible circular plastic cages up to 160 m diameter. Net depths will vary between 5 and 50 m. Most ongrowing sites are operated in a single year class basis. Initial site stocking numbers are based on a calculation of terminal stocking density at harvest although initial stocking density numbers per m^3 will vary depending on cage type and site location. Grading per size in sea-water is usually done once (often after the first winter at sea) to separate harvest sizes and reduce stocking density. Re-stocking of the sites generally does not take place until the previous year class has been completely removed and the site cleaned and disinfected. Water renewal in cage systems is dependent on site location, water currents, but biofouling (algae coverage of nets) can affect free water moving and either net replacement or *in situ* cleaning devices are used. Feeding in sea-water is done either by automatic feeders on timer control, or manually. During the ongrowing stage fish are usually fed between 2 to 4 meals a day. Artificial light is normally used during winter in order to extend the day-length to improve growth and also to avoid early sexual maturation. The artificial light is normally supplied from lamps either above the cage or more commonly submerged.

Salmon **broodstock** are normally reared in sea-cages until just before sexual maturation (typically 2 years in sea water), when maturing fish are identified and transferred to special broodstock facilities, with freshwater tanks, during summer or autumn just before spawning.

Some broodstock are reared in land-based tanks with access to both fresh water and sea-water. In the freshwater phase, broodstock are kept in group tanks of mixed male and female populations until spawning time. Regular physical checks are performed to determine stage of maturation and time of spawning. Hormone treatment with GnRh is sometimes used to synchronise spawning in either males or females or both. Photoperiod and temperature control can be used to simulate natural spawning conditions (decreasing day length and temperature) and thus control timing of spawning in salmon broodstock. Broodstock are normally fed on appetite up to 3 to 4 months prior to spawning when maximum body weight is achieved and the fish naturally ceases to feed.

4.1. Production system

Atlantic salmon is farmed in a variety of production systems. The exact numbers of the various systems used is mostly unknown although some information is available at national level. The large majority of Atlantic salmon are produced for human consumption. Small numbers of Atlantic salmon are produced for river restocking.

Production of re-stocking Atlantic salmon is based on wild broodstock of the same river where re-stocking will occur. Restocking can be done by release of eggs, fry or smolts. The production systems used are similar to those used for production of fish for human consumption although in general of smaller size and lower technology.

4.1.1. Egg incubation

Between fertilisation and hatching, salmon eggs are normally held in either bucket or silo type containers ranging in capacity between 5 litres and 200 litres. The water supply is either upwelling (water in at perforated base, flow upwards through eggs and overflow from top) or downwelling (water in at top, downward flow through eggs through perforated screen and side discharge. In silo type incubators, removal of dead and non-viable material must be carried out at the earliest stage possible (i.e. eyed stage ca 250 degreedays) to prevent contamination and fungal development

Figure 3. **Egg incubators - detail of silo or zoug jar incubator and commercial silo incubator system**

An alternative system would be to use shallow baskets with perforated sides and base in a square or rectangular trough or tray. The water inlet is located at one end and discharge at the other end. These trays may be stacked in a tier system with a cascade water supply. All systems are protected from light at all times during incubation.

Figure 4. **Trays - stacked tier incubation trays**

4.1.2. Hatching trays

Prior to point of hatch, eyed eggs are generally transferred into shallow troughs (100-150mm deep), either square or rectangular and between 500 and 1,500mm long, with water flowthrough from end to end, or the troughs may be stacked vertically with a cascade water flow system. The eggs are laid in thin layers (1-2 eggs deep) in baskets with a perforated side and bottom to allow water movement and free oxygen transfer. Once hatched, the alevins will pass through the perforations and rest on suitable substratum (stones/ gravel, astroturf, biomatting or similar) at the bottom of the tray or trough. There is normally protection from light up to point of feed.

Figure 5. **Hatching trays - Hatching eggs in shallow layers**

Figure 6. **Hatching trays - Multiple hatching baskets in a rectangular trough**

4.1.3. First feed tanks

Tanks designed for first feeding fry are generally either round or square tanks, of a diameter ranging from 1 metre to 10 metres, and working depths up to 1.5 metres. The tanks are usually either Glass-Reinforced Plastic (GRP) or smooth concrete construction, with flat bottoms to allow alevins and fry to maintain station on the tank base without progression to outlet screens. The outlet screens are designed to prevent the passage of alevins and fry, but will allow removal of waste products.

Water inlets are designed to provide necessary water flows and spin speeds for the fish, and the tanks are fitted with sufficient numbers and type of feeders to supply the desired rations and meals for the stock, and to ensure even distribution such that all fish have access to feed as required. The tanks are generally shaded from direct sunlight, usually by enclosure within a building.

Figure 7. **First feed tanks**

4.1.4. Parr or smolt freshwater tanks

Once feeding has been established, fry and parr may be transferred into larger tanks for freshwater ongrowing. These are generally round tanks, of a diameter ranging from 2 metres to 15 metres, with working depths up to 3 metres. Tanks are typically of either GRP or steel construction, and have coned bases to allow self-cleaning action by directing waste products to centre screen. Tanks will either have jump guards in place, or operate with sufficient freeboard to prevent fish jumping out of the tank. Outlet screens are fitted that prevent egress of fish, but allow removal of waste products, and also convenient and biosecure collection of mortalities at effluent point of exit. Access to the effluent point is usually via overhead walkways to minimise disturbance of fish during husbandry operations. The water inlets are designed to provide necessary water flows and spin speeds for the fish requirements, and the tank is fitted with sufficient numbers and type of feeders to supply the desired rations and meals for the stock, and to ensure even distribution such that all fish have access to feed as required.

Since these tanks are often outside, it is important that all tanks are fitted with protection systems designed to prevent access by predators.

Figure 8. **Large diameter parr to smolt rearing tanks**

4.1.5. Parr and smolt production in recirculation systems

Recirculation systems are of increasing importance in parr and smolt production, especially since the newly introduced EU Water Framework Directive (Directive 2000/60/EC) will put pressure on freshwater cage systems and the inability to control effluent discharge.

Recirculating water systems are designed to minimise or reduce dependence on water exchange and flushing in fish culture units, typically when there is a specific need to minimise water replacement, to maintain water quality conditions which differ from the supply water, or to compensate for an insufficient water supply. All recirculating systems operate on four basic principles, namely.

a) Oxygenation: Water must be re-oxygenated to maintain adequate dissolved oxygen concentrations for fish and for proper functioning of the biological filter.

b) Removal of particulate matter: Solids resulting from fish waste and uneaten feed contribute a portion of the oxygen demand and toxic ammonia in the system and should be concentrated for removal, typically through mechanical filtration. This will also increase the operational life and efficiency of the biological filtration.

c) Biological filtration: To control ammonia levels in recirculating water systems, extensive surface area is provided for bacteria which biologically oxidize ammonia to relatively harmless nitrate (NO_3). Bacterial nitrification is a two-stage process resulting first in the transformation of ammonia to nitrite (NO_2^-), then a further oxidation of nitrite to nitrate. To ensure bacterial populations are sufficient to remove ammonia and nitrite at rates required during operation, a biofilter is typically conditioned for several weeks by adding ammonia and monitoring its breakdown prior to stocking fish. The media used must ensure maximum surface area for bacterial growth, high dissolved oxygen levels, uniform water flow through the filter, sufficient void space to prevent clogging, and proper sizing to ensure adequate ammonia removal capability.

d) Buffering of pH: Since fish metabolism and bacterial nitrification result in the formation of acids that lessen the buffering capacity of water and lower the pH, it is necessary to replace lost alkalinity and sustain the buffering capacity of water by the addition of carbonate. Frequent monitoring of water hardness, alkalinity and pH is required.

The other benefit of recirculating water systems is the opportunity for efficient temperature control.

4.1.6. Parr and smolt freshwater cages

Once feeding has been established, parr may be transferred into cages in freshwater lakes. These cages are usually square or rectangular floating collars of wooden construction with polystyrene flotation, or plastic construction either square or round. Cage sizes vary between 9 to 15 m^2, and 10 to 25 metres diameter. Nylon mesh nets are suspended from the collars and suitably weighted to prevent ‘bagging’ in winds or strong currents. Net depths are generally 3-5 metres depending on the lake depth, and are usually fitted with a ‘sock’ in the centre of the base where mortalities will collect. Mortality removal is either by manually gathering the ‘sock’ at the surface and removing mortalities by hand, or by using an airlift system. Automatic feeders are usually suspended from walkways and placed over the cage to ensure maximum distribution of feed.

Figure 9. **Freshwater cages - square freshwater cages**

4.1.7. Grower sea-water cages

On transfer to sea-water following smoltification, smolts are placed in cages of either wooden or steel construction square or rectangular floating collars, with sizes varying between 9 and 20 metres square, or in flexible circular plastic collars up to 160 metres diameter. Mooring systems using shore or seabed anchors, or a combination of both, are essential to ensure stability and security. Nylon mesh nets are suspended below the collars and suitably weighted to prevent bagging in strong winds or tidal currents. Net depths will vary between 5 and 50 metres, depending on site location and management systems.

Figure 10. **Sea-water cages**

4.1.8. Broodstock: sea-water and freshwater tanks

In production systems where broodstock are retained in land based facilities for the duration of the life cycle, the fish are transferred at smolt stage into tanks of generally large diameter (between 10 and 25 metres diameter) and shallow enough to allow human access for sorting activities without exposing the broodstock to excessive crowding densities. The tanks will have sufficient water inlet capacity to provide water flows necessary to sustain the stock within the tank, and sufficient outlet capacity to allow removal of waste water and products without the tank overflowing at any point. The water supplies will be twofold, freshwater and sea-water. In addition, emergency back-up oxygenation is available in the event of flow interruptions.

Figure 11. **Broodstock tanks - 12 metre diameter sea-water tanks for broodstock production**

4.2. Atlantic salmon Production in Europe

European production of Atlantic salmon constitutes more than 90 percent of the world farmed salmon market, and more than 50 percent of the total global salmon market (FAO, 2006). Atlantic salmon constitutes the main species produced by European aquaculture. The major producing countries are Norway and UK followed by Ireland and Iceland (Figure 12).

Table 2. **Yearly production of Atlantic salmon in Europe (tonnes)**

	1995	2000	2001	2002	2003	2004
EU 15	83748	146952	162267	169476	162575	172954
EEA	347861	589606	601015	633442	675827	745480

(Source: Eurostat, 2007).

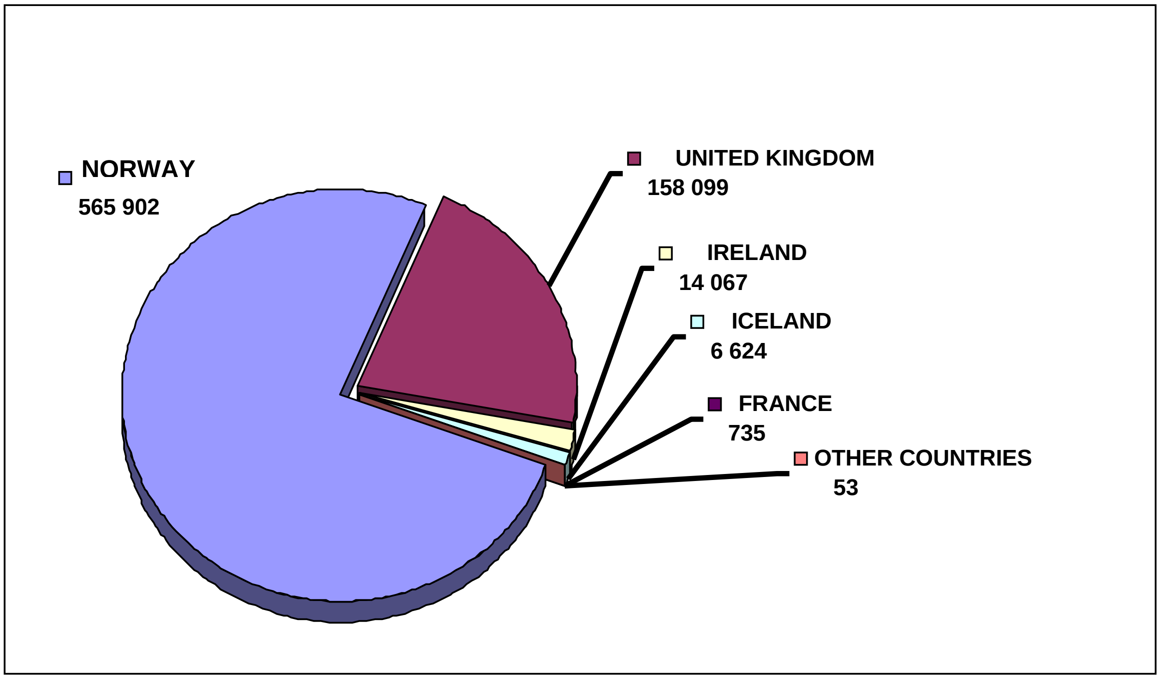

Figure 12: **Atlantic salmon EEA productions in 2004 (tonnes of live weight)**

Furthermore Salmon constitutes the third largest animal production in terms of total numbers (Table 3)

Table 3. **Farmed Atlantic salmon and other terrestrial species input to the food chain in EU-25 in 2005**

	number of animals [thousands]	**volume [tonnes]**
Poultry	4 402 796	981 478
Pigs	238 949	21 099 766
Sheep	64 598	985 182
Salmon	(estimated) 36 201 – 72 401	144 801
Bovines	28 098	7 853 802
Equidae	254	63 561
Goats	7 597	73 383

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5. Biology of salmon

5.1. The needs of salmon

To have access to appropriate oxygen concentration

Salmon of all ages are significantly less tolerant to low oxygen partial pressure in water than many other fish species (Kramer, 1987; Bickler and Buck, 2007). On the other hand hyperoxic conditions may also be harmful to salmon (e.g. (Olsvik et al., 2005)) due to potential toxic effects of very high oxygen partial pressure.

To avoid extreme temperatures

Thermoregulation in salmon, where it occurs, is behavioural, and hence they require access to water within their preferred temperature range. In the marine environment salmon seem to prefer the warmest place in stratified water in cages provided that the water temperature is not too high (Johansson et al., 2006; Johansson et al., 2007; Oppedal et al., 2007) but need to avoid extreme temperatures where the tolerance depends on life-stage and physiological condictions.

To osmoregulate

Salmon encounter a range of salinities and need to regulate body fluid concentration. This is especially difficult during the period of smolting when the animal moves from a freshwater to a marine environment. The challenges are opposite in freshwater and sea-water. In freshwater, salmon produce urine with low osmotic strength to get rid of surplus water, while monovalent ions are actively taken up by the gills to compensate for their passive loss. In sea-water, salmon excrete monovalent ions over the gills and divalent ions in the urine. Water loss is compensated by drinking sea-water and subsequent excretion of the resultant salt uptake. Rapid changes in salinity can stress the fish.

To have space for movement

Whilst it is known that salmon swim and utilise space, their needs are not clearly established except for some data on adverse effects of high stocking density such as higher incidence of fin damages. The need for space is related to swimming behaviour, schooling ability and ability for appropriate social interactions. The swimming behaviour and swimming speed in salmon can depend on a range of factors such as stage of development, group size and stocking density, environmental conditions such as light intensity and water currents, space for movement and feeding motivation (Juell, 1995; Juell et al., 2003). Temporary crowding of salmon during husbandry operations typically induce panic reactions, and can prevent them from being able to show some directional or vigorous movements (Turnbull et al., 2005).

To have appropriate social interactions

Salmon parr are sometimes aggressive to one another, whilst salmon smolts tolerate social contact better and tend to form schools. Agonistic behaviour is seen to a much lower extent in the sea-water phase and the preferred schooling. The preferred schooling density and stocking density for salmon during is not well known for the different life stages, and optimum stocking densities to reduce agonistic behaviours will probably depend on life-stage and other environmental factors such as water current speed, water depth, light conditions, feeding regime and shape and size of the rearing enclosure.

To feed for maintenance and growth

Salmon are adapted to a diet of animal origin and require a variety of nutrients. If nutrients are lacking being unbalanced or anti-nutrients or toxic substances are present in the diet, there can be a range of adverse effects on the fish.

5.2. Feeding behaviour

Salmon are selective feeders and are able to differentiate between various kinds of feed. Feeding behaviour in wild salmon is significantly different for freshwater and sea-water stages of the life cycle. In freshwater, the parr captures food items, primarily invertebrates, drifting in the flow of the river. Parr are territorial, with dominant fish holding territories through which a larger number of prey items pass. In aquaculture systems however, the restricted living area provided by tanks and cages, combined with production stocking densities do not allow for the formation of territories, however the fish may show aggression like that shown in territorial behaviour and will sometimes defend territories if space allows.

Fish on sea cages will feed in a daily rhythm which can vary with environmental and seasonal variables (Noble et al., 2007). Feeding rhythms in a tank environment may also be related to rhythms of aggressive activity (Kadri et al., 1997).

Endogenous feeding patterns of wild salmon in freshwater have developed to meet the natural variation in drift items, providing for example, a peak in seasonal appetite in May among tank-held parr in Scotland co-inciding with the number of optimally sized drifting prey items in rivers (Simpson and Thorpe, 1997). In autumn, wild parr separate into upper and lower modal groups (UMG and LMG), suggested on the basis of growth rate with the UMG fish undergo an appetite increase for some weeks, while LMG fish become anorexic over winter, even when in an environment where food is readily available (Metcalfe et al., 1986). This state of anorexia is maintained so long as the individual’s energy stores are anticipated to remain above a critical minimum: where this is not the case, the fish will re-commence feeding in order to maintain sufficient energy stores for the over-wintering period (Bull et al., 1996). As water temperature reduces, UMG fish on the other hand, tend increasingly to take shelter by day and feed nocturnally (Fraser et al., 1993) trading off efficiency in capturing food items with predator avoidance at a time when the salmon are unable to move quickly due to the cold water. However, when shelter is not available, these fish will chose to feed by day.

In sea-water, wild salmon are predators and, like many such animals, in both aquatic and terrestrial environments, they tend toward crepuscular feeding patterns, this behaviour is maintained in production cages (Kadri et al., 1991). As with parr, populations of wild adult Atlantic salmon will separate into two groups in autumn: those which will undergo sexual maturation and return to rivers the following year to spawn, and those which will remain in the sea for at least a further year. Maturing fish are likely to maintain a higher level of appetite through the remainder of the autumn and early winter. In spring, maturing salmon will undergo an appetite surge, feeding heavily in order to provide for a build up of energy reserves in preparation for gonad development and upriver migration, while their immature counterparts will use available food to increase body length and thereby improve fitness for spawning in future years (Kadri et al., 1996). Maturing salmon do not feed during migration upriver to spawning grounds, i.e. they become anorexic on entering freshwater, and remain so until spawning, which can be as long as 14 months. Most Atlantic salmon die after spawning but a small percentage (around 6 % in Scotland) recover (“mended kelt”) and return to the ocean. When such fish return they are rarely very different in size from their size on first spawning.

In aquaculture, sexual maturation is a disadvantage because of related effects on food conversion rates, carcass quality and increased aggressive behaviour. Fish are usually slaughtered prior to maturity and farming practices currently used such as fish age at transfer to sea-water, grading and photoperiod manipulation tend to delay the maturation

5.3. Swimming behaviour

In the wild, salmon alevins rest in the gravel, fry and parr tend to hold station in a current, smolts tend to school and drift downstream, while post-smolts and salmon at sea swim large distances. Maturing fish migrate long distances back to the river and swim upstream to the spawning grounds. In nature the salmon change behaviour during smoltification, from a territorial river dwelling fish with positive rheotaxis, to a schooling fish with negative rheotaxis.

In the farming situation factors like group size, hunger level, light conditions and evenness of the environment (i.e. water quality, shelter, light or disturbance) affect the swimming behaviour (Juell, 1995). Fish in tanks with a marked water current normally swim against the current and often tend to maintain their position in the tank. An increased tendency for shoaling during and after smoltification (Björnsson, 1993) has been observed. Shoaling behaviour depends on group size, experimental studies of post-smolts in sea cages demonstrate that 300-500 individuals are needed to form schools (Juell and Westerberg, 1993) which is considerably lower than the average stocking density of approximately 50 smolts/m^3 for smolts in cages used currently by the industry. Salmon post-smolts can swim with high body speeds (2-3 body lengths/s) over extended time periods (Cotterell and Wardle, 2004). However, cruising speed in schools are lower, typically 0.2-1.9 body lenghts/sec in sea cages (Juell, 1995). High swimming speed/water current may reduce agonistic behaviour like fin biting in salmon and char (Jørgensen and Jobling, 1993; Damsgård and Arnesen, 1998). Moderate exercise can also reduce the cortisol stress response in salmon (Boesgaard et al., 1993). Available space as well as water current can affect swimming speed, and it is believed that larger rearing units can stimulate or allow higher swimming speed based on commercial experience with larger sea cages. In sea cages, salmon normally swim in a structured school provided sufficient light for visual contact. Schooling is a part of the behavioural repertoire in wild salmon, and may be a condition of relative relaxation in terms of visual stimuli with a low level of agonistic behaviour (Juell et al., 2003; Juell and Fosseidengen, 2004). At night-time, and if the water current speed is very high, the fish tend to maintain their position in the cage by swimming against the current (“standing” on the water current). The effect of domestication of the swimming behaviour is not documented even if some scientific works highlight dramatic change of swimming behaviour in five generations of selection for growth (Mork et al., 1999).

5.4. Alertness and Exploration

Alertness can be defined as an appropriate response to biotic and abiotic cues, especially anti-predator behaviour, while exploration refers to the behaviour of a fish in a new location, such as that observed following displacement. Atlantic salmon also display a range of behaviours directed on various environmental cues (light, currents, gravitation, magnetism) such as phototaxis, rheotaxis and geotaxis or in response to environmental factors (e.g. photokinesis).

These behaviours change during the life-cycle, e.g. from alevin to fry stage, from parr to smolts and upon sexual maturation.

Other fish, predatory birds, predatory mammals and humans may elicit anti-predator behaviour in salmon. Problems related to anti-predator behaviour in aquaculture can be divided into two parts: i) an inability of the fish to respond to predator cues appropriately and ii) those situations where predator-type cues are presented and the fish are not able to act to reduce the risk from such cues. If fish are released into open water conditions there can be elevated post-release mortalities; up to 65% in the first 37 km of the marine migration (Thorstad et al., 2007). However some studies show no difference in survival after between wild and hatchery reared salmon (Hvidsten and Lund, 1988; Thorstad et al., 2007).

Farmed strains of fish differ to some extent from wild types in their risk taking and anti-predator behaviour. Newly hatched fish appear to be able to recognise some cues from a piscivorous predator (Hawkins et al., 2004b) although learning may be required to refine the response (Kelley and Magurran, 2003). Hatchery-reared salmon fry have been shown to respond less quickly to a visual predator stimulus than wild fry (Hawkins et al., 2004a). The presence of shelters is important in anti-predator behaviour of juvenile salmon. Even if the shelter is not used its presence was shown to result in a reduction of metabolic rate and adoption of a lighter colouration, indicative of reduced stress levels, in juvenile salmon (Millidine et al., 2006). For farmed fish in closed systems, predation is not usually an issue.

Atlantic salmon strains selected for growth have been shown to have similar behaviour in response to a model piscivorous fish (darting for cover or freezing) but started moving about and feeding after an attack faster than the wild-type (Einum and Fleming, 1997; Fleming and Einum, 1997). In other species it has been demonstrated that prior experience of predators can alter the anti-predator behaviour of hatchery reared fish (see (Huntingford, 2004).

Individual differences in risk-taking are often associated with differences in reactivity of the hypothalamic-inter-renal axis: “proactive” individuals show active, predominantly adrenaline-based responses, while “reactive” individuals show predominantly passive, cortisol-based responses (Korte et al., 2005). Such behavioural and physiological diversity (or variable “coping strategies”) has major implications for the welfare of animals in intensive husbandry systems, since these normally reproduce the conditions in which reactive animals will fail to thrive (Korte et al., 2005), resulting in poor welfare for any animals using this strategy.

Periods of rapid growth is often associated with increased boldness, possibly related to increased activation of the growth hormone axis. This has, for example, consequences for the vertical positioning of the fish in the water column; during the sea-water stage bolder fish appear to swim closer to the surface where there is a higher predation risk and increased feeding opportunities. Salmon typically dive following disturbances that induce panic reactions (Juell et al., 2003).

In sea cages there seems to be a range of trade-offs in relation to feeding behaviour, predator avoidance and environmental preferences affecting the vertical distribution and swimming behaviour of salmon (Fernø et al., 1995; Juell, 1995; Oppedal et al., 2001; Juell et al., 2003; Oppedal et al., 2007).

In the wild, fry and parr will continually explore their local environment, visiting several preferred feeding locations and building up a local map. The presence of a map has been demonstrated following experimental displacement of the fish. On moving upstream they show exploratory behaviour until they get within a certain distance (pers. comm. De Leaniz) before they swim directly to normal feeding locations. Exploration also enables the fish to learn the location of refuges within their normal range.

Parr will tend to swim upstream following displacement, possibly as an adaptive reaction to freshets (Huntingford et al., 1998). In rivers smolts alter their behaviour from the territorial, benthic, positively rheotactic behaviour of parr to shoaling, pelagic negatively rheotactic behaviour (Kalleberg, 1958), although some work appears to contradict this (Damsgård and Arnesen, 1998). Movement downstream is relatively slow with the fish mostly orienting upstream while moving down until they get within a short distance of the estuary at which point they swim straight to sea (Johannesson, 1987). Once at sea we have very little idea about the behaviour of the wild fish whether movement to the feeding grounds is direct or intermittent. On-growing salmon forage in the sea until they return to spawn during which time they swim along the coast using a range of sensory cues including olfactory cues provided by rivers to navigate back to their native stream. They often move some distance up a number of rivers before deciding to migrate fully up one particular river (Bailey and Saunders, 1984).

5.5. Social behaviour

Wild Atlantic salmon perform a range of social behaviours, including complex agonistic behaviour, feeding and mating behaviour. Agonistic behaviour such as aggression plays an important role for the welfare of the fish throughout the lifespan. Increased aggression must be considered a natural response by the fish, meant to optimise its chances of survival, growth and reproduction. Salmon in nature produce a large number of offspring to an environment with resource limitation, leading to a strong intraspecific competition, including aggression, in particular during the freshwater stage. Aggression is mainly documented in the freshwater phase in Atlantic salmon, particularly in parr, (Huntingford et al., 1990; Adams et al., 1998), and the level and intensity of the aggression is believed to be a balance between the advantageous and disadvantageous consequences of this behaviour for the individuals concerned (Grant, 1997). The parr-smolt transformation in nature also includes an ontogenetic shift in aggressive behaviour, but the changes in appetite and feed intake in farmed fish is not directly linked to the smoltification *per se* (Damsgård and Arnesen, 1998), indicating that the behavioural shift is linked to the habitat shift from the river to the sea

Variability in risk-taking behaviour or boldness has been documented in salmonids (Sneddon, 2003; Overli et al., 2004) and a correlation between boldness and aggression has been reported (Sundstrom et al., 2004; Schjolden et al., 2005). Both deliberate selection for fast growth and inadvertent selection of fish have generated inherited behavioural differences between farmed fish and the wild stocks from which they originated (Huntingford, 2004): while fish from farmed stocks tend to be bolder and to take greater risks when foraging; they may also be more aggressive. depending both on conditions during selection and the environment used to screen aggressiveness Fish from the risk-avoiding/non-aggressive end of the behavioural spectrum may fail to flourish in conditions that usually prevail in intensive husbandry systems (Huntingford and Adams, 2005). Other studies indicate that selection for growth have indirectly modified behaviour of wild animals from an initial high aggressiveness to protect their water volume and tank surface observed from F1 juveniles that stay swimmming at the tank surface to a lower aggressiveness and an occupation of all the water column indicating that selection can modify very quickly some behaviours and that scientific results obtained some years ago for these species and behaviours may need to be reconsidered in view of genotypes reared today (Mork et al., 1999).

Feeding aggression in farmed Atlantic salmon is generally based on getting exclusive rights to areas with high feed availability, such as close to a feeder. Laboratory studies indicate that subordinate salmon parr have a lower feed intake and growth compared with dominant fish

(Metcalfe et al., 1989). The question which fish in a group that become dominant is underpinned by several complex behavioural mechanisms, including both short term behavioural traits and long term developments of feeding hierarchies.

The importance of aggression as a decisive factor in social hierarchies has been demonstrated by consistently superior performance of the most aggressive fish. The existence of proximate physiological links between aggression and feeding status are demonstrated in behavioural studies of growth hormone (GH) transgenic salmon, leading to a higher feeding motivation and elevation of aggression (Abrahams and Sutterlin, 1999), similar to the changes in GH treated fish (Johnsson and Björnsson, 1994). The benefits of defending a resource increase if it becomes limited and the behavioural consequence of restricted feeding is often the formation or enforcement of feeding hierarchies. This seems to occur in several salmonid species, including Atlantic salmon (Huntingford et al., 1990; Adams et al., 1998).

Aggressive behaviour involves direct attacks between individuals, with displacement or bites (Keenleyside and Yamamoto, 1962). The best-known physical damage caused by aggression is inflicted on the fins, and results in symptoms signs like splitting of fin rays or tissue loss (Turnbull et al., 1996). In farming conditions it is observed that competitive, aggressive behaviour may also lead to reduction of feed intake and growth of subordinate fish. The long-term chronic social stress probably leads to reduced immune functions (Pickering, 1993). To control this problem grading is a common practice in salmon farming.

Aggression has genetic and environmental components. Although feed ration is the most studied factor, sub-optimal conditions can also include poor feed management, low water current speed, and low fish stocking density (Jørgensen et al., 1996). The formation of social hierarchies may be suppressed at high stocking densities in freshwater farming systems (Turnbull et al., 1996). Under high fish densities this may look somewhat different, as (MacLean et al., 2000) found that the largest, and presumably dominant fish, were most likely to have damaged fins due to attacks by conspecifics. Wild Atlantic salmon display a diversity of physiological and behavioural adaptations for reproduction, including several reproductive life history strategies, development of male and female specific secondary sexual characters and breeding behaviour and increasing levels of sex steroids leading to gonadal investments (Fleming, 1996).

In farming conditions, a variable proportion of the fish matures during the sea-water production (such fish are known as grilse) during the production cycle, but most fish are slaughtered before the mating period to avoid the strong negative impact of sexual maturation on growth, flesh quality and survival (Bilinski et al., 1984). It has been shown that the initiation of maturation involves a period of elevated feed intake and rapid growth early in the summer (Kadri et al., 1996). During the reproduction period, sex steroids (androgens) are known to affect aggression in fish, and androgen treatment in several fish species is shown to increase aggression the same relationships probably also exist in salmon. The causes and consequences of this relationship are, however, unclear, e.g. an increase in the plasma level of 11-ketotestosterone in males could be a result of social dominance, and not necessarily the cause for the dominance (Cardwell et al., 1996). Wild salmon males show overt aggression and fighting on natural spawning grounds, and although such behaviour is less documented in farming systems, farmed male broodstock are found to have wounds and physical damage indicative of agonistic behaviour and aggression and the prevalence of wounds is higher in males than in females (Johnsson et al., 2001; Weir et al., 2005) .

In the wild the actual spawning behaviour (i.e. digging of redds in the river gravel, egg release, sperm release and the covering of eggs with gravel) is believed to depend on appropriate environmental signals (e.g. water temperature, gravel size and water flow) and direct physical interaction (vibrational signals) between the individual female and a male (reviewed by (Esteve, 2005). Large (sea run) males defend territories at the spawning ground by overt aggressive behaviour and fighting, whereas small precocious males (maturing in freshwater) have adopted a "sneaking" strategy to get access to females in order to fertilise eggs at spawning. Natural spawning behaviour normally does not happen in the farming situation, and eggs and sperm (Guy et al., 2006) are manually stripped from the fish or surgically removed following killing of the broodstock.

Husbandry systems of whatever type, remove many of the circumstances that affect the behaviour of salmon. For example, while wild animals have to compete to gain access to limited resources, food is not normally a limiting factor for the farmed animal. In reproductive behaviour, the salmon slaughtered for food does not survive long enough to reproduce and there is no evidence that the lack of opportunity for the salmon to express reproductive behaviours in a farm situation is a welfare issue.

6. Factors affecting Farmed Atlantic salmon welfare

A list of factors with potential to cause a welfare risk for Atlantic salmon farmed in Europe was identified. The description of the factors and its potential welfare impact constitutes the first step of the risk assessment methodology described in chapter 7. The factors were derived from the practical and academic experience of the working group members and the literature on fish welfare.

6.1. Environmental conditions Abiotic Factors

Atlantic salmon are exposed to a range of abiotic, external environmental factors during the life-cycle in farming. The risk-factors for impaired welfare differ among the production systems, and the different life-stages can display various optima and tolerance limits to several abiotic factors such as water quality, light conditions (photoperiod (Boeuf and Falcon, 2001), intensity, spectral composition, variability (Kiiskinen et al., 2003)), sound, hydrostatic pressure, water currents and waves (Johansson et al., 2006). The nature of the production facility also defines physical limits for the salmon, such as available water depth (Armstrong et al., 2003), the physical shape and colour of tanks and cages.

The physico-chemical characteristics of water have the most profound influence on biological function in Atlantic salmon. These include pH (acidity or alkalinity; (Fivelstad et al., 2003b)), hardness (Hansen et al., 2002) and salinity (Goncalves et al., 2006), temperature (Caissie, 2006; Johansson et al., 2006), dissolved carbon dioxide (Fivelstad et al., 1998) and oxygen content (Armstrong et al., 2003; Geist et al., 2006), particulate matter (Haitzer et al., 1998) and dissolved content of toxicants such as nitrite (Williams and Eddy, 1989), ammonia (Eddy, 2005), and metals (Matschak et al., 1998), aluminium, (Fivelstad et al., 2003b; Teien et al., 2005), cadmium (Soengas et al., 1996), zinc (Hansen et al., 2002; Dean et al., 2007) and copper (Dean et al., 2007).

Some of these factors can be controlled by farm management practices while others relate to the environmental characteristics of the site. When a salmon farm is set up, if the environmental conditions do not allow the needs of the salmon to be met, the welfare may be poor and economic success of the farm is unlikely. Hence farmers are normally very careful to evaluate these environmental conditions so as not to make a mistake in selecting the site for a farm.

For the welfare of farmed fish, the quality of the water is fundamental. Fish exist in intimate contact with the water through the huge surface area of the gills and skin, and it is widely acknowledged that fish are vulnerable to inappropriate water quality. Water quality variables affect physiology, growth rate and efficiency, cause pathological changes and organ damage and, in severe cases, cause mortality. The sub-lethal effects of poor water quality are also commonly linked to increased disease susceptibility, although scientific evidence for direct relationships is lacking (MacIntyre et al., 2008).

All aquatic organisms have certain tolerance limits with regard to water quality where they are able to maintain homeostasis. However, limits for good welfare may be narrower and more difficult to determine. In addition fish have developed a range of compensatory mechanisms that may over time adjust the welfare impacts by acclimation. The threat to fish welfare from water quality relates not only to the absolute levels, but also to the rate of change and a number of complex interactions.

6.1.1. pH

Several factors may cause water pH to drop or rise, but generally in sea-water the pH is more stable due to a higher buffering capacity. In freshwater pH can be affected by increased carbon dioxide due to respiration, inadequate filtration in recirculation systems and acutely by acid rain affected water. Improper functioning of systems for treatment of acidic inlet water with $CaCO_3$ or other pH increasing chemicals can also result in low pH.

The water pH is important since fish need to maintain a constant internal pH and an acid/base balance in the blood. Fish alter their pH by using bicarbonate ions or acidic carbon dioxide. If blood pH becomes acidic, bicarbonate ions are released to buffer the pH back up to normal values. In contrast, the addition of carbon dioxide or the removal of bicarbonate ions helps to lower the blood pH. This mechanism utilises carbonic anhydrase in the blood and gills.

Atlantic salmon when exposed to sudden decreases of pH show gill and skin irritation Acid irritates the gill and skin resulting in excessive mucus production and reddened areas particularly on the ventral body. Alkalosis usually occurs above pH 8 to 9.

It has been stated that the optimal pH range for salmon is 6.0-8.5 in freshwater and 7.0-8.5 in sea-water (Staurnes et al., 1995; Kroglund and Staurnes, 1999; Fivelstad et al., 2004), but experience within industry shows that many farms can operate satisfactorily below pH 6 if the pH is stable and aluminium levels are not high.

Safe levels of water pH depend on the interaction with a range of other water quality parameters, especially aluminium (Al) and ammonia. As an example, it was shown that pH in the range 5.4 – 6.8 in freshwater did not affect growth or mortality in Atlantic salmon when Al toxicity was reduced or eliminated by complexing with citrate (Fivelstad et al., 2004).

Eggs can tolerant extreme pH and high aluminium levels as they are partially protected by the eggshell, whereas alevins are very sensitive to extremes of pH and toxic metals (Finn, 2007). However, different river strains of Atlantic salmon seem to have different sensitivity to low pH (Donaghy and Verspoor, 1997). In a study on Atlantic salmon eggs and alevins, hatching and larval growth were reduced significantly at pH 4.5 and 5.0, and larval mortality increased at pH 4.5. Larval feeding and swimming behaviour were impaired at pH 6.5 and lower. Hatching was not affected at pH 5.5 in the presence of aluminium however larvae exposed to 124 µg Al/l at pH 5.5 incurred significant increases in mortality. The inhibition of feeding observed among fish exposed to pH 5.5 was intensified at all concentrations of Al tested. At pH 5.5, reduced growth occurred among larvae exposed to 71 µg Al/l and higher (Buckler et al., 1995).

6.1.2. Water temperature

The temperature of the water regulates the amount of dissolved oxygen that a body of water can hold, and the ionisation of ammonia (Colt and Tomasso, 2001). Additionally, increasing temperature increases the growth and infectiousness of many fish pathogens (Roberts, 1975) and increases the toxicity of many dissolved contaminants (Wedemeyer, 1996). All of these interacting factors have the capacity to compromise the health of farmed fish.

As fish are poikilothermic, increasing the water temperature increases the metabolic rate and hence oxygen consumption. In water at higher temperatures the reduced solubility of oxygen (Table 4) at the same time that there is increased metabolic demand for oxygen, often leads to life threatening oxygen deficit. This is exacerbated should there be enhanced oxygen demand due to feeding or to any reduction in respiratory efficiency due to parasitism or hyperplasia of the gill secondary lamellae (Roberts and Shepherd, 1997).

The major effects of extreme temperatures are changes in metabolic rate, a disturbance in respiration, blood pH imbalance, and a breakdown in osmoregulation and intolerance of handling. Standard behavioural criteria for stress at critical temperatures are associated with equilibrium loss, sudden bursts of activity with frequent collisions with the tank sides, followed by rolling with rapid ventilatory movements (Elliot and Elliot, 1995). Temperature also affects growth and development and can lead to various deformities such as abnormal heart development (Takle et al., 2006) and skeletal deformities (Ornsrud et al., 2004), Temperature also causes rapid desmoltification (Handeland et al., 2004) and broodstock maturation or spawning failure (Taranger and Hansen, 1993; Taranger et al., 2003; King and Pankhurst, 2004; King et al., 2007). Temperature tolerance is highly dependent on acclimation, and in general salmon seem to be able to adapt to temperatures in the range of 0-20°C provided the fish are supplied with well oxygen-saturated water. The lower lethal limit is considered to be around -1°C, and at temperatures approaching that level permanent eye damage is a characteristic feature (Ferguson et al., 2004). Temperature optimum for growth of salmon appears to be in the range of 12-16°C depending on stage and size (Goncalves et al., 2006; Johansson et al., 2006).

Incubation temperatures generally accepted by the industry are 8 ºC maximum from fertilisation to eyed stage, 10°C until hatch and 12°C at first feeding. It is generally considered that in order to reduce the risk of abnormal development, eggs have to be kept at temperatures below 8°C, and alevins should be kept at temperatures below 12°C (Poxton, 1991). High temperatures (above 8°C) have been claimed to result in higher incidence of a range of deformities including spinal deformities (Wargelius et al., 2005; Takle et al., 2006). However, anedoctal evidence indicates that the main factor may be the stability of temperature at key development stages, rather then absolute temperature. Different fish strains also seem to have different tolerance to temperature limits. Spinal deformities have been proven to be generally due to poor formulation of early feeds rather than the high temperature effects or genetic effects (Sullivan et al., 2007a; Sullivan et al., 2007b; Sullivan et al., 2007c). Alevins are believed to tolerate somewhat higher temperatures, up to 12°C (Poxton, 1991). Lower temperature tolerance is assumed to be around 0°C based on commercial experience.

Salmon smolts are considered to have somewhat less tolerance than parr and ongrowing salmon, but can tolerate temperatures between 3 and 18 ºC (Arnesen et al., 1998). Salmon smoltify poorly on water temperatures below 3 °C (Arnesen et al., 1998). Temperature influences the development and loss of sea-water tolerance (Handeland et al., 2004).

Ongrowing salmon tolerate temperatures between 1 and 18 °C, and seem to display a preference for 16-18 °C (Johansson et al., 2006; Oppedal et al., 2007) although such temperature may lead to oxygen shortage problems. This thermoregulatory behaviour will influence the density at which caged post-smolts school, but is not indicative of tolerance.

At ovulation and spermatogenesis until spawning, broodfish can be adversely affected at temperatures higher than 12 °C (Taranger et al., 2001), and possibly lower than 8 °C.

Water temperature can modulate the timing of spawning in salmon brood stock (Taranger and Hansen, 1993; Taranger et al., 2000), and high water temperature can inhibit ovulation (King et al., 2007; Vikingstad et al., in press) and sperm release (Taranger et al., 2003) in salmon. Lowering the water temperature to 6-8 °C can stimulate spawning (Taranger et al., 2000), but very low temperatures can also delay or inhibit spawning.

6.1.3. Salinity

Salinity changes affect osmoregulation in fish and many species have limited tolerance. In the marine stage salmon are euryhaline i.e. they can tolerate a wide range of salinities (Goncalves et al., 2006). Reduced ambient salinity may reduce the osmoregulatory cost of the fish although the physiological significance of this is not known. In contrast to marine fish, freshwater fish normally do not experience variations in salinity and they have osmoregulatory mechanisms to lose excess body water, and to extract ions from the ambient medium.

During the early stages from eggs up to pre-smolts Atlantic salmon are adapted to salinities below 10 ppt, and are normally reared in freshwater up until smoltification (Craik and Harvey, 1988). Eggs must be kept in pure freshwater just after fertilisation to allow normal water hardening (egg swelling), but thereafter small amounts of saltwater (typically up to 1 ppt) can be added to in order to adjust pH, detoxify aluminium, and increase ion concentration in acid water sources that typically have a low ionic content.

The ability to tolerate salinity above 10ppt increases with increasing body size in freshwater parr, but full osmoregulatory capacity in full strength sea-water (> 30 ppt) is only achieved after a proper smoltification (Kiiskinen et al., 2003) , which in turn mainly depends on attaining a certain body size and proper photoperiod signals (Handeland and Stefansson, 2001). Water temperature affects the development and loss of sea-water tolerance, and hence the time window for transfer to sea-water (Handeland et al., 2004).

Atlantic salmon loses much of the ability to osmoregulate in full strength sea-water when sexual maturation progresses to spawning, and they suffer high mortality if kept in sea-water throughout maturation (Taranger and Hansen, 1993). Sexually mature salmon broodstock needs be kept in freshwater or brackish water with salinity below 10 ppt.

The ability to tolerate rapid changes in salinity also changes during the life-cycle. In general this ability is supposed to increase with body size, but fully smoltified fish and salmon in the on-growing phase in sea-water are believed to be most tolerant to such changes.

Salmon parr have limited ability to maintain osmoregulatory balance (hypo-osmoregulation ability) in full strength sea-water (Duston, 1994). Mortality of Atlantic salmon parr in 31 ppt sea-water was found to be size dependent and reached 47 %, while mortality was < 10 % at salinity of 20 ppt (Duston, 1994). In the same study, a salinity of 20 ppt was also shown to temporarily decrease growth in salmon parr compared to 10 ppt. The ability to hypo-osmoregulate is only fully acquired after a successful parr-smolt transformation, which depend on appropriate photoperiod signals (e.g. (Berge et al., 1995; Handeland and Stefansson, 2001)). Prior to the completion of the parr-smolt transformation, it is generally recommended to maintain salinities below 10 ppt. The early transfer of salmon pre-smolts to full strength sea-water represents a large risk for impaired welfare. If a smoltified fish is not transferred to sea-water, the smolt process reverses and the fish adapt to freshwater again, a process termed desmoltification (Mortensen and Damsgård, 1998; Stefansson et al., 1998).

Salmon broodstock are normally held in tanks or ponds with freshwater or brackish water (less than 8 ppt) prior to spawning. Keeping broodstock in sea-water in cages is possible, but may compromise egg and sperm quality and is believed to represent a large physiological stress to the broodstock. High salinity (full sea-water) may also compromise ovulation and sperm release (Haffray et al., 1995). Salmon broodstock appear to lose much of their ability to relate water and ion balance in full strength sea-water as sexual maturation proceeds, and high mortality is observed in salmon that are maintained in sea-water tanks during the winter following maturation (Taranger and Hansen, 1993). It is therefore recommended to maintain the brood stock in freshwater or brackish water (< 8 ppt) prior to and after spawning.

6.1.4. Dissolved gases

Risk-factors associated with gas saturation differ among production systems and with life-stages. Oxygen is often the first limiting factor in most productions systems (e.g.(Fivelstad, 1988; Johansson et al., 2006; Johansson et al., 2007)), but in recirculated systems or oxygenated tanks where O_2 is added artificially carbon dioxide (CO_2) can be the primary limiting factor (Forsberg, 1997; Fivelstad et al., 2003a; Helland et al., 2005; Geist et al., 2006). The concentration of carbon dioxide and oxygen dissolved in a water body has a major effect upon aquatic organisms (Helland et al., 2005; Johansson et al., 2006; Fivelstad et al., 2007).

6.1.4.1. Oxygen

The amount of dissolved oxygen in water differs with temperature, salinity and the partial pressure of oxygen in the air that is in contact with the water. The amount of dissolved oxygen (mg/l) at 100 % water saturation (e.g. in equilibrium with atmospheric oxygen) decreases with increasing water temperature and salinity (Geist et al., 2006). Often the O_2 saturation shows marked variability with time of day and during the season in farming units, due to variability in fish metabolism, algal production and consumption of O_2 as well as variability in water exchange (e.g. in freshwater and sea-water cages) (Johansson et al., 2007).

The relative oxygen consumption (mg O_2/kg fish per min) of the salmon increases with temperature, activity, feed consumption and stress level, while it decreases with increasing body size (Johansson et al., 2006).

Table 4. **Solubility of oxygen in freshwater in equilibrium with air at 101.325 kPa (mg/l) and minimum recommended DO concentrations for coldwater fish in aquaculture**

	Oxygen solubility mg/l	**Minimum DO required**	
Temperature ºC	**100% saturation**	**mg/l**	**% saturation**
5	12.8	9.1	71
10	11.3	8.8	78
15	10.1	8.3	81
20	9.1	7.8	85

Adapted from (Wedemeyer, 1996)

The dissolved oxygen concentration is considered as one key factor for welfare in salmonid farming, but suggested critical levels for normal physiological functioning, feed intake and optimum growth vary between different studies and for various life stages (Ellis et al., 2002). Oxygen levels are often given as concentration (mg/l), but the relative oxygen saturation in water (% saturation) is regarded as the most important parameter for the physiology of the salmon as it is the relative difference in partial pressure of oxygen that drives the diffusion of oxygen over the gills and into the blood stream (Helland et al., 2005).

The minimum of oxygen required varies amongst fish species, and varies also with size, age, physiological condition and health (Bickler and Buck, 2007). Salmon of all ages are significantly less tolerant to low oxygen partial pressure in water than many other fish species (Kramer, 1987; Bickler and Buck, 2007). In general, low oxygen levels and hypoxia are known to affect growth, behaviour, food consumption and physiological states in salmonids (Booth, 1978; Borch et al., 1993; Bindon et al., 1994; Jobling, 1994; Raaij et al., 1996; Gilmour, 2001; Ellis et al., 2002; Johansson et al., 2007). Minimum oxygen requirements for Atlantic salmon appears to differ between life-stages and conditions (Crisp, 1993; Armstrong et al., 2003). Severe problems were noted when O_2 saturation was around 50 % over some time, and mortality have been noted to occur around 40 % (Powell et al., 2000).

Recommendations on minimum O_2 saturation depend on production strategy and developmental stage (Forsberg and Bergheim, 1996; Bergheim et al., 2006). Minimum oxygen concentration for fast growth has been suggested to be around 60% for salmonids (Jobling, 1994). In young stages of salmonid, different values of low oxygen have been reported to affect egg development and cause early hatching, delayed emergence of alevins, deformities in young fish and high mortality (Matschak et al., 1998; Malcolm et al., 2005; Geist et al., 2006; Roussel, 2007).

Oxygenation is nowadays commonly used in the freshwater stage, in order to increase biomass, improve feed efficiency, and limit oxygen variation especially during or immediately after feeding or during stressful handling procedures. The potential effects of hyperoxia (DO levels > 100% saturation) on fish welfare are largely unknown. The physical effects of supersaturation are discussed in section 6.1.4.3, but supersaturation is considered to be a less significant problem for oxygen than for nitrogen. Exposure to hyperoxia reduces the respiration frequency, which causes accumulation of CO_2 in the blood and further respiratory acidosis in rainbow trout (Bernier and Randall, 1998). Several studies have indicated problems in terms of reduced growth, increased stress levels and increased susceptibility to viral diseases following use of hyperoxygenated water (> 150 % in inlet water) on salmon pre-smolts (Fivelstad et al., 1991; Brauner et al., 2000; Helland et al., 2005; Toften et al., 2006; Fridell et al., 2007). However, the negative effects may in part be due to a parallel increase in CO_2 and ammonia in the water as a consequence of reduced specific water flow (Helland et al., 2005; Toften et al., 2006). Hyperoxic conditions may also be harmful to salmon (Olsvik et al., 2005) due to potential toxic effects of very high oxygen partial pressure but more studies are needed to validate this statement.

Embryonic development in teleosts is profoundly affected by environmental conditions, particularly temperature and dissolved oxygen concentrations (Johnston, 2006). Suboptimal environment and treatment at the egg and alevin stage can lead to life-long problems related to fish welfare such as different soft tissue and bone deformities. Hypoxia can lead to premature hatching of eggs or mortality (Oppen-Berntsen et al., 1990), as well as affecting developmental patterns such as the numbers of muscle cells (Johnston, 2006).

In the farming situation fry and parr are often exposed to high levels of CO_2 in combination with hyperoxia as a result of low specific water usage and oxygenation (Fivelstad et al., 2003b). However, only minor effects were noted on osmoregulation and hydromineral balance when exposing salmon parr to conditions typically found in the farming situation (Helland et al., 2005).

Oxygen is normally regarded as the limiting factor (occurring before major effects of ammonia or carbon dioxide) in sea cages ongrowing (Johansson et al., 2007). The size of the cages and their location with respect to ambient water currents and fouling on the nets are of major importance with respect to oxygen availability for the fish (Johansson et al., 2007). Variability in flow and fish metabolism as well as algal production and consequent oxygen consumption create high levels of spatial and temporal variation in dissolved oxygen (Johansson et al., 2006; Johansson et al., 2007). The link between this observed variability in oxygen saturation in salmon sea cages and welfare is, however, poorly understood. It is believed that oxygen levels below 60 % creates welfare problems for Atlantic salmon, but there are indications in commercial farms that reductions in O_2 levels to around 70 % saturation give a reduction in feed intake and growth rate in commercial sea cages, suggesting compromised welfare (Johansson et al., 2007). Recent studies with reduced O_2 levels in controlled sea-water tank experiments indicate a gradual decrease in appetite and growth as O_2 saturation was reduced from 80 to 50% (WEALTH, 2008). Altogether, this suggests that O_2 levels should be kept above at least 60% to avoid neative effects on disease resistance and general welfare, and above 70 % to maintain full appetite and growth, but further studies are needed to validate these assumptions.

There is no available information on stage-specific oxygen requirements and metabolite tolerance in salmon brood stock.

6.1.4.2. Carbon dioxide

Carbon dioxide (CO_2) is found naturally in most surface waters at levels of 1-2 mg/l and originates from diffusion from the atmosphere, microbial decomposition of organic matter in sediments and the respiration of micro-organisms, algae and aquatic plants (Wedemeyer, 1996). Naturally higher levels of CO_2 can be found in well or spring water. Within aquaculture systems, the primary source of CO_2 is fish metabolism and with the practice of supplementary oxygenation of the water higher stocking densities and reduced water exchange may be used, the consequential increase in CO_2 is considered to be an important limiting factor.

Carbon dioxide (CO_2) is in equilibrium with the non-toxic bicarbonate ion, and its concentration depends on pH, temperature and salinity of the water as well as the respiration of the fish and other organisms in the water. Since the solubility of carbon dioxide increases with decreasing temperature (Fivelstad et al., 2007), the same partial pressure (pCO_2) in mm Hg is obtained with a higher concentration of carbon dioxide in terms of mg/l at low compared with high temperatures (Fivelstad et al., 2007). It is, therefore important to also consider the partial pressure (pCO_2) and not only the concentration (mg/l) of CO_2.

Carbon dioxide concentrations recorded in the effluent of Norwegian salmon smolt farms are often in the range of 10–25 mg/l, especially during the spring (yearlings) and autumn (under-yearlings) when Atlantic salmon is smelting (Fivelstad et al., 2007).

High and medium increases in carbon dioxide associated with pH and Al can lead to gill lesions, and high levels of CO_2 can also elicit a severe stress response (Fivelstad et al., 2003b). Recent studies on the impact of elevated water carbon dioxide in parr revealed reduced growth in the groups exposed to 12 mmHg CO_2 partial pressure, compared with the low level groups at 0.3-0.5 mmHg, the reduction was more pronounced at 5 than at 15 °C. No significant gill lesions, mortality or nephrocalcinosis were detected (Fivelstad et al., 2007). Smolts may suffer stress and growth retardation in freshwater when carbon dioxide exceeds 10 mg/L (Fivelstad et al., 2003b) however the authors concluded that it was not possible to separate the effects of $CO_{2,}$ pH and Al. In sea water reduced weight gain and reduced condition factor were observed in Atlantic salmon post-smolts after 43 days exposure to higher concentrations of carbon dioxide but no nephrocalcinosis was recorded (Fivelstad et al., 1998). CO_2-specific changes in haematocrit, plasma cortisol, and plasma chloride responses were also noted indicating physiological stress (Fivelstad et al., 1998).

6.1.4.3. Supersaturation

Total gas supersaturation causes a condition known as gas-bubble disease. This is an uncommon but serious cause of mortality in farmed fish. Most commercial farms are designed to avoid it, as it is primarily an engineering problem but when it occurs it has serious welfare implications (Harvey and Cooper, 1962). Originally observed in fish below entrained hydro-electric flows, it closely resembles the human condition of diver's-bends, and is generally caused, in farms or in public aquaria, by leaks in pump or valve systems or sudden temperature gradients. It has also been associated with altitude gradients in fish transported by air (Hauck, 1986).

The degree of supersaturation is the most important factor defining an eventual outcome. The effect of the supersaturation is to cause bubbles of supersaturated gas in the bloodstream of affected fish as it comes out of solution. In small vessels this can lead to rupture and haemorrhage and even in larger vessels the bubbles can obstruct blood flow. Fish may die without obvious signs, but those that survive may be blind, or suffer cerebral, renal or hepatic vascular rupture and haemorrhage and often clear gas bubbles can be seen as bubbles below the cornea and epidermis. They are invariably compromised in one way or another, and do not thrive (Roberts and Shepherd, 1997).

Negative effects of low levels of supersaturation (up to 110 %) do not necessarily cause acute mortality but it has been indicated by the industry as inducing potentially sub-lethal effects, such as reduced growth.

A maximum figure for supersaturation is difficult to indicate since maximum chronic safe exposure limits vary with species, size and environmental conditions (Wedemeyer, 1996). No data were found for Atlantic salmon.

6.1.5. Ammonia

Ammonia is produced as a waste product by the fish and leads to a rise in pH. Ammonia is present in 2 forms: un-ionised and ionized. Un-ionised ammonia (NH_3) is the most toxic form. The level of un-ionised ammonia is dependent on total ammonia nitrogen (TAN = $NH_3 + NH_4^+$), pH level, temperature and salinity (Table 5 and 6). Ammonia toxicity is higher at high pH, e.g. at pH 8, 5 % of the total ammonia is in the toxic NH_3 form, whereas at pH 9 it is 20 % (Fivelstad et al., 1991; Eddy, 2005). Furthermore, five times more toxic ammonia is available at 25 °C than at 5 °C, and the proportion of the more toxic NH_3 form increases as salinity drops. Therefore, pH, temperature and salinity needs to known in order to estimate the toxic level of ammonia (Ackerman et al., 2006).

Table 5. **Freshwater: Percentage of un-ionised ammonia which is toxic for fish compared with total ammonia, in relation to pH and temperature**

	Water temperature (°C)			
pH	**5**	**10**	**15**	**20**
6	0.01	0.02	0.03	0.04
6.4	0.03	0.05	0.07	0.10
6.8	0.08	0.12	0.17	0.25
7.2	0.20	0.29	0.43	0.63
7.6	0.50	0.74	1.08	1.60
8	1.24	1.83	2.68	3.83
8.4	3.07	4.47	6.47	9.09

(adapted from (Wedemeyer, 1996)

Table 6. **Sea-water: Percentage un-ionised ammonia which is toxic for fish compared with total ammonia, in relation to pH and temperature**

	Water temperature (°C)			
pH	**5**	**10**	**15**	**20**
7.2	0.17	0.24	0.35	0.51
7.4	0.26	0.38	0.56	0.81
7.6	0.42	0.60	0.88	1.27
7.8	0.66	0.95	1.39	2.00
8	1.04	1.49	2.19	3.13
8.2	1.63	2.34	3.43	4.88
8.4	2.56	3.66	5.32	7.52
8.6	4.00	5.68	8.18	11.41

(adapted from (Wedemeyer, 1996)

The Knoph and Fivelstad groups (Fivelstad et al., 1991; Knoph and Olsen, 1994; Knoph and Thorud, 1996) noted no effects in post-smolts with ammonia administered chronically for up to a month with concentrations up to 0.043 mg/l NH_3-N (5.50 mg/l TAN). However, (Wood, 2001) states that the values are in the range of 0.2-2.0 mg/l, of which the sub-lethal threshold is about 5 % of these levels: i.e. 0.01-0.1 mg/l NH_3-N. Wood also makes it clear that NH_4^+ can also have toxicity associated with it, depending on water hardness, pH, and temperature.

Ammonia perturbs osmoregulation resulting in fish producing an increased volume of urine in freshwater and increased drinking in saltwater (Knoph and Olsen, 1994; Knoph and Thorud, 1996; Eddy, 2005). Ammonia also affects the gills by destroying the mucous layer and causing both intracellular and sub-epithelial oedema (Wood, 2001). Following an acute ammonia exposure there is increase in the thickness of the respiratory epidermis and reduced translamellar oxygen transfer. Lethal concentrations result in epidermal necrosis, and focal haemorrhage within the skin, intestine, meninges and peripheral capillaries (Knoph, 1996).

At sub-lethal concentrations ammonia can also impair immune function leading to increased susceptibility to infectious disease (Wedemeyer, 1997; Ackerman et al., 2006).

In general the ammonia toxicity (96 h LC50 for adult Atlantic salmon held in sea-water (0.09-3.35 mg/l NH_3) appears to be roughly similar to that for freshwater salmon (0.068-2.0 mg/l NH_3) (Eddy, 2005), but in the marine environment the toxicity of ionised ammonia (NH_4^+) should also be considered. During ammonia exposure, whether chronic or episodic, alevins and smolts are most at risk especially at elevated temperatures (Eddy, 2005). Ammonia levels can become critical in systems with restricted water flow, such as high stocking density fish tanks with added oxygen, during transport and in recirculated systems.

6.1.6. Nitrite

In the presence of oxygen, ammonia is converted into nitrite which is slightly less toxic than ammonia. Nitrite breaks down red blood cells and oxidizes the iron in haemoglobin resulting in reduced oxygen carrying capacity and causes listlessness. Nitrate also has adverse effects on salmon but at higher concentrations than those at which nitrite causes such effects. Levels of nitrite in farming systems are generally very low, with the compound rapidly converted to the significantly less toxic nitrate by nitrobacter bacteria (Lewis and Morris, 1986; Wood, 2001; MacIntyre et al., 2008). Nitrites are not usually a problem in aquaculture with flow-through (where nitrogenous wastes are adequately flushed away) or in adequately oxygenated water so that oxidation rate of nitrite exceeds the oxidation rate of ammonia. Nitrites build up can occur in ponds or hatcheries from anthropogenic sources including sewage effluent, agricultural effluent, as well as malfunctioning of biofilters (Wedemeyer, 1996; MacIntyre et al., 2008). Concentrations < 0.1 mg/l (as NO_2^-) have been indicated as adequate to protect fish health under most water quality conditions (Wedemeyer, 1996).

6.1.7. Metals

Toxic metals, such as iron, aluminium, copper and zinc pose a potential risk to the welfare of salmon. The likelihood of exposure to toxic levels should be assessed for enclosures bearing in mind the interrelationship between temperature, pH, and alkalinity and hardness of the water and the potential toxicity of heavy metals, for example the risk of precipitation of salts of iron and aluminium in water with low pH, which can result in reduction of oxygen transfer and iono-regulatory failure.

6.1.7.1. Aluminium

Aluminium (Al) toxicity is usually associated with acid rain and acidified freshwater systems. It is well established that positively charged aluminium in acidic waters (Dickson, 1978) is toxic to fish due to accumulation of Al in fish gills (Muniz and Leivestad, 1980; Exley et al., 1991), causing iono-regulatory and/or respiratory failure (Neville, 1985; Wood and McDonald, 1987; Rosseland and Staurnes, 1994; Gensemer and Playle, 1999). A range of problems have been noted in Atlantic salmon with aluminium in acid water (Fivelstad and Leivestad, 1984) (Jagoe and Haines, 1997; Kroglund et al., 2001; Fivelstad et al., 2003b; Kroglund and Finstad, 2003; Fivelstad et al., 2004). Mean respiration frequency is increased by aluminium toxicity and gill lesions consist of focal to diffuse hypertrophy and hyperplasia of chloride cells and adhesion of lamellae (Fivelstad et al., 2003b). At relatively low exposure concentrations responses are identified at the histological and physiological level. In freshwater, Al can be present in different physico-chemical forms varying from simple cations and hydrolysis products, complexes and polymers, to colloids and particles (Salbu and Oughton, 1995; Sposito, 1996) depending on pH, temperature, and the presence and concentration of Al complexing ligands. The consequences of exposure to toxic Al at the freshwater stages may not become apparent until the sea-water stage (Exley et al., 1991). In acidic water (pH 4–5), toxic effects are seen in salmon cages near freshwater outlets. Acute mortality of Atlantic salmon has been described from fjord-based fish farms in Western Norway (Bjerknes et al., 2003). Mortality is often related to snowmelt and heavy rainfall in the catchment areas during the winter. Increased freshwater runoff reduces the surface water salinity from >20 to <10, while water temperature is reduced from 8 to 3 °C. Aluminium transported by acid rivers to the fjords during these episodes is the cause of the mortality. An increased deposition of aluminium on gills of these Atlantic salmon (from < 10 to >200 µg/g dry weight of gill tissue) has been demonstrated and occurs when there are high concentrations of the reactive form of aluminium (Bjerknes et al., 2003). The increases in gill Al were related to increased discharge episodes where acidic, Al-rich freshwater elevated the surface water concentrations of Al from < 20 to >70 µg/l. Increased mobility of reactive Al (Al-a) and increased Al accumulation on gills during flood episodes was the probable cause of the massive salmon mortality (Bjerknes et al., 2003) but mixing of freshwater with sea-water can also exacerbate the problem.

Non-lethal concentrations of aluminium may severely affect the osmoregulatory capacity in smolting salmon, especially as there is an increasing susceptibility towards aluminium at periods with low pH during spring due to acidification eg (Staurnes et al., 1993). Aluminium should be kept below 20µg/l which is the critical level smolts can tolerate (Rosseland et al., 2001). Pre-smolts and smolts are most sensitive to Al followed by younger stages whereas adults are the most tolerant (Rosseland et al., 2001).

6.1.7.2. Other metals

Metals, such as copper, iron, zinc and cadmium, are toxic to salmon and have profound negative physiological effects causing stress and at high concentrations mortality (Dubé et al., 2005). Environmental conditions such as pH, oxygen concentration, temperature, hardness, salinity and presence of other metals may modify metal toxicity to fish. Hypoxic conditions, temperature increase, and acidification usually render the fish more susceptible to intoxication. Alternatively, an increase in mineral content (hardness and salinity) reduces metal toxicity. Interactions among various metals present in the water may modify their toxicity, synergistic, additive or antagonistic effects may occur (Witeska and Jezierska, 2003). Unnaturally high zinc and low copper of farmed eggs leads to increased egg mortality. However, factors such as time of stripping, and salinity in which broodstock are held, are known to exert much greater influence on egg viability than these metals (Craik and Harvey, 1988). Cadmium has adverse effects on growth and reproduction and causes osmoregulatory stress, and it was shown to alter the structure and function of various organs, including the liver (Lemaire-Gony and Lemaire, 1992; Soengas et al., 1996).

6.1.8. Suspended solids

All natural waters contain some suspended solids. During spates (heavy floods) these can rise considerably, but while wild fish can avoid them farmed fish do not have the opportunity and effects such as gill surface hyperplasia, and excessive mucus generation on skin and gills are common. Furthermore, suspended organic solids can reduce oxygen availability. Waste associated with industries such as quarrying and sand and gravel extraction are particularly liable to generate spasmodic suspended solid levels which, because they containing sharp particles, can cause serious damage to the gill tissue of fish held many miles downstream (EIFAC, 1965).

Suspended mater (organic and inorganic) with a diameter greater than 1µm is defined as particulate matter (Chen et al., 1994). Solids >100 µm are settle out and are not problematic but smaller particles have been associated with mortalities (Chen et al., 1994).

In aquaculture conditions most suspended solids derived from fish e.g. faeces, are removed to prevent them becoming too high. The design of the culture system influences the amount of suspended solids and self-cleaning systems are designed to prevent this problem. Water velocity > 3cm/s prevents solids such as uneaten food from settling (Wedemeyer, 1996). Wedemeyer suggests that suspended solids should be below 100 mg/l but points out that this can be affected by the sharpness of the particles involved (Wedemeyer, 1996).

6.1.9. Water flow

Water flow rate (i.e. water renewal, l/min) is important for determining water quality aspects such as oxygen supply and removal of metabolites in tanks and cages, self-cleaning of tanks (removal of faeces and excess feed) and also for setting up a water current speed (body lengths/ min) that affects the behaviour and distribution of the salmon in the rearing unit. This is an important abiotic factor since too low and too high flows can be detrimental to salmon welfare. If flows are too low then waste products are not removed efficiently and oxygen saturation can become critically low. As a consequence, accumulation of these waste products can lead to detrimental indirect effects such as disease, whereas too high flow can result in high energy expenditure and stress leading to poor growth (Fivelstad, 1988; Fivelstad et al., 1991; Enders et al., 2004). In farming water speeds of 0.5 to 2.5 body lengths /sec are frequently used.

Tolerance to high flow and water currents depends on life-stage and body size, e.g. in the wild freshwater parr prefer high flow rates whereas fry prefer areas of low flow within rivers (Whalen et al., 1999; Heggenes et al., 2002; Armstrong et al., 2003; Hedger et al., 2005).

6.1.10. Water depth

Salmon tanks typically have a water depth from 30 cm to a few metres depending on the stage of the fish, whereas cages for salmon typically range from 5 to 35 m deep, but they can be up to 50 m deep. In the various rearing systems, the water depth will affect available space, gradients in hydrostatic pressure and light, as well as time for feed to sink through the water column – all factors that can affect salmon welfare (Oppedal et al., 2007). In the wild parr in small streams prefer different depths dependent upon activity (Turgeon and Rodriguez, 2005). The spatial distribution of active fish differs markedly from that of resting fish, apparently as a result of the selection for water greater than about 30 cm depth by active fish and for the presence of rocky cover by resting fish (Turgeon and Rodriguez, 2005).

Water depth also affects the ability of the farmer to readily inspect and monitor the behaviour of the fish, such as feeding behaviour, panic behaviour or behaviour indicative of disease. The monitoring of salmon with underwater cameras (Petrell et al., 1997) is commonly used in large rearing facilities; their use allows not only estimations of fish size but also inspection of fish feeding and swimming behaviour.

In open freshwater and sea-water cages, increased depth can allow for better opportunities for the fish to choose micro-environment in relation to gradients in water temperature, light and water quality, as well as presence of biotic factors such as micro-algae, jelly-fish and predators.

The vertical positioning in sea cages depends on light, temperature and salinity gradients (Oppedal et al., 2001; Juell et al., 2003; Juell and Fosseidengen, 2004; Johansson et al., 2006; Oppedal et al., 2007), and is modulated by feeding motivation (Juell et al., 1994) and health status. Atlantic salmon held in cages show variable depth distribution depending on the environmental conditions at the site during different seasons (Johansson et al., 2006). The fish appear to distinguish between two different environments separated by the pycnocline (i.e. sharp vertical gradient in water density created by gradient in salinity and or water temperature). In the upper part, the salmon crowd at high relative schooling densities both during the day and at night. Temperature is one key environmental factor associated with the depth distribution of the fish and the resultant schooling density at each depth. Avoidance of high light intensities during the day is another important factor, resulting in the highest observed relative densities at night. At high stocking densities some of the fish may be displaced to areas with sub-optimal environmental conditions such as low O_2 saturation and to high temperatures (Johansson et al., 2006).

Thus, there is a complex interplay between available depth, environmental gradients and stocking density in affecting the swimming behaviour and depth distribution of salmon in sea cages. Deeper cages offer better opportunities for the fish to select the preferred environment at any time, and also provide more space for movement, but this also represent a challenge for the farmer to readily monitor the fish.

Another issue related with water depth is the use in salmon farming of submersible cages. Atlantic salmon attempt to maintain neutral buoyancy at a certain water depth by varying swim-bladder inflation. They refill a depleted swim-bladder by taking air from the surface as they do not have the retae mirabile for oxygen secretion into the bladder that some other fish have (Berenbrink et al., 2005) it may take up to 40 days to refill the swim bladder by arterial diffusion (Dempster et al., 2008). Salmon have been observed to swim with large tilting angles in deep commercial sea cages when swim-bladder inflation has been insufficient (Ablett et al., 1989). Salmon typically expel gas from the swim-bladder during panic or stress situations, and they tend to dive to the bottom of the rearing units in such situations. Hence it is generally assumed that Atlantic salmon needs contact with surface air to refill the swim-bladder, in order to maintain neutral buoyancy. This can have implication for design of rearing systems such as submersible cages.In a recent study by (Dempster et al., 2008) on the impact of intermittent and continuous submersion it was reported that salmon kept in cages submerged 5m below the surface for continuous periods swam 1.5 times faster. No evidence of acute buoyancy control problems or changes in feeding behaviour were observed. A small reduction in growth rates may be explicable by the slightly lower temperature at the lower depth.

During the alevin stage alevins cannot maintain a position that ensures survival unless there is a bottom substratum that gives vertical support e.g. gravel or artificial grass. Lack of vertical support results in hyperactivity, development of yolk sac constrictions, lower yolk sac utilisation, less growth and lower first feeding success (Hansen et al., 1990).

At first feeding there is no longer need for vertical support as seen in alevins, and the need for self-cleaning (removal of excess feed and faeces) is more important for first feeding success, hence a flat tank bottom is suited. Tank shape, water current and water depth are together with light and shading important component of the environmental complexity at first feeding. These factors are normally optimised for a given tank design if the farming situation to achieve optimal first feeding rate, survival, health and growth. However, there is limited scientific knowledge on the exact consequences of these specific factors for the welfare of the salmon fry and later development. Introduction of partial shelter, uneven lightning or uneven currents may result in aggregation of individuals in part of the tank and create local crowding. It is considered beneficial to have an even distribution of individuals over the area of the tank, but scientific evidence is scarce on optimal behaviour at this stage. Water depth can have an influence on the ability of the first feeding fry to inflate their swim-bladder and to get access to feed. On the other hand, very shallow water depth make it more difficult to catch the feed in the water column and may result in more problems with excess uneaten feed on the tank bottom and larger problems with tanks self-cleaning and resultant gill irritation or fungal growth.

6.1.11. Light

Light is a complex ecological factor whose components include colour spectrum (quality), intensity (quantity) and photoperiod (periodicity). An aquatic environment has peculiar and extremely variable characteristics. Moreover, "receptivity" of fish to light changes profoundly from one species to another and, within the same species, from one developmental stage to another (Boeuf and Falcon, 2001).

Prior to first feeding, the eggs and alevins are adapted to a life in darkness or very low light intensities as they are living in gravel in their natural environment in rivers. Exposure to light at the egg and alevin stage are considered negative as light stimulates physical activity which results in poorer yolk sac conversion into somatic growth (Boeuf and Falcon, 2001). From first feeding onwards light is considered as a positive production factor, and long days or continuous light stimulate growth and rapid development (Stefansson et al., 1991). Low light intensity (less than 10 lux) at the parr stage may have negative effects on growth, whereas intensities between 30 and 1000 lux did not have different effects on growth (Stefansson et al., 1993).

Photoperiod is a key factor affecting growth and development in salmon parr and smolt. Continuous light or long days stimulate somatic growth up to smoltification, but pre-smolts must be subjected to short days followed by long days or natural light to achieve proper smolt quality (Stefansson et al., 1991; Forsberg, 1995; Fjelldal et al., 2005; Berrill et al., 2006b).

Maintaining pre-smolts and smolts on continuous light throughout the freshwater phase compromised development of the hyperosmoregulatory capacity of the salmon and has been shown to negatively affect sea-water performance and survival (Stefansson et al., 1991). Pre-smolts must be subjected to short days followed by long days or natural light to achieve proper smolt quality (Stefansson et al., 1991; Forsberg, 1995; Fjelldal et al., 2005; Berrill et al., 2006a). A adequate photoperiod regime is therefore essential for good smolt quality, and the ability for successful transfer to sea-water and subsequent survival, feed uptake and growth (Boeuf and Falcon, 2001). By the combination of early hatching, optimal growth conditions and photoperiod control, under-yearling smolts can be produced in the first autumn after hatching. Such out-of-season smolt production requires either full photoperiod control in indoor tanks or covered outdoor tanks or ponds or use of additional light a specific time of the year in outdoor tanks or freshwater cages. There are fewer possibilities for photoperiod control in freshwater cages compared with tanks, and this can represent a hazard in terms of inappropriate photoperiod signals and failed smoltification. It can also be produced by use of specific mineral receptor stimulation which avoids the requirement for photoperiod manipulation. Out of season smolt can, in principle, be transferred to sea-water in any month of the year, but sea-water temperature sets some constraints in many regions. Studies on the performance of out-of-season smolts with emphasis on growth and maturation (Duncan et al., 2002; Lysfjord et al., 2004) showed that out-of-season smolt were not disadvantaged during the early phase of sea-water rearing and that overall growth is similar to natural smolts and maturation can be reduced or increased depending on the transfer date. The main objective of this study was to compare the development of sea-water adaptation and changes in body composition of smolt produced using three different strategies, and to investigate growth during the first month in sea-water. A more recent study on the possible impact of smolt production strategy (Fjelldal et al., 2006) show that under-yearling smolt may have an increased risk of developing vertebral deformities and it is possible that this risk can be reduced by postponing the start of the short-day treatment. This will reduce the temperature during smoltification, the temperature and day length during the early sea-water phase, and increase the age at smoltification.

Photoperiod is also a key factor in control of age at puberty and timing of spawning in the season for salmonids (Taranger et al., 1998; Taranger et al., 1999b; Bromage et al., 2001). Continuous light during winter and spring stimulates somatic growth in salmon post-smolts and can reduce the proportion of sexually maturing fish (Oppedal et al., 1997; Taranger et al., 1998; Porter et al., 1999; Taranger et al., 1999a; Porter et al., 2003). Photoperiod treatments also affect precocious sexual maturation in salmon parr in freshwater (Berrill et al., 2003). Continuous light treatment is commonly used on salmon sea cages to avoid or reduce the proportion of early sexually maturing fish both in normal and under-yearling smolts and to enhance growth (Oppedal et al., 1997; Oppedal et al., 1999; Oppedal et al., 2006).

In the Northern hemisphere Atlantic salmon broodstock typically spawn between October and January depending on strain and water temperature (Heggberget et al., 1988). Photoperiod is regarded as the key environmental factor for controlling the timing of gonadal development and spawning in Atlantic salmon (Taranger et al., 1998; Bromage et al., 2001). Photoperiod control is therefore commonly used to alter the seasonal timing of egg production in salmon broodstock (Taranger et al., 1998; Hansen et al., 2000). Temperature also has a modulating effect on spawning time (e.g. (Taranger and Hansen, 1993), and photoperiod treatments have often to be combined with temperature control to allow out-of-season egg production and high egg survival (Taranger et al., 2003).

The swimming behaviour of caged Atlantic salmon is influenced by both natural and artificial light conditions. Light regimes and the positioning of lamps on swimming depth and fish density in groups of 170 000-230 000 Atlantic salmon (0.2-0.7 kg) held in 25 m deep production cages (17 500 m) has been investigated (Oppedal et al., 2001; Juell and Fosseidengen, 2004). In February, April and June, salmon groups swam consistently deeper and at lower density during both day and night in cages illuminated by lamps at a depth of 15m than in cages with lamps at 3 m. The impact of light on distribution of salmon in sea cages has also been corroborated in later studies (Oppedal et al., 2007). Therefore, artificial light can be used as a tool to control salmon swimming depth in cages, and indirectly the actual fish density (Juell et al., 2003). Light treatments can also decrease salmon lice infestation (Hevrøy et al., 2003; Juell et al., 2003).

The welfare consequences of artificial photoperiod treatments are not fully known. Extensive use in industry has not so far revealed any negative welfare effects of use of continuous light, and the use of light is an efficient way of reducing the welfare problems associated with salmon maturing in sea-water. However, the use of light to accelerate growth and stimulate early out-of-season smoltification has been associated with lowered skeletal mineralisation and bone strength under given conditions (Fjelldal et al., 2006), suggesting a possible link to skeletal deformities in under-yearling smolts. Moreover, inadequate photoperiod control can result in poor smolt quality or failed smolting (Stefansson et al., 1991), and improper combinations of photoperiod and temperature may result in failed spawning in salmon broodstock (Taranger et al., 2000). This implies that extensive knowledge is needed to ensure welfare of salmon subjected to photoperiod and light manipulations at the various life-stages.

6.2. Environmental conditions Biotic Factors

6.2.1. Predation

Potential predators of salmon during the life cycle vary depending upon the farming system. In freshwater the principal predators are fish eating birds and mammals, primarily mink and otters. In the marine environment seals and some birds are important predators and there may be some predation by piscivorous fish. Predators cause mortalities, inflict damage on fish and are responsible for distress and feeding interruptions. The impact of predators on farmed Atlantic salmon varies across the life stages. Eggs and alevins are kept in conditions isolated from the wild so that predation is not really a factor at these stages. For the fry and parr stages predation is largely irrelevant in tank systems but may be a problem in any outdoor systems especially cages. For smolts predation is again really only a problem in unprotected outdoor tanks and cages. Ongrowing fish and broodstock are exposed to predators in both tanks and cages. A study of observed predators of caged salmon in Scotland listed 12 potential predators, in order of decreasing estimated problems, as seals (harbour & grey), shags, herons and cormorants, gulls, otters, mink, gannets, fulmars, small land birds and guillemots (Quick et al., 2004). Seals were noted as a problem by 81% of respondents in the study, while 56% considered predators to be causing loss or damage and only 2.5% were not using any form of predator control (Quick et al., 2004). Several aquaculture producers' codes of practice make the recommendation of the use of anti-predator mechanisms such as net coverage of cages.

Predators can have an adverse affect on the welfare of salmon in sea cages, whether they are in the proximity of the cage or actually enter it. In the wild, it is possible to flee predators, while in salmon cages, the fish are confined and hence must be properly protected from contact with predators in order to ensure that good welfare is maintained. Birds may prey upon salmon from above, and hence the cages should be equipped with anti-bird nets to prevent entry of such predators and avoid the stress that presence of these would cause to the stock. Large aquatic predators such as seals, sharks and dolphins can cause stress to the fish by simply being close to the cage, causing the salmon to behave unusually. Such predators are generally excluded by large submerged nets surrounding the cage, or by manufacturing the cage net of more rigid material. However, such equipment must be properly installed to prevent the predators from using their weight to get close enough to the fish to be able to cause extreme stress, as well as possible damage to some which may be wounded. Smaller aquatic predators, such as otters and mink, are far more difficult to exclude, as they are able to climb over the cage walkway and into the net. Fortunately these are rather rare, but where present, they will of course cause stress to the stock. Marine mammals can also be excluded using sonar devices – however in many cases these devices are not an effective deterrent over the long term. There is lack of published scientific literature on anti-predatory behaviour in farmed Atlantic salmon.

6.2.2. Species that may invade sea cages

Various invasive species can affect farmed salmon, the most important of which are algae and jelly fish. Within tank systems, both freshwater and sea-water, these problems are generally well controlled. In open cages invasive species can become a serious problem. In freshwater cages, during the smolt stage, the fish could encounter freshwater algae at levels sufficient to cause a problem. In sea-water cages the fish can be affected by algal blooms and jelly fish strikes, both of which can damage or kill large numbers of fish.

Algal blooms have been reported around the world throughout recorded history and can be devastating to both farmed and wild fish (Bruslé, 1995). Up to 550,000 Atlantic salmon were killed in 1988 in incidents in Loch Torridon and Shetland (Bruno et al., 1989) while over 120 farms in Norway and Sweden were affected by a bloom in 1988 (Bruslé, 1995). Between 1954 and 1994 there were blooms causing finfish mortalities somewhere within Europe almost every year. In addition there can be significant sub-lethal effects of algal blooms as reported from 4 farms in Scotland in 1998 (Treasurer et al., 2003). Total mortalities at the four farms ranged from 0.45 % to 4.39 % of the stocks (total loss of 13,732 fish) during an algal bloom. In addition fish were shown to be inappetent and lethargic in all cages with some showing respiratory distress. The loss of appetite resulted in a drop of 20-80 % of daily food intake, resulting in an estimated lost fish production of 170 tonnes, with an estimated market value of £408 000 (Treasurer et al., 2003). There is little published information available on the frequency or impact of jellyfish strikes on farm cages, but insurance records indicate situations where whole farms may be eliminated with large losses (Roberts and Shepherd, 1997; Roberts and Rodger, 2001a).

6.2.3. Inter-specific interactions

There are very few inter-specific interactions that farmed fish are subjected to. As with the issue of invasive species the control of tanks is sufficient to exclude other species of fish. In cages other species of fish can get into the cage and in some systems fish such as cleaner wrasse are added to sea cages. There is little information available on the impact of these species on salmon with most studies focussing, for example, on their use for pest control (e.g. (Tully et al., 1996).

6.2.4. Stocking density

There are only a few published studies investigating the behaviour and welfare of fish farmed at different stocking densities, in particular during the sea-water phase, and effects of stocking density on welfare are complicated by a range of factors including environmental preferences that affects the actual schooling density of salmon, as well as water exchange and currents in the rearing unit and size as well as size and shape of the rearing unit (Juell, 1995; Oppedal et al., 2001; Turnbull et al., 2005; Johansson et al., 2006; Adams et al., 2007; Johansson et al., 2007; Oppedal et al., 2007). In addition most studies of the effects of density have been carried out on other species, such as rainbow trout (e.g. (Ellis et al., 2002; North et al., 2006)).

Wild fry and parr live at very low stocking densities (~0.5 kg/m^3), actively defending feeding sites. In the rearing environment stocking densities are always much greater than this, typically ranging from 0.5 to 50 kg/m³ depending on life-stage and rearing unit (Soderberg et al., 1993). Soderberg (Soderberg et al., 1993) looked at the effects of different stocking densities on growth, survival and food conversion in Atlantic salmon parr and recommended densities of less than 26 kg/m³ for this life stage. Levels of aggression have been shown to vary with stocking density during the freshwater phase, such that the lowest levels of aggression occur at an intermediate density (e.g. (Pickering, 1992; North et al., 2006) for rainbow trout). In terms of minimising aggression there is therefore an ideal stocking density for fry and parr. Higher densities may lead to increased levels of aggression or physical damage to the fish. They may also lead to a reduction in the quality of the rearing environment. Lower densities, which are below the optimum level, may also result in increased aggression. Aggression in smolts is generally less than for parr in the wild. Salmon in this life-stage show shoaling rather than territorial behaviour (Kalleberg, 1958).

Stocking density between 15 and 25 kg/m³, for ongrowing fish are generally used in salmon farming in Europe. High stocking densityies are associated with several effects on ongrowing fish and broodstock as for other stages in that there may be increased aggression levels, physical damage and decreased water quality with related problems. A study analysing the relationship between the stocking density and the welfare score suggested that there was no trend up to an inflection point of approximately 22 kg/m³ after which increasing stocking density was associated with poor welfare scores (Turnbull et al., 2005).

Intermediate stocking densities (25 kg/m³ compared with 15 and 35 kg/m³) were found to have the best welfare scores in another study in sea-water tanks (Adams et al., 2007), although this was complicated by the effects of disturbance and aggression. (Adams et al., 2007) found aggression levels among on-growing salmon to be generally low but they increased after feeding and were negatively related to disturbance and density.

The effect of intra-specific aggression depends upon many aspects of the rearing environment including water flow, stocking density and others. There is some evidence that aggression is minimised at intermediate stocking densities in both rainbow trout and Atlantic salmon (e.g. (Pickering, 1992; North et al., 2006; Adams et al., 2007)). Some experiments have suggested that the inclusion of small numbers of larger individuals in a population may reduce aggression although this has not yet been translated into a useful management strategy under commercial conditions (Adams et al., 2000).

Although stocking density in salmon cages receives a lot of public attention, scientific studies of the issue in relation to welfare presents serious technical challenges which are only recently being overcome through use of novel technologies and statistical approaches. The welfare status of individual fish within production populations of caged salmon has been observed to vary widely with fish in states of both good and poor welfare observed at all densities between 10 and 30 kg/m^3 (Turnbull et al., 2005). Such variation in welfare status between individuals within production populations makes it difficult to provide definitive conclusions regarding limits on stocking density. The problem of defining stocking density limits is further exacerbated by the observation that the “packing density” (i.e. the density at which the fish choose to swim within a cage) tends to be much higher than the stocking density and varies in response to environmental conditions such as light level (Juell and Fosseidengen, 2004). (Johansson et al., 2006) further examined this behaviour and concluded that the location of the caged population and their subsequent packing density is determined as a trade-off between preferred ambient light levels and water temperature, while dissolved oxygen levels did not exert any influence on the fish behaviour. Both (Turnbull et al., 2005) and (Johansson et al., 2006), using different methods of data collection and statistical analysis, concluded that stocking densities in marine cages above 22-23 kg/m^3 were more likely to lead to welfare problems, especially when fish are exposed to potentially catastrophic circumstances (e.g. storms, poor water quality, algal blooms etc.).

The question of whether stocking densities can cause poor welfare by virtue of being too low has only been addressed to date by a study in tanks, in which densities of 15, 25 and 35 kg/m^3 were studied. In this study, welfare of fish at the intermediate density was found, on the basis of the measures used, to be significantly better than that of the higher and lower densities, with particularly poor welfare recorded among individuals stocked 15 kg/m^3 (Adams et al., 2007). The poor welfare at lower densities was considered to potentially be the result of aggressive interactions between individuals, particularly after feeding.

Maximal stocking density of salmon broodstock will depend on the rearing system and the water quality. Mature salmon males are aggressive and stocking density as well as sex ratio may affect the occurrence of overt antagonistic behaviour. However, there are no scientific reports on optimal stocking density and sex ratio of salmon broodstock.

Male and female broodstock are commonly held together in the same tank/system. There is evidence for pheromonal communication between the sexes that may affect the reproductive performance and behaviour of the brood stock. The complex behavioural and possibly pheromonal interactions between the sexes are needed for natural spawning (oviposistion and sperm deposition). However, natural spawning is not used in salmon farming. Salmon broodstock is typically large individuals (typically 5-20 kg body weight) and there are normally held in large units (i.e tanks with 5 m diameter or larger).

6.3. Feed and Feeding

Farmed salmon are mainly fed industrially produced dry pellets to meet size and life cycle specific requirements. Unbalanced diets or deficiency of nutrients have caused severe health and welfare problems for farmed salmon, either caused by low quality feed components, improper storage or handling of the raw materials, improper balance of micro-nutrients or high levels of dietary toxins. Diets are also modified in the attempt to boost immune system and as a carrier for probiotics.

Feed additives such as glucans, in combination with vitamin C, have been demonstrated to improve immune function, so providing a welfare benefit to adult salmonids (Verlhac et al., 1998) and have been incorporated into some commercial diets.

Animals given one formula diet can only regulate intake of a specific nutrient by eating eat less or more (Simpson and Raubenheimer, 2000). If the feed is sub-optimally formulated relative to the needs of the fish, this inevitably leads to either under- or over-consumption of another nutrients, with associated deleterious consequences for growth, survival and feed efficiency. Studies on trout and goldfish have shown that fish are able to compose a complete diet by choosing among three single macronutrient diets (i.e. protein, lipid and carbohydrate). Thus, it appears that fish, as other farmed animals, are able to select a nutritionally adequate combination from different sources of macronutrients (Sanchez-Vazquez et al., 1999).

Nutritional requirements of salmon are generally well known and properly addressed in the manufacture of feeds. However, there have been instances where nutritional deficiency caused serious welfare problems, as a result of dietary adjustments for compliance with new regulatory requirements or environmental concerns. Although it is accepted that skeletal deformities are the result of several potential contributing factors, recent studies demonstrate that in the case of rapidly growing fish (e.g. under-yearling smolts), or when feed conversion is very efficient, a low supply of certain micro-nutrients such as phosphorus can lead to soft bones with insufficient mineralisation (Helland et al., 2005; Sullivan et al., 2007c). Dietary phosphorus has been reduced in salmon diets in order to minimise environmental impact but, as growth rates improved, phosphorus incorporation did not keep up with requirements.

The diets of Atlantic salmon contain a high proportion of marine fish meal and oil, both in order to cover the high protein demand, but also the demand for polysaturated fatty acids (PUFA). The bioavailablity of various micro nutrients vary among different feed sources such as different fish meals,which may lead to inadequate supply of essential micro-nutrients (see (Kaushik, 2005) for review). The increased demand for marine feed components, not merely for fish but also for other intensively reared species, has placed a focus on alternative terrestrial feed resources. The feeding of vegetable protein and lipid sources to adult Atlantic salmon has been indicated as a possible cause of poor welfare, particularly with respect to alterations of the immune system and gut function (Krogdahl et al., 2000) as well as fatty acid metabolism (Bell et al., 2001; Bell et al., 2002). More recent studies demonstrate a potential for several plant ingredients, to partly replace high-quality fish meal in diets for Atlantic salmon based on nutrient digestibility and absence of pathologies in the stomach and intestine (Bakke-McKellep et al., 2007). Anti-nutritional factors can be a direct consequence of feeding vegetable-based diets to a carnivorous animal and hence treatment of the ingredients in order to ensure they do not impact on the function of the fish is essential to maintaining good nutritional and welfare status.

In many carnivorous fish and specially salmonids, the most used sources of protein have been soybean meal for both juveniles (Escaffre et al., 1997) and adults (Storebakken et al., 1998; Mambrini et al., 1999) pea meal, lupin meal (Glencross et al., 2005) and other plant meals as corn, wheat, rapeseed and rice (Davies and Morris, 1997; Palmegiano et al., 2007). From the experiments, recommendations for soy product incorporation in salmonid diets vary among the studies (Kaushik, 2007). For example, the weight gain and feed efficiency ratio data showed that soybean meal and pea protein concentrate had the best potential for replacing at least 33 % of the fish meal protein in extruded salmon feeds. But it is recognized that the utilisation of several plant protein sources could induce problems: many plant proteins do not contain all of the essential amino acids. For example, lysine is absent from corn, rice, and wheat, whereas corn also lacks tryptophan and rice lacks threonine. Soybeans are lacking in methionine. So, feed palatability, feed intake, growth, feed conversion, apparent digestibility and utilisation of macronutrients and energy, liver fat deposition, intestinal integrity through a patho-histological response of the distal intestine, activities of digestive enzymes in the mid- and distal intestinal mucosa, faecal trypsin and plasma insulin concentrations, plasma cholesterol, plasma protein levels, respiratory burst of kidney leucocytes and plasma myeloperoxidase values can be affected (Krogdahl et al., 2000) (Carter and Hauler, 2000; Escaffre et al., 2007). A negative, dose-dependent effect of extracted soya bean meal on nearly all performance parameters in salmon has been reported with the notable exception of feed intake (Kroglund and Finstad, 2003).

The physiological changes during the smoltification period affect the feeding of the fish (Berrill et al., 2004; Berrill et al., 2006a). However, it has not been demonstrated that smolting salmon differ greatly in their dietary needs compared with other life stages (Helland and Grisdale-Helland, 1998; Hemre and Hansen, 1998; Tocher et al., 2000; Hemre et al., 2002; Nordgarden et al., 2002). If a poorly smoltified fish is transferred to saltwater the osmoregulatory problems will affect feed intake for a long period of time. Even well smoltified fish have a temporal appetite reduction for some days (Arnesen et al., 1998), which normally will be compensated by a later short-term increase in feed intake.

Commercial salmon feeds are much higher in energy compared with the diet of wild salmon and the fish experience a growth rate in culture that are not common in the wild both in rate and maximum size. Salmon have a large range of growth capacity, and farmed fish thus do not experience abnormal growth, but most farmed fish probably adapt a growth strategy similar to the upper modal fast-growing salmon in the wild. There may be a behavioural link between such a developmental pathway and aggression pattern in salmon (Nicieza and Metcalfe, 1999). The growth pattern is regulated by individual appetite, leading to a growth trajectory with a deterministic set-point regulation, enabling the salmon to compensate for any deviations from this growth plan (Mortensen and Damsgård, 1993)

Feeding rations for farmed salmon are calculated based on water temperature and body size, and such rations are estimated for example as weight units per day. Fish farmers normally attempt to optimise the amount of feed in order to meet a maximum growth rate, but if time is not a limiting factor in production, the feeding ration may also be optimised for maximum feed conversion rate.

Feed delivery methods are of primary importance to the success of feeding. If feed is not equally distributed to the fish, both due to technical limitation in ensuring overall dispersal in the tank, or due to social interactions leading to feeding hierarchies, a consequence may be that individual fish have less than optimal ration even if the total feed amount is in surplus. In salmon-farming conditions, feed sinking rates can be altered to make feed more available at different depths, feeding rates and times are altered to ensure that feed is available for sub-dominant fish (which helps them lose sub-dominant status), feed delivery systems and cameras as well as direct stock supervision by staff can assess when fish are feeding.

Short-term feeding stops are commonly used in salmon production, for welfare reasons, e.g. before handling or transporting fish, when feed in the digestive tract leads to mortalities, Reduction of ration for this period, and the following catch-up growth are known to increase aggression (MacLean and Metcalfe, 2001), leading to an increase in plasma cortisol level, and fin damage. It is not known whether the increase in cortisol is due to metabolism changes or distress. The variation in feed intake is to a large extent related to other biotic and abiotic environmental factors, such as water quality and water current. Several changes in the environment (e.g. O_2, CO_2) may lead to reduced feed intake, while water current may affect the inter-individual distribution of feed. All types of handling of the fish will affect the appetite, but most of these feed reductions will be compensated.

It is common practice in aquaculture to feed ongrowing Atlantic salmon to appetite, by either fully automated systems, or manually via some sort of pneumatic blower. These approaches generally ensure that the caged salmon populations are fed daily according to their needs at a population level, and hence lack of food is not, on the whole, considered a welfare issue. However, there are certain circumstances under which a lack of feed may arise particular with respect to the following:

- poor weather preventing feed delivery
- some individuals within the population being unable to access food
- routine starvation prior to harvest

In respect of a lack of feed delivery, whether enforced due to poor weather conditions or resulting from normal husbandry practice prior to slaughter, a study carried out on the effects of feed deprivation in production cages showed a rise in blood glucose after 7 days without food, while other variable remained unaffected (Bell, 2003). It is not clear whether or not missing a day or two of feeding or pre-slaughter fasting of fish are likely to impair their welfare.

Lack of access to feed by some individuals in a farmed population may, however, be a consequence of normal feeding practice, depending on the manner in which the fish are fed. Swimming activity and the number of fish observed to have been feeding in response to a given feed delivery have been considered indicators of scramble competition at meal times in salmon cages (Andrew et al., 2002). Such competition can cause scale loss, and no doubt stress to the fish involved. (Andrew et al., 2002) observed that where fish are fed by demand in production scale systems, such activity and competition at meal times was significantly reduced.

Starvation, describes a situation where the fish are deprived of food over a long period and starvation starts when the animal begins to metabolise tissues that are not food reserves, but are functional tissues (Broom and Fraser, 2007). During starvation fish will lose biomass as they mobilise energy stores, mainly lipid but also some proteins (Jobling et al., 2001). The biomass reduction due to starvation will slow down after a few days as the fish become hypometabolic, down-regulating metabolism to conserve body substrates (Damsgård et al., 2004). Adult Atlantic salmon starved for 86 days lost less than 12 % of the body mass and 50 % of this reduction occurred during the two first weeks (Einen and Thomassen, 1998). Thus, salmon seem able to sustain prolonged periods of starvation with relatively moderate loss of body mass. Energy conservation during starvation is strictly controlled and energy requirements in different tissue seem related to their function; protein turnover in gill tissue does not change as starvation progresses whereas protein turnover in the liver can be substantially reduced (Martin et al., 1993). Farming operations, like intraperitoneal vaccinations, have been shown to result in long-term reductions in feed intake, and this was not due to the general handling of the fish, but directly linked to the damage to vital systems caused by the antigens and adjuvant in the vaccines (Sørum and Damsgård, 2004). The development of disease in salmon can also affect the appetite of the fish, both long-term as with IPN virus (Damsgård and Arnesen, 1998) and short-term with e.g. cold water vibriosis (Damsgård et al., 2004). Long periods of starvation are most commonly used prior to slaughter. There is no published data on the impact of this on welfare.

6.4. Husbandry and Management

6.4.1. Handling

Handling can cause stress to fish, resulting in a primary stress response, leading to increased activity and oxygen demand (Davis and Schreck, 1997) with various secondary implications, as reviewed by (Portz et al., 2006). Contributory factors to handling-related welfare problems include water quality, crowding and increased activity as fish struggle. These may result in acute or chronic stress, with potential tertiary responses such as a compromised immune system. Therefore, while handling may be managed so as to minimise welfare impacts upon the fish, in situations where this is not the case, there may be both immediate and long term effects upon fish welfare (Barton and Iwama, 1991).

While handling may be necessary as part of standard husbandry practice, it is important that the frequency and duration of such events is minimised, and that the handling process be designed and implemented in order to avoid any adverse effects. Handling in salmon farming is classified as ‘wet’ where fish are not removed from water but by using special mechanical pumps, or ‘dry’ using manually operated nets. Mechanical pumps have a variable piping size that is adjusted to fish size and speed of pumping is low in order to avoid damage to the fish. Netting is normally only used in the freshwater stages pre-smoltification. The main constraint of netting is the length of time out of water.

Eggs are very vulnerable to physical disturbance at specific times during their development, especially during water hardening and blastopore closure (Jensen and Alderdice, 1989; Crisp, 1990; Krise, 2001). Any stress and physical damage that occur at this stage may result in deformities later in life (e.g. (Wargelius et al., 2005), but when they reach the eyed stage they can be easily handled and transported. The alevins are rather fragile to handling, especially in the period just after hatching when the vulnerable yolk sac is still large. They are more robust for handling closer to first feeding, when most of the yolk sac has been resorbed.

Smolts are generally considered to be at a very vulnerable stage in the salmon life cycle, both due to physiological changes such as high plasma cortisol levels and morphological changes such as looser scales (Carey and McCormick, 1998). Smolt may be handled and transported, at a time when they are very fragile for physiological stress and physical handling.

Salmon broodstock are normally inspected on a weekly basis for ovulation or the presence of running milt. Frequent handling represent a stress to the broodstock and physical handling may also cause damage. Some farms use GnRH treatment to induce spawning of large volumes of milt from males at a single stripping and slaughter the males at that time which prevents the need for further handling, (Zohar, 1988). One GnRH analogue is approved in EU and Norway for spawning induction in Salmonids such as Atlantic salmon (Haffray et al., 2005). The large body size of the salmon broodstock represents a challenge in terms of handling and proper sedation with anaesthetics is normally required for handling and inspection. It is considered that the immune function is impaired by sexual maturation in the broodstock, which among other things can lead to increased problems with fungal infections in freshwater. Physical damage related to antagonistic behaviour (fighting), handling or caused by individuals jumping into the tanks structure can increase the risk of fungal infections. Altogether, the almost universal secondary infection which occurs in mature males represents a serious welfare hazard in broodstock. Proper training of personal, use of adequate anaesthetics and appropriate tank design are all essential to prevent physical damage of the broodstock. Salmon from river systems are occasionally trapped, transported to hatcheries and stripped so that their eggs can be used and their offspring reared. When this is done, the trapping, transport and handling of these wild fish at this sensitive stage of their lives would be very stressful.

6.4.2. Crowding

Crowding is an essential process for handling of fish at all life stages, prior to grading, vaccination, transport and slaughter. Crowding to very high densities, associated with pre-slaughter levels (>200 kg/m^3) has been identified as causing an increase in stress indicators such as cortisol concentration in adult salmon (Veiseth et al., 2006). In practice some adjustments to tank design and crowding systems have been developed in order to minimise the adverse effects of crowding such as decreasing depth to diameter ratio.

6.4.3. Sample weighing

Sample weighing is carried out to validate predicted weight for feeding ration updates and providing an indication of stock health. In early freshwater stages this is usually carried out by weighing a representative sample in a known volume of water. Larger fish from pre-smolt onwards fish are normally anaesthetised and dry weighed but both operations involve handling. In larger production units (tanks or cages) the use of passive biomass estimators are increasingly common. Individual weighing is also done in order to estimate the size variation in the stocks and to evaluate the need for grading and adjusting feed size.

Salmon are regularly monitored for weight and health during the ongrowing phase. While many salmon producers use remote weight estimation systems, some continue to net and hand weigh samples of fish, particularly during the early stages of ongrowing, which can cause handling stress. Such checks do however provide for a correction of feed rations to ensure the population is being fed sufficiently, so also providing a welfare benefit.

6.4.4. Grading

Grading is essential in salmon farming. Failure to grade by sizes will result in hierarchies developing but grading itself may also affects the welfare of the fish due to handling. Grading (or sorting) can also be done in broodstock, to remove immature fish, to obtain an appropriate sex ratio and to divide fish into groups according to stage of maturity. Sorting is also conducted at the egg stage to remove unfertilised and dead eggs. The robustness of the fish to sorting operations varies with life stage and the grading process. Parr and mature broodstock are more robust to physical handling than smolts and ongrowing salmon. Some eggs stages are also very vulnerable to handling, and should only be handled at the eyed stage.

Grading in freshwater is common particularly during the parr stage. Typically size grading is carried out between 2 and 5 times, starting at around 1g during the freshwater phase. It occurrence depends on the efficacy of previous grading and subsequent growth distribution which is related to feeding adequacy. Grading is carried out by netting or pumping the fish and then making them pass through an immersed bar grader, where sorting is usually by body thickness rather than weight.

Grading in freshwater cages is done with the same sort of equipment on land-based systems, with fish being pumped or netted onto the grader. Typically grading is carried out fewer times in cages than tanks, and the fish are stocked into cages as a graded population. To access fish in cages, nets have to be lifted which causes a twofold problem: crowding (that is unavoidable) and higher light intensity due to raising fish to the surface. Both are stressors, and there is also the risk of abrasion from contact with the net material. As such, grading frequency in freshwater cages is usually lower.

Grading in sea-water is usually less frequent as the fish are more susceptible to handling. Two grading systems are commonly used: the first being passive grading using a panel net in the cage allowing small fish to pass through, and the second is using pumps (vacuum or air lift) to a large size bar grader usually in a well-boat. Grading at sea is usually done prior to slaughter of the fish.

Size sorting in parr is usually carried out once or twice during that life stage using a grading machine, with fish pumped in and out of tanks through a grid. This system is set up to minimise the time fish are out of their tanks, and water quality is maintained to minimise physical stress on the fish.

Salmon are readily harmed by handling during smoltification. Smolting salmon have naturally increased cortisol levels (Sundell et al., 2003), combined with an increased sensitivity to environmental stressors (Iversen et al., 1998). Handling and other stressors can cause a delay in the smoltification process, potentially resulting in an inability to osmoregulate properly on transfer to sea-water. Such a situation will lead to prolonged osmoregulatory stress and may result in mortality. Size sorting is especially important prior to smoltification as larger individuals will tend to smolt earlier, and consequently also begin reversion to parr status earlier than smaller fish. Hence smolting populations, which will inevitably have some size variation, will have an associated variation in smolt status. Grading smolts is not practised due to adverse stress effects and risk of physical damage and scale loss; hence populations of smolts tend to be transferred to sea together. The wider the size range at sea-water transfer, the more likely it is that a number of individuals within the population will be unable to osmoregulate properly. Inability to osmoregulate in the early stages post-smolt transfer can cause prolonged stress and lead to an increased susceptibility to disease and a higher mortality.

Handling of salmon during the ongrowing phase is usually associated with grading and harvest, but may also be carried out at regular intervals as a means of weight estimation. Grading and harvest are usually performed using a well-boat in modern salmon farming, so minimising handling and associated welfare impacts.

6.4.5. Transportation

This topic is discussed in the EFSA Scientific Report "The welfare of animals during transport" (EFSA, 2004).

Transport of fish may be carried out between trays and tanks (alevins and fry), between tanks (fry and parr), between tanks to cages (in freshwater and from fresh to sea) and between cages. Transport between rearing units represents a challenge both in terms of potential physical damage, handling stress and confinement in smaller transport units. Water quality issues, such as the ones indicated in previous sections, may also be a problem due to both the effects of intense crowding and a lack of water renewal.

Transport between rearing units may also present a welfare challenge in terms of physical damage, handling stress and confinement. In addition water quality may cause a problem.

6.4.6. Anaesthesia

Proper use of anaesthetics can be of importance and to avoid physical damage during certain husbandry procedures such as vaccination, growth measurements and broodstock inspections. However, the effect of anaesthesia and the anaesthetic on fish is limited for Atlantic salmon, in particular with respect to analgesia. Conditions of recovery are also of great importance but again there is insufficient knowledge of the effects on fish. Anaesthetics are veterinary medicinal products and their administration is done under veterinary supervision. There is only one anaesthetic licensed for use in fish destined for human consumption, MS222 (Table 8), but benzocaine can be used for culling fish or in broodstock when carcasses are not for human consumption.

6.4.7. Monitoring

Proper monitoring and recording is essential in salmon farming. This includes effective and repeated monitoring of key environmental factors such as oxygen and temperature. In some production systems other environmental factors such as pH, CO_2, ammonia, salinity, nitrate, alkalinity, turbidity and light should also be monitored with appropriate equipment. A monitoring system should also include factors such as biomass and weight control, fish counting, and feed and appetite control. Sampling must also take into account developmental stages, e.g. to assess correct timing of first feeding, sea-water transfer and spawning. Monitoring of water quality parameters can either be done manually or automatically, at regular intervals or continuously. Staff training is essential in interpreting data but also in evaluating fish behaviour. Monitoring systems can be connected to alarms and/ or to automated emergency response systems. The level and complexity of monitoring and alarm systems increases with the intensification of the production systems. Open systems such as flow-through, and especially freshwater and sea cages, are also exposed to contaminants in the inflow water. In land-based systems it is possible to interrupt water supply provisionally if problems are detected.

6.4.8. Health monitoring

Monitoring of fish health and disease including detection of behaviour changes is very important. Most fish farms have a health monitoring programme supervised by a veterinarian. Both Scottish and Norwegian salmon farmers have codes of practice that include a recommendation for health monitoring plans, as does the Council Directive 2006/88/EC that includes fish health veterinary supervision as a legal requirement. Health monitoring is a preventive strategy in the management of disease.

Monitoring for health status takes place daily in the form of checks on the behaviour of fish, using cameras and/or cage side inspection, especially during feeding. Regularly, more targeted though less frequent health checks are performed by sampling, killing and inspecting fish both externally and internally for parasites and disease. Both checks are considered essential to provide a welfare benefit to the fish population in providing information about health status of stocks that should resulting in remedial action when problems are detected. Lack of monitoring can endanger the welfare of salmon populations as this may result in underfeeding and/or disease outbreaks.

6.4.9. Removal of dead fish

Dead fish must be rapidly removed, counted and recorded. They are removed by netting from the surface or from the tank or cages that are designed to provide an area for collection of the dead fish. In tanks this is usually in the outlet, whereas in cages the collection area in the bottom panel of the net. The removal of dead fish in cages can be done by pumping or by a removable basket that is included in the collection area or when the net is lifted. When a net is lifted crowding of the fish occurs. In sea cages, divers are often used to collect dead fish and that will reduce the frequency of other deaths but it also allows inspection of fish and net integrity. Removal of dead fish is important to reduce organic and pathogen loads and to deter predation. The recording of both numbers and cause of mortality is important as an indicator of disease incidence and welfare.

6.4.10. Cleaning

Cleaning is a high priority procedure in salmon farming but cleaning procedures can produce disturbance among the fish, e.g by physical cleaning of tanks or nets, or by changing nets. Inadequate self-cleaning of tanks due to poor design or flow pattern can result in a build up of uneaten feed. Cleaning of tanks can be done by brushing and flushing which involves crowding and remobilization of nutrients and suspended solids into the water column. Cleaning of nets is essential where biofouling occurs resulting in reduced water flow through the cages. Cleaning can be carried out by net changes which involve crowding and transfer of fish to fresh cages. The transfer may be either passive or mechanical, and can involve crowding and handling or various *in situ* cleaning systems that can lead to short term deterioration of water quality.

6.4.11. Staff training

Staff training in good husbandry and care of stock is essential to good welfare of all farmed animals including salmon (FAWC, 2007). Where this is not provided, fish may be subjected to various negative welfare impacts such as underfeeding, handling stress, disease etc. In order to prevent such occurrences, most salmon farming companies provide training in salmon husbandry for their staff, as well as ensuring adequate opportunities for informal training via working alongside experienced stockpersons during the initial period of employment.

6.4.12. Tagging

Tagging of fish is mostly used for scientific purposes, but also to some extent in farmed broodstock. A tag may identify a fish on group levels or as individuals. A tag may be natural (a genetic marker) or artificial, and an artificial tag may be externally fixed, superficially injected or internal for example in the peritoneal cavity. The tags should be easy to read and for a long period after tagging. It was previously common to tag groups of fish by fin clipping, e.g. removing the adipose fin on salmon. Other external tags may be attached to the dorsal fin, and fish may also be tagged by colouring under the skin, cold branding or small numbered metal plates behind the eye of the fish. Common internally injected tags are coded wire or an inert glass capsule with a coded passive integrated transponder within it, enabling an automatic or manual reading of individual fish using an antennae or a handheld reader. Internal tags normally involve minor surgery to place them, and are not commonly used in a normal farming situation. Fish may also be tagged with changes in the otoliths after chemical or physical treatments. The tagging procedure, including handling, anaesthesia and tagging may have some welfare consequences for the fish (Reimchen and Temple, 2004). The treatment may be invasive and stressful for the fish. Tags may also affect the behaviour, physiology and health of the fish. For example, oversized tags or fin clipping may affect the swimming ability of fish if fish are too small for a tag size, and external tags may lead to pathological lesions, and such lesions may lead to secondary infections (Roberts, 1973b; Roberts, 1973a).

6.4.13. Smoltification testing

Smoltification is monitored in several ways, each of which has a different potential impact upon fish welfare. Visual monitoring of the fish for signs of smoltification (e.g. silvering and darkened fin margins) can be done with minimum impact, but is the least accurate and may result in early or late transfers to sea-water and consequent osmoregulatory stress. However, regular invasive physiological monitoring of smoltification in a sample of fish from each population is common practice and involves several possible methods. In the "standard sea-water challenge test" a subgroup of the fish is exposed to full sea-water (> 30 ppt), and after 24 hours the fish is killed and the blood plasma chloride (or other osmolytes) are analysed. A high level indicated that the hypo-osmoregulatory capacity is poor, and the level usually decreases during the spring. This test may however create a poor welfare environment, particularly in the early stages of smoltification when the fish cannot osmoregulate properly. A test with water salinity beyond the normal sea-water (i.e. 40 ppt) level has also been used, simply linking the mortality with the sea-water tolerance, but this test should not be used since the fish is exposed to a severe and lethal environment over a long time period. As an alternative to the sea-water challenge test a gill sample may be used to measure gill Na^+ K^+-ATPase activity. This test requires that fish are rapidly killed, immediately after being removed from water, hence overcoming the welfare issues associated with the other monitoring methods described.

6.5. Genetics

Farmed salmon have only been subjected to systematic breeding since the early 1970s (Gjedrem et al., 1991), and are still less than 10 generations from the wild and compared with terrestrial livestock, and so fish can still be considered in the early stages of domestication. Selection has been for rapid growth, late sexual maturation, improved harvest quality and resistance to disease (Gjøen and Bentsen, 1997; Midtlyng et al., 2002)

(Kanis et al., 1976) report that early survival is not easily modified by genetic selection. Important modification of carcass traits and body composition are possible (Rye and Refstie, 1995; Rye and Gjerde, 1996). Low to medium estimations of heritability for vertebral malformation are reported (Gjerde et al., 2005), however the variation from year to year invalidates the hypothesis of a strong genetic effect and indicates that such traits are mainly controlled by husbandry practices. Recent publications underline the high potential of improvement of genetic resistance against viral and bacterial diseases (Kjoglum et al., 2008).

Salmon intensive rearing systems may lead to higher environmental microbial levels as well as favourable disease transmission conditions due to high stocking densities. For example, (Guy et al., 2006) have reported that increasing the genetic resistance of farmed salmon to IPN greatly reduced disease outbreaks. However, there is a possibility that selection for resistance to one disease may compromise resistance towards another. This reduction in genetic variability has been studied in other biological systems but there is only limited scientific evidence for Atlantic salmon (Dupont-Nivet et al., 2006).

The experience in terrestrial farming is that poorly structured breeding programmes run the risk of inbreeding (Falconer and Mackay, 1996) with associated poor reproductive performance, loss of genetic variation and development of some undesirable physiological side effects such as deformities or loss of variability in disease resistance. Consequently, the main salmon breeding companies in Scotland, Norway and Chile use technologically based modern breeding programmes where these issues are comprehensively addressed by sophisticated selection algorithms (Gjedrem, 2000).

There are currently legislative and consumer barriers to the development and marketing of transgenic salmonids in Europe. Transgenic salmonids have been developed in the US in the 1990s by injecting DNA constructs from other salmonid species into newly fertilized eggs.

These are slowly going through the approval process in the US but as yet no approval has been given. Dramatically increased rates of growth in transgenic fish have been demonstrated (Devlin et al., 2001) against a genetic background of relatively unimproved or wild strains but the benefit was not so apparent where highly selected strains were used (Fletcher et al., 2001). Disrupted physiology due to the transgenes is a risk unless a very high degree of screening for defects is carried out as part of the development phase (Devlin et al., 2004).

Triploid salmon (i.e. 3 chromosome sets, two maternal and one paternal as induced by pressure or heat shock following fertilization) are functionally sterile (Tiwary et al., 2004), and could be used to combat potential genetic impact of farmed salmon escape on the wild salmon populations. Use of triploid salmon has been tested previously in the European farming industry, as triploid salmon are sterile and not able to reproduce. Female triploid salmon did not grow large gonads, and did not suffer the negative effects of gonadal growth on somatic growth and flesh quality which affect normal diploid salmon. In contrast, triploid male salmonids did grow gonads in spite of their inability to produce fertile sperm, and as a consequence triploid male salmon display the negative effects of sexual development on growth and flesh composition in a similar manner as normal maturing diploid salmon. Therefore triploidy would normally be expected to be combined with the use of all-female populations to avoid the negative effects of sexual development of aggression by precocious males, somatic growth and flesh quality. However such techniques are not currently practised in European salmon culture.

Evidence from earlier work suggested that triploid salmon are more prone to develop production disorders such as lenticular cataracts and spinal deformities, and are more sensitive to extreme environments compared with normal diploid salmon (Sadler et al., 2000a; Sadler et al., 2000b; Sadler et al., 2001). Triploid Atlantic salmon were also found to have lowered anaerobic capacity compared with diploids when forced to swim (Cotterell and Wardle, 2004). While some features of triploid salmon may have negative welfare consequences, particularly in suboptimal rearing environments or following stressful husbandry practices, the advantages of removing the potential risk of escapees affecting the wild salmon stocks as well as to avoid negative welfare consequences of sexual maturation, justifie further research on this area.

6.6. Impact of disease on welfare in Atlantic salmon

Infectious and non-infectious diseases of Atlantic salmon have the capacity to afect the welfare of fish at various stages of their development. Farmed Atlantic salmon are susceptible to a range of viral, bacterial, fungal, parasitic and nutritional diseases as well as various physical traumas. A number of serious infectious diseases are listed in the Aquatic Animal Health Code (OIE, 2007) and Council Directive 2006/88/EC. The present report does not attempt to cover all diseases of Atlantic salmon but instead will consider several infectious and non-infectious diseases that may have important implications in terms of welfare at some stages of the production cycle in order to serve as examples of the ways in which disease can impact on welfare. The relation between husbandry practices and systems and disease exposure and impact will be considered for each disease.

The following diseases (Table 7) were considered to be of particular significance to fish welfare because of their: i) severity of effect on physiological integrity of fish, ii) known frequency of occurrence in farming systems and iii) impact of preventive and/or curative measures.

Table 7. **Diseases of farmed salmon with potential welfare significance**

Disease / Disease agents	**Life stage affected**	**Environment**
Furunculosis (Infection with *Aeromonas salmonicida* subspecies *salmonicida*	Fry, parr, smolt, ongrowers	Freshwater, sea-water
Winter ulcers	Ongrowers	Sea-water
Saprolegnia infection	Eggs, fry, parr, smolt, broodstock	Freshwater
Infectious pancreatic necrosis (IPN)	Fry, parr, smolt, ongrowers,	Freshwater, sea-water
Infectious salmon anaemia (ISA)	Ongrowers	Sea-water
Sea lice *(Lepeophtheirus salmonis)* infestation	Ongrowers, broodstock	Sea-water
Pathology resulting from jellyfish invasion	Smolt, ongrowers, broodstock	Sea-water
Eye lesions	Fry, parr, smolt, ongrowers	Freshwater, sea-water

Data on the prevalence of non-notifiable diseases in Salmon farming is mostly not available. However, data on notifiable diseases in accordance to Commission Decision 2005/176/EC in EU Member States are available. With the implementation of the new Fish Health directive, farmers are legally obliged to report outbreaks of the following diseases: Infectious Haematopoietic Necrosis (IHN), Infectious Salmon Anaemia (ISA) and Viral Haemorrhagic septicaemia. The ADNS (Animal Disease Notification System) annual report (EC, 2006) reports 9 outbreaks of IHN in 2005 and 10 in 2006 and 29 outbreaks of VHS in 2005 and 30 in 2006.

6.6.1. Furunculosis

Furunculosis is a systemic bacterial disease caused by the Gram-negative bacterium *Aeromonas salmonicida* subspecies *salmonicida*. *A. salmonicida salmonicida* may enter the fish by water ingestion or via skin abrasions. It can cause severe mortalities at all life stages and may take various forms from peracute to chronic infection. Although furunculosis can be treated with antibiotics, most farms would probably have to stop operations if they did not use vaccination. This is due to the effect of the disease as well as consumer opinion on the use of antibiotics in fish for consumption. Chronic forms of the condition tend to occur more often in unvaccinated adult fish that can present with severe internal haemorrhages, splenomegaly, kidney necrosis and, in some cases, muscle lesions or furuncles from which the disease got its name (McCarthy and Roberts, 1980).

The clinical manifestation of furunculosis may be divided into different forms such as:

- Peracute furunculosis – sudden mortality with few clinical signs, a form usually restricted to young fish that have been stressed or to smolts, where cortisol levels are naturally very high, and disease resistance compromised.

- Acute furunculosis – more common in older fish and characterised by low mortality, lethargy, loss of appetite, and darkening and ulceration of the skin.
- Subacute/chronic furunculosis – usually more common in older fish and mortality is less than in the acute form. Skin darkening and loss of appetite are less common than in the acute form, but furuncles are more likely to be observed.
- Intestinal furunculosis – usually associated with low mortality and the only sign of disease in this form is prolapse of the anus and intestinal inflammation and haemorrhages (Hiney et al., 1999).

Effective oil adjuvanted vaccines are available and widely used for prevention and control of furunculosis of Atlantic salmon. However, such oil-adjuvant based vaccines often produce severe inflammatory reactions (inflammation, granuloma and pigmentation) at the injection site (Midtlyng, 1997) and this may impact on their welfare point of view.

Figure 13. **Large 'furuncle' caused by infection with *Aeromonas salmonicida* subspecies *salmonicida*.**

6.6.2. Winter ulcer disease

Winter ulcer disease is a bacterial condition caused by *Moritella viscosa*. It affects ongrowing Atlantic salmon in sea-water and pre-smolts in hatcheries that use sea-water. *Moritella viscosa* has also been isolated from various marine fish species. The disease is characterised by skin ulcers that may extend to cover large areas of the body. Over an extended period of time these can affect osmotic balance and predispose fish to secondary infections. Infections can become systemic in severe cases (Lunder et al., 1995).

Moritella viscosa produces extracellular toxins and proteolytic enzymes that are important in terms of epidermal damage leading to ulceration (Benediksdottir et al., 1998). These ulcers of varying size may cover large areas of the body. Affected fish are usually inappetent and darken in colour. Mortality figures are usually low, less than 2 % per week.

Moritella viscosa is most virulent below 10 °C and is virtually non-pathogenic above 12 °C. The disease occurs most frequently in the period February to April and affected fish recover when the water temperature rises above approximately 7-8 °C. Outbreaks are usually associated with sub-optimal conditions such as high fish density, poor water exchange, low water temperatures. In addition, prior attacks with salmon lice as well as nutrition may play a role in the development of disease (Bruno et al., 1998).

Antibiotic therapy has been used for treatment of winter ulcers. In Norway, during the year 2000, 45 % of all prescriptions were for antimicrobial agents to control this condition (Coyne et al., 2006). It is reported that 13 % of all prescriptions were for fish under 290 g and 85 % for fish under 1 kg. Therefore, although the condition has been reported in market-sized fish (Bruno et al., 1998), the Norwegian experience is that it occurs most frequently in post-smolts in their first sea winter. However, the effect of such treatment (florfenicol, oral administration in medicated feed) has been variable, and studies suggest that, within a cage population, ulceration and death from *M. viscosa* infection are largely confined to sub-populations that are poorly adapted to the marine cage environment and are not feeding. Preventive methods including improved husbandry practices but where it is commonly, vaccination is the best choice. A multivalent commercial salmon vaccine, containing *M. viscosa* as one of five antigens and a mineral oil adjuvant, has been on the market for several years and has successfully lowered the incidence of this disease (Benediksdottir et al., 1998) but, according to responses to a survey, this vaccine appears to be less than fully effective (Hastein et al., 2005).

Figure 14: **Extensive winter ulcer lesion**
(Photograph courtesy Douglas Johnstone)

6.6.3. Saprolegnia infection

External fungal infections have the capacity to cause serious disease in all freshwater stages of Atlantic salmon. If not treated, such infections can cause extensive destruction of the epidermis, osmotic imbalance and haemodilution, in severe cases leading to death. *Saprolegnia* infection may occur anywhere on the body of all fish, but normally appears as a conspicuous, circular or crescent-shaped, white, cotton-like mycelium, particularly around the head and the caudal, adipose and anal fins (Willoughby, 1989). They are generally considered to be saprophytic opportunists, multiplying on fish that are physically injured, stressed or infected (Pickering and Willoughby, 1982).

The fungus can grow on decaying organic matter and numbers of the motile infectious spores increase within the water column in autumn and winter and it is at this time fish are more susceptible to infection, especially adult male salmon undergoing androgen driven skin changes associated with sexual maturation (Richards and Pickering, 1978). Environmental stress factors, including poor water quality, adverse water temperatures (see section 6.1.2) and, in aquaculture, handling or overcrowding, can all result in increased incidence of fungal infections (Bailey, 1984). High levels of organic matter are associated with increased infection by *S. parasitica* (Toor et al., 1983), but the main factor determining whether *Saprolegnia* infection occurs is considered to be the physiological state of the fish (Cross and Willoughby, 1989).

Sexually mature, stressed or damaged fish are the most susceptible to infection. Fungal outbreaks in hatcheries can result in substantial egg mortality (Smith et al., 1985), as hyphal growth on the chorionic membrane spreads rapidly, especially if dead eggs are not removed. The primary sequel of uncomplicated saprolegniasis is an osmotic imbalance, due to loss of epithelial integrity and tissue destruction, caused by penetration of the hyphae (Copland and Willoughby, 1982). Currently, the most successful strategy for the control of *Saprolegnia* in farmed fish represents a combination of farm management, husbandry practices and chemical bath treatments. Generally, a combination of these practices is important in preventing or limiting fungal outbreaks. Fungal overgrowth on developing salmonid eggs and fry is a widespread problem. Overcrowding, handling, temperature changes, parasitism, increased organic loading and sexual maturation increase the likelihood of *Saprolegnia* and other infections (Pickering, 1994). Where fungal infections are slight, lesions may be treated with some success. Wild fish may also recover if they migrate naturally or are moved to estuarine or sea-water (Pickering and Willoughby, 1982). However, salmonids with significant saprolegniasis do not normally recover, since, once the fungal spore has germinated and has developed its thick plant cell wall, it is largely resistant to available chemical treatments. For many years *Saprolegnia* infections were treated by bathing fish or eggs in malachite green. However, malachite green is not listed as a veterinary therapy under Council Regulation (EEC) No 2377/90 and its administration for that purpose is not permitted in aquaculture.

There are no vaccines available for salmonid saprolegniasis and the unavailability of malachite green means that there is now no satisfactory chemical means of controlling the disease, as bronopol, the only available authorised veterinary medicine for treatment of external fungal infections in fish, appears to be rather less effective than malachite green in aquaculture practice. In practice, with salmon, there are two welfare issues. The first relates to the susceptibility of parr after handling and vaccination, when stress and epidermal damage combine to render them particularly vulnerable, especially when reared in freshwater cages and the second related with handling of mature broodstock. Under such circumstances there is little that can be done therapeutically. Husbandry however can modify the risk significantly by careful handling and disinfection of work surfaces and use of stress modulators and mucus enhancers in the holding water before vaccination. In the second case is that broodstock, when reintroduced to freshwater, Saprolegnia infection is prevented by careful handling and, where access to sea-water is available, addition of 1 % sea-water to the incoming water. Techniques which allow spawning males, which are the most vulnerable, to be stripped as few times as possible, under anaesthesia following GnRH stimulation, are considered by the industry as good practice to avoid the invariable Saprolegnia infection that accompanies frequent milt stripping.

Figure 15: **Saprolegnia parasitica**
Hyphae growing on a salmon skin surface showing a zoosporangium containing zoospores (Photograph courtesy Dr Guy Willoughby)

6.6.4. Infectious pancreatic necrosis (IPN)

IPN is one of the most widespread and serious viral diseases affecting Atlantic salmon. It affects fish in both freshwater and sea-water phases of development. The disease is most common in first feeding fry and post-smolts, causing extensive mortalities, but has occasionally been recorded in ongrowing fish and broodstock, where it inhibits egg development. The virus is a member of the Birnaviridae and pathogenic strains are, as with other birnaviruses, immunosuppressive and capable of remaining in infected carrier fish for long periods. In fry IPN is acquired via the digestive tract where it establishes and extends to the pancreas and renal haemopoietic tissue. Acute pancreatic necrosis and necrotic enteritis follow and frequently prove fatal. In smolts and adults the liver is also severely necrotic (Roberts and Pearson, 2005).

IPN virus can be vertically transmitted both on the surface of the salmon egg and inside it (Bullock et al., 1976). Although testing for the presence of detectable virus by tissue culture or quantitative PCR are helpful in relation to detecting carrier parents, it cannot be relied on entirely and so vertically transmitted IPN which can spread from one tank to a whole facility very quickly may be a major problem in young salmon fry. Affected fry are generally darker, with swollen abdomen and vent, and are pop-eyed. They also have behavioural aberrations which allow very early clinical identification of an outbreak and instituting precautions can help prevent the typical epizootic losses of up to 90 %.

IPN can have a significant effect on the welfare of fry. Vaccination is impossible in such young fish but genetically resistant strains are becoming available and are reducing incidence in fry (Guy et al., 2006). Recent improvements in biosecurity coupled with water sanitization have transformed loss levels in fry where they have been applied quickly and assiduously (M. Pearson pers com. 2007). In recirculation systems some success in managing outbreaks in fry has been claimed for raising temperatures to above 14 °C. Commercial vaccines are now licensed for use in EU and are becoming routine to protect against IPN in smolts, although effectiveness is as yet unproven in field conditions.

In post-smolts the disease characteristically breaks out 2-3 months after transfer to sea. Outbreaks are always worse in populations where there has been poor husbandry during transfer or thereafter, and although outbreaks can occur even in the best operated farms, attention to fallowing of sites, biosecurity, low stress transport, sea louse control and proper feeding in the first few months all help minimise the level of losses (Smail et al., 1992). Careful management of the clinical outbreak with rapid and careful removal of dead fish into disinfectant and biosecurity between nets, cages etc also help limit losses.

Figure 16. **Acute IPN in a salmon parr**
The liver is very pale and there are obvious punctate haemorrhages over the pancreatic area. (Photograph courtesy of Dr Marianne Pearson)

6.6.5. Infectious salmon anaemia (ISA)

Infectious salmon anaemia (ISA) is a serious viral infection in Atlantic salmon caused by a virus belonging to the family of Orthomyxoviridae (Fauquet et al., 2005). The disease has caused salmon farming industry high economic losses due to mortalities and required destruction, slaughtering of fish and fallowing of affected farms (OIE, 2006).

Atlantic salmon is the only species in which ISA disease occurs naturally but the ISA virus has been shown to replicate in Pacific salmon and rainbow trout, usually without clinical disease. Such species may be of importance as carriers of virus and as reservoirs where they are cultivated together (Kibenge et al., 2001).

Replication of ISA virus has been demonstrated in experimentally infected brown trout *(S. trutta*), rainbow trout (*O. mykiss*), Arctic char (*Salvelinus alpinus*), chum salmon (*O. keta*), coho salmon (*O. kitsutch*), herring (*Clupea harengus*) and Atlantic cod (*Gadus morhua*). No replication has been found in bivalves (Hellberg et al., 2005; Skår and Mortensen, 2007).

Infectious salmon anaemia (ISA) is a systemic disease affecting the circulatory system. Atlantic salmon suffering from ISA shows severe and macroscopic lesions including ascites, petechiae on internal organs and haemorrhagic liver necrosis (Thorud and Djupvik, 1988).

Final stages of the disease are characterised by circulatory collapse and anaemia. Pathological changes include dark liver due to haemorrhagic necrosis, moderately swollen kidneys with interstitial haemorrhaging and tubular necrosis, dark red guts due to bleeding within the intestinal wall, and blood accumulation in the gill filaments. Changes indicating a systemic infection with oedema and eye haemorrhage, skin and serosal surfaces are characteristic of ISA. It is noteworthy that haemorrhagic lesions may be absent or very rare in the initial stages of an outbreak, leaving only the anaemia and the more subtle circulatory disturbances as diagnostic clues.

There is significant variation in the susceptibility to the ISA virus in different families of Atlantic salmon(Gjøen and Bentsen, 1997) and it has also been claimed that farmed fish are more susceptible than wild fish (Nylund et al., 1995).

Epidemiological investigations have shown that ISA often occur after periods with other disease problems and/or non-specific problems (Lyngstad et al., 2007).

Generally, the daily mortality stays low, but often increases in early summer and winter to more significant levels (0.5–1 %). Without intervention the cumulative mortality may become very high. The mortality due to ISA may vary considerably and it has been reported to be from 15 % - to nearly 100 %. Older fish seems less susceptible than younger fish.

Several studies have shown that ISA virus is spread by horizontal transmission, but vertical transmission cannot be excluded based on the literature (VKM, 2007).

The management and control of ISA must be based on biosecurity measures including restrictions on movement of live fish, year class separation, instructions regarding containment of dead fish and handling of material liable to transmit the disease, as well as cleaning, disinfection and fallowing of affected farms.

Vaccines are available commercially, but experiences from Canada indicates that vaccination of fish do not fully protect the fish against ISA. In Europe, only the Faeroe Islands has introduced vaccination as a control measure and restocking of fish in marine farms are only allowed if the fish have been vaccinated.

Figure 17. **Infectious salmon anaemia infection in Atlantic salmon**
(Photograph courtesy of Dr Tore Hastein)

6.6.6. Sea lice

Sea lice are crustacean ectoparasites that can cause severe infestations in Atlantic salmon at any stage of their marine existence. Two caligid species are principally involved, *Lepeophtheirus salmonis* and *Caligus elongatus* (Wootten et al., 1982). The parasites are released from the egg sacs of adult females and undergo a number of free-living stages before attaching, grazing and severely damaging the skin of affected fish. Osmotic damage, frequent secondary bacterial infection, and the distress caused by the activities of the lice to the fish leads to starvation, reduced growth, and mortality. Moribund fish are dark, and inactive. Infestations result in irritation. This is particularly a problem in young fish infected with *Caligus* and causes the fish to leap from the water to 'flash' i.e. to scrape against ropes or of the net, all of which causes the fish to seriously traumatise themselves. In addition the adult lice themselves cause ulceration by their feeding activities (Barber, 2007). Sea lice may be implicated in the transmission of a number of diseases (McLoughlin and Graham, 2007). Sea lice can transfer between farmed and wild populations and it is claimed may have a negative impact on both, in particular on sea trout in the wild. (Heuch and Mo, 2001; Heuch et al., 2005; Krkošek et al., 2006; Barber, 2007) Oral and bath treatments are available for farmed salmon but there are serious practical difficulties in their application as well as concerns regarding environmental impacts and the risk of development of resistance to the limited range of effective therapeutants. Although there are no commercial vaccines against sea lice, which are emerging as the biggest economic and welfare risk of all farmed salmon in the marine environment, there are some preliminary data to suggest that it might be feasible. Similarly work on attractants (Bailey et al., 2006) is showing some promise as a means of trapping mobile lice stages away from the salmon. Preliminary research with breeding companies is showing that there is significant variability in susceptibility between families and this is an area which justifies considerably greater input (Glover et al., 2005; Kolstad et al., 2005).

Figure 18. **Sea Lice affected salmon**
(Courtesy Dr. Tore Hastein)

6.6.7. Pathology resulting from jellyfish strikes

Mass mortalities can occur if large swarms of jellyfish are carried into areas where salmon are being ongrown. Small jellyfish can be washed into cages whereas larger jellyfish tend to be broken up against the nets and tentacles or parts of tentacles enter the cage and sting the fish. In some cases the quantity of jellyfish can cause anoxia in the cages or obstruct respiration which may cause respiratory distress. In such cases mass mortality of a whole crop can occur. In the case of blooms of the lionsmane jellyfish (*Cyanea capillata*) very serious welfare issues arise from the intensely irritant whiplash like injuries which the nematocysts of broken tentacles, passing over the surface of the fish, inflict. Affected fish immediately traumatise themselves by severely scratching the affected surface on net, rope or any other hard surface available. Traumatic enucleation of the eye and large traumatic gashes in the side of the fish are common and secondary infection with opportunistic bacteria always occurs. Losses of up to 200 tonnes of market size salmon due to a single invasion have been recorded (Roberts and Rodger, 2001a).

Fish do not feed for some time after a strike which is often recurrent over several days so feeding antibiotic to prevent secondary infection is not possible and slaughter on welfare grounds has been the optimal solution. Prevention is difficult although some areas are more likely to be affected than others.

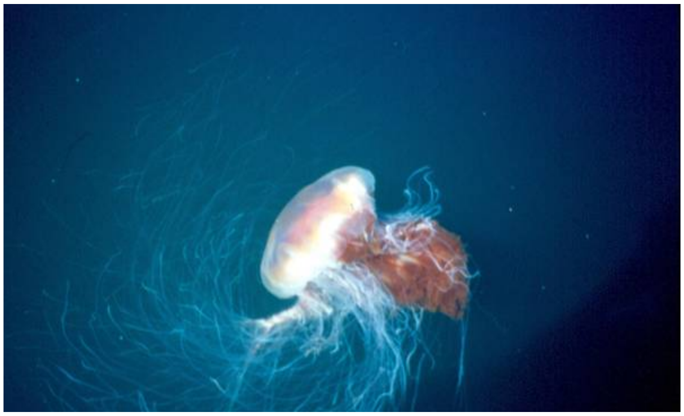

Figure 19. **Lionsmane jellyfish**
(Photograph courtesy Carol Small.)

6.6.8. Eye lesions

Many different factors can cause eye lesions in Atlantic salmon, including vitamin deficiency, parasites, viral and bacterial infections, mechanical damage, irritants, neoplasia, genetic factors, light and gas-bubble disease. Eye lesions are common but they vary in severity and even severe eye pathologies may not be fatal *per se*. However, they can result in poor growth and increased susceptibility to a range of infectious diseases (Ersdal et al., 2001; Roberts and Rodger, 2001b)

In particular cataracts leading to blindness and failure to feed have been frequently associated with dietary imbalance and are a serious welfare problem. Exclusion of histidine rich blood meal following BSE legislation was a major cause of this problem in the past but nowadays this trace deficiency is well managed (Wall, 1998; Breck et al., 2003; Waagbo et al., 2003; Ferguson et al., 2004; Hamre et al., 2004).

6.7. Effect of poor welfare on disease

All disease conditions can constitute a cause for poor welfare but it should be noted that poor welfare, often resulting from negative husbandry factors, can also enhance the susceptibility to disease by various mechanisms. For example, clinically normal Atlantic salmon may harbour low numbers of the bacterial pathogen *A. salmonicida* without showing any signs of disease. However, disease can be precipitated by a variety of stressors such as increases in water temperature, handling or following transfer of smolts to sea-water. This is supported experimentally by the finding that asymptomatic carriers of *A. salmonicida* suffer clinical furunculosis following injection with a corticosteroid and elevation of water temperature (Bullock and Stuckey, 1975; Scallan and Smith, 1985).

Disease in fish is closely linked to environmental conditions including host husbandry status and frequently clinical disease, even at a low level in a population, is a significant welfare indicator *per se*. Most disease conditions occurring in farmed fish are not caused by primary pathogens but by stressful environmental or husbandry conditions allowing a relatively poorly infectious agent to overcome the defence mechanisms of the host (Snieszko, 1972). Thus poor welfare and economic loss from disease have links. Secondary infections of mechanical gill or skin trauma induced during handling and opportunist flexibacterial invasions of surfaces enriched by presence of increased bacterial loadings due to poor water quality or damage by sharp sediments are very frequent harbingers of poor fish condition. Conversely, significant environmental improvement without recourse to treatments of any kind can frequently resolve such infections, although general disinfection of the surfaces by use of formalin or disinfectant bath at the same time will resolve matters more quickly (Winton, 2001).

6.8. Disease Control Measures

6.8.1. Medical control measures

In addition to management and husbandry, other preventive measures (e.g. vaccination and biosecurity measures, described below) different pharmaceutically active compounds are used to prevent and control outbreaks of infectious and parasitic diseases. These involve the use of external baths with antiparasitic solutions for managing external parasitism, use of pharmaceutically active compounds such as antibiotics and other chemotherapeutics, generally in the diet but occasionally given parenterally. In addition a range of neutraceuticals such as immunoenhancers or feed components which may reduce stress, are also increasingly incorporated into the diet to support improved health management during specific husbandry events.

The number of veterinary medicinal products available for use in Salmon aquaculture is reduced and different in the various European countries (Table 8). The lack of availability of potentially useful veterinary medical products is widely considered within the industry as a major welfare constraint.

The technical requirements relating to the marketing authorisation, production, labelling, classification, distribution and advertising of veterinary medicinal products have been laid down by Directive 2001/82/EC. The approval system follows various procedures: i) National; ii) Decentralised to be used for products that have not yet received authorization in an EU country; iii) Mutual recognition meaning that EU countries may approve the decision made about a medicinal product by another EU country; and iv) Centralised when in accordance with Regulation (EC) No 726/2004 the application is submitted to the Committee for Veterinary Medicinal Products - EMEA and if approved the marketing authorisation is valid throughout the Community. Veterinary medicinal products intended for use in aquatic species have to satisfy all the usual requirements for approval prior to marketing authorization. The main criteria for authorization are quality, efficacy and safety. Safety for humans both operators and consumers is crucial for the approval decision. The impact of the aquaclture industry on the prevalence of human pathogens resistant to important antimicrobials is mostly unknown and determining such impact is problematic for a variety of reasons (MacMillan, 2001). Issues such as the environmental fate and impact, the probability of resistance transfer, and the probability of human exposure have to be considered.

There is a significant cost to securing the necessary information to allow a Veterinary medicinal or immunological product to be authorized on the EU market. Since food fish are husbanded in ways to ensure minimal requirement for such therepeutics, and the value of the single animal is low, often the market size for such products does not justify the manufacturer investing in the cost of licensing. Both national regulatory agencies and the EMEA have made special arrangements such as simplified procedures for minor species or the application of the “cascade” principle to attempt to address this problem, but Salmonids are considered as major species and the cascade mechanism has been used in a limited way because of the difficulties in extrapolating between different fish species, and from terrestrial animals to fish. In fact the number of authorized VMPs is at the moment extremely low. It is important to consider that absence of an authorized VMP might favour the illegal usage with severe consequences for human health, animal health and the environment.

Table 8 **Veterinary Medicinal Products authorized for use for Atlantic salmon in 2008.**

	Antibacterial	**Antiparasitic**	**Antifungal**	**Anesthetics**
Czech Republic	flumequine for oral solution,			
Finland	benzalkonium chloride, formaldehyde, chloramine, orimycin, potassium chloride	formaldehyde, emamectin benzoate	formaldehyde	benzocaine
France	flumequine oxolinic acid trimethoprim+sulfadiazine	none	none	none
Greece	trimethoprim+sulfadiazine flumequine powder oxolinic acid oxytetracycline			
Ireland	oxytetracycline	emamectin benzoate, teflubenzuron, cypermethrin, teflubenzuron[a], deltamethrin[a]		MS222
Norway	flumequine oxolinic acid oxytetracycline florfenicol sulphadiazine + trimethoprime	cypermetrin, deltametrin, diflubenzuron, teflubenzuron, praziquantel	bronopol	metacaine benzocaine
Sweden	flumequine, oxolinic acid, oxytetracycline florfenicol			metacaine, benzocaine
United Kingdom	oxytetracycline florfenicol trimethoprime + sulfadiazine amoxycillin	cypermethrin azamethiphos emamectin benzoate teflubenzuron	bronopol	MS222

Source: Data collected by questionnaire at the consultation meeting (EFSA advisory forum and stakeholders representatives) on Animal Welfare aspects of Husbandry Systems for Farmed Fish held on 4 March 2008 in Parma.

Also, vaccines which are worth registering in very large markets such as Norway or Chile, are not so easily justified in the smaller EU industries where registration costs are higher and emergency licensing procedures such as are readily used in Norway do not seem to be so available or financially attractive in the EU.

Another welfare constraint which is currently emerging is the trend towards ‘Organic’ salmon production. This requires, *inter alia*, that only a limited range of treatments can be used. One major disadvantage is that generally certain drugs such as antibiotics can only be used on a single occasion, or the fish lose their organic status. This can be most disadvantageous to fish health if in the course of a two year life cycle two separate bacterial incidents occur. Similarly anti-parasitic treatments may have to be used, but would be forbidden under ‘organic’ certification schemes, even when the fish are in significant distress. The economic cost to a farmer of losing the ‘organic’status for a crop in the latter stages of production is such as to cause severe pressures between economics, ‘organic correctness’ and welfare.

6.8.2. Vaccination

As with any animal husbandry system, the intensification of fish farming has inevitably resulted in the emergence of disease problems, in particular of diseases of infectious origin. Since the establishment of fish farming as an industry, antimicrobials have been used for “fire fighting” of infections in order to keep disease problems in aquaculture at an acceptable level. In the longer term, however, such usage is never a sustainable option, and while initially, considerable volumes were used, the level of antibiotic usage for control of infectious diseases has been greatly reduced (Fig 20), due to better husbandry methods, selective breeding for disease resistance, and particularly, due to the introduction of vaccines into the major sectors of farmed fish production (Hastein et al., 2005; Berg et al., 2006a).

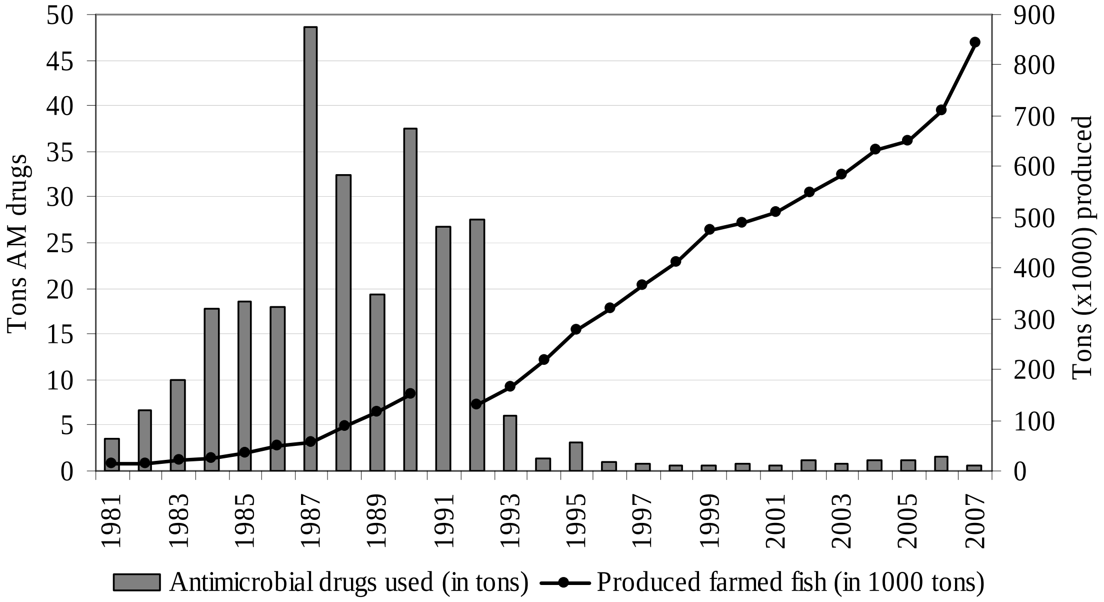

Figure 20. **Sales, in tonnes of active substance, of antimicrobial drugs for use in farmed fish in Norway versus produced amounts of farmed fish in the period 1981-2007** (Grave et al., 1996)(Kari Grave, unpublished data)

In Scottish farms 79 out of 135 sites in production used vaccination in 45.5 million fish during 2006. Vaccines were used to provide protection against furunculosis and in some sites against Enteric Red mouth, Infectious Pancreatic Necrosis and vibriosis. Vaccination is usually carried out at the pre-smolt stage by intraperitoneal injection (FRS, 2006).

The principles in vaccination of fish are the same as for terrestrial animals and all teleost fish possess immunological memory and specific cell mediated and circulating antibody, though both are temperature related in their speed of response and fish only produce macroglobulin antibodies (gamma M) (Ellis, 2001). They do not possess lymph nodes and the processing of antigens and antibody production occurs principally within the haemopoietic tissues of the spleen and kidney, and is especially associated with pigmented areas, the melano-macrophage centres, which are believed to be analogous to germinal centres in higher animal lymph nodes (Agius and Roberts, 2003).

In fish, killed vaccines (bacterines) are generally used and are based on growth of a given pathogen in culture followed by inactivation, usually by means of formalin. They are usually based on whole cell proteins. The first vaccines against classical vibriosis (*Listonella anguillarum*, previously *Vibrio anguillarum*) and coldwater vibriosis (*Vibrio salmonicida*) in Atlantic salmon were based on this principle. Fish may be exposed to killed vaccines by immersion, as a component of the diet or by injection. The majority of fish vaccines are, of necessity, applied by the injection route. In welfare terms the other routes are preferable, but, in most cases protection is limited unless injection, along with an adjuvant, is the route of administration.

Attenuated vaccines for viral infection are based on virulent virus that has been made avirulent *in vitro* through several passages in cell-culture prior to use. Attenuation is performed in order to weaken or eliminate the virulence without losing its immunogenicity. Attenuated vaccines usually give a better protection than killed vaccines but in fish, in particular, there is always considerable concern that the attenuated virus might mutate and resume its virulent state. Currently there are no attenuated virus vaccines available.

Recombinant vaccines are based on the principle that genes of pathogens that code proteins responsible for stimulating an immune-response in fish may be introduced to another organism (bacteria) that then will produce significant volumes of so-called recombinant proteins to be used in vaccine production. DNA viruses work on the principle that single genes for a specific protein of a pathogen, introduced into the host’s muscle, incorporates the gene and produces pure immunogenic protein of the pathogen, stimulating a strong host response. Although experimentally DNA virus technology appears to work well in fish, currently only one DNA vaccine is in commercial use, against infectious haemopoietic necrosis, in Atlantic and Pacific salmon in Canada (Garver et al., 2005; Lorenzen and LaPatra, 2005). Although they show considerable promise in terms of efficacy, there are still concerns regarding the development of immunological tolerance, the development of autoimmune diseases, and possible increased frequency in mutation (Gudding, 2000).

Adjuvants are widely used in vaccines to increase and prolong the immunogenic effect of the antigenic components of a vaccine. The addition of adjuvants in fish vaccines is necessary when antigens are characterised by a low degree of immunogenicity or in most of the cases to enhance the immune response to induce an early, strong and long lasting immunity. In fish vaccines, although aluminium hydroxide adjuvants may be used on occasion, the most frequently used adjuvant is an oil adjuvant (incomplete Freund’s adjuvant). Oil adjuvants are emulsions of compounds such as saponins or mineral oils containing one or more detergents, and sometimes salts. The types of emulsion include oil in water emulsions and water in oil which cause the most intense local reaction. The water in oil emulsion causes a localised chronic inflammatory response at the site of injection, trapping the antigen and ensuring longer exposure to the macrophage and lymphoid elements of the immune response to it. In accordance with the Note for Guidance on the use of adjuvanted Veterinary Medicines from the CVMP – EMEA (EMEA, 1998) the ideal adjuvanted vaccine is safe for the treated animals, does not cause clinical or local reactions or allergic reactions and is safe for consumers. Unfortunately such an ideal adjuvanted vaccine is not available and the guidelines indicate that some limited local and systemic reactions have to be tolerated and a risk /benefit analysis has to be carried out with account being taken of animal welfare, the target species and the type of the antigen. Table is a summary of vaccines available for Atlantic salmon in several EEA countries.

Table 9 **Authorised Veterinary Immunological Products for Atlantic salmon**

Country	Vaccines
Czech Republic	Furunculosis (an emulsion for injection) Furunculosis (an aqueous suspension)
Finland	Furunculosis and vibrosis (emulsion for injection) Furunculosis (an aqueous suspension) Vibrosis (water-based suspension for immersion or injection)
France	Furunculosis (an emulsion for injection) Furunculosis (an aqueous suspension)
Greece	Enteric Red mouth Vibrosis
Ireland	Furunculosis + Vibriosis (an emulsion for injection) Furunculosis (an emulsion for injection) Enteric Red mouth Furunculosis (an aqueous suspension) Vibrosis (immersion & injection) Furunculosis + IPNV (an emulsion for injection)
Norway	IPN Classical vibriosis Coldwater vibriosis PD Furunculosis Ulcer winter disease
Sweden	duovaccin for furunculosis/classical vibriosis
United Kingdom	Furunculosis (an emulsion for injection) Furunculosis + IPNV (an emulsion for injection) Furunculosis + Vibriosis + Coldwater vibriosis (an emulsion for injection) Furunculosis (an aqueous suspension) Pancreas disease virus (an emulsion for injection)

Source: Data collected by questionnaire at the consultation meeting (Members states and stakeholders representative) on Animal Welfare aspects of Husbandry Systems for Farmed Fish held on 4 March 2008 in Parma.

6.8.3. Methods of Vaccination (vaccine application)

In most farmed species, where vaccines are employed they are given parenterally route, since adjuvants are usually required and this generally precludes other routes. Vaccination cannot be used in very small fish which are not yet fully immunocompetent, or able to tolerate the volumes of antigen necessary

Vaccination by injection is generally into the peritoneal cavity, but in potential brood fish, the adhesions induced by the adjuvant produce major clinical effects on the developing ovaries and testes and, significantly, limits fecundity. In such fish vaccination is usually into the dorsal median sinus, which renders them unsuitable for human consumption. Vaccination can be done manually or mechanically. According to the NIVA Report concerning freshwater Atlantic salmon production in Norway, 67 % of the fry were vaccinated manually and 33 % mechanically (NIVA, 2007).

Immersion vaccination, where it is feasible, may be carried out by direct immersion or by hyper-osmotic infiltration by treating the fish in hypertonic saline prior to or during the vaccination procedure, or by the so called “shower” method in which the vaccine is sprayed onto the fish. The immersion method may induce an effective immune response in fish and an advantage of the method is that a large number of fish may be vaccinated at the same time with a minimum of handling. It cannot however be used with multivalent vaccines and even where the system lends itself to use of immersion vaccination, higher dose levels required means that for economic reasons it is only economically feasible with very small fish.

Incorporation of vaccines within the feed would be considered, *a priori*, to have great advantages in that it can be administered to the fish without any handling stress. It depends however on how much food the individual fish consume, and most vaccines are denatured by the digestive tract or are poorly absorbed, so special methods of manufacture are necessary. Although in principle an ideal method, it is rarely used (Sommerset et al., 2005; Berg et al., 2006a).

6.8.4. Welfare aspects of vaccination

The most important effect of vaccination in fish is that, provided other factors such as husbandry and welfare are adequate, it prevents disease outbreaks, reduces mortality considerably and reduces the use of medicinal products. Where vaccination is effective, few fish will suffer from the disease it protects against, and the environmental loading of such pathogens is also reduced for other fishes, in the absence of outbreaks. In the case of bacterial diseases, where vaccination has had the greatest effect, introduction of vaccination has dramatically reduced the use of antimicrobials and also modified the multiple disease resistance patterns of such pathogens, which were emerging

Although, vaccination is proven effective in protection against many serious fish diseases, and this undoubtedly represents a major welfare benefit, there are also certain disadvantages to be considered (Midtlyng et al., 1996; Speiberg, 2003). These are:

- Handling stress at vaccination
- Growth retardation

- Deformities in the vertebral column
- Adhesions in the peritoneal cavity

Stress associated with vaccination relates to the distress induced by the process of crowding and catching, the stress of anaesthesia, and the pain associated with the post-vaccination reaction.

These are all very limited in the processes involved in oral or immersion vaccination, but where an adjuvanted vaccine is given by injection they may be considerable. Recently the development of S0 salmon smolt production has required vaccination of parr at high summer temperatures, 19-21 °C, where mortality from stress related problems can be considerable. The use of stress modulation by the use of feeds containing exogenous chaperone (heat shock protein) stimulation has shown encouraging results that could also apply to other stressful situations for fish. There is considerable evidence from breeding companies (Sørum and Damsgård, 2004)(Guy pers com) that unvaccinated salmon consistently gain up to a kilo more than their vaccinated peers in the same time period to harvest under the same conditions. This is a considerable growth penalty and since poor growth is generally considered a welfare indicator, suggests that the serious growth limiting effects of the current generation of oil adjuvanted vaccines is of welfare significance.

There are a number of different causes of spinal deformity. (Vagsholm and Djupvik, 1999) have shown that the time of vaccination and particularly in S0 fish has a significant effect on the subsequent development of one type of post-smolt deformity which was, until recently, the commonest form (Sullivan et al., 2007b).

The efficacy of water in oil adjuvants depends for its activity on stimulating a chronic inflammatory response at the site of injection of the vaccine, which holds the antigen *in situ* and also attracts into the area macrophages and lymphocytes as well as stimulating an enhanced blood supply to ensure maximal uptake of the antigen by the host (Ellis, 1988; Mutoloki et al., 2006a; Mutoloki et al., 2006b). Without such an inflammatory response vaccines against many fish bacteria, such as the inactivated furunculosis vaccine (European Pharmacopeia, 01/2005:1521) in particular, are very poor. In addition, the essential endotoxin antigens of the aeromonad and vibrio bacteria are among the most dangerous fish pathogens being highly necrotoxic and aggressive.

The inflammatory peritonitis that they evoke is generally considerable and causes adhesions to develop within the peritoneal cavity, e.g. attaching visceral and parietal peritoneum, the formation of ligatures around viscera and attaching them to the abdominal wall (Poppe and Breck, 1997). The degree to which such adhesions form is dependent on many variables, but they are an essential component of the stimulus to immunity. Vaccine manufacturers make efforts to limit them, and some progress has been made using less aggressive oils not only for welfare reasons but also because of the growth penalty and the processor resistance they invoke, leading to serious financial losses. A classification scheme for intra-abdominal lesions, known as the Speilberg scale (Midtlyng et al., 1996) has been used by vaccine manufacturers and regulatory agencies to classify associated lesions when animal efficacy testing of vaccines is performed

All chronic inflammatory responses in fish ultimately lead to the melanisation of the tissue and its contraction as collagenous scarring develops (Agius and Roberts, 2003). The melanisation is a serious quality problem but the contraction may also cause constriction of the gut and other organs. Peritoneal adhesions are, therefore, the most serious welfare issue in relation to the use of injectible vaccines. However, there is little doubt that the use of such vaccines, since their commercial introduction in the US in 1987, has transformed the ability to control serious, often lethal diseases. Nevertheless, there is strong justification for seeking alternative methods of inducing protective immunity against these serious diseases to reduce such severe side effects while retaining their efficacy.

Apart from the nature of the vaccine itself, there is now a considerable amount of field evidence that the husbandry conditions of the fish can affect the degree to which vaccinal lesions develop**.** These include the size of the dose (i.e. volume rather than concentration) the size of the fish, the temperature at the time of the vaccination and a variety of environmental and husbandry factors prior to, during and after vaccination.

In Atlantic salmon, the risk for lesions is reduced if the size of the fish is at least 70 g and the water temperature is 10 °C or below. Injection of vaccines without adjuvants may however be carried out in fish down to 10 g (Gudding, 2000). Nevertheless, improved results from both welfare and vaccine effectiveness are achieved when fish are larger (before smoltification) and also low water temperatures at the time of vaccination (Berg et al., 2006b).

6.8.5. Biosecurity

The biosecurity concept covers implementation of a set of programmes and procedures preventing the entry, establishment or spread of unwanted pests and infectious disease agents in people, animals, plants or the environment. Biosecurity is the state of having applied appropriate measures to prevent or limit the possibility of pathogens entering populations from an extraneous source. It may be applied at various levels: international, national, region, farm and even between particular holding facilities. Biosecurity measures involve disease monitoring, border controls, as well as national and international controls, stock and equipment movement controls, disinfection, husbandry disciplines and good record keeping. A particular requirement, often recognised solely in the breach, is disinfection of transportation equipment both before and after transportation of fish (Danner and Merrill, 2006). Although these are increasingly being applied and by preventing disease outbreaks have significant welfare significance, currently, they are hindered in many areas, by a lack of understanding of the principles or awareness, lack of enforcement, and a failure to understand the risk basis upon which they are applied. Also the degree of discipline they require in their application is somehow inimical to many farmers. Enhancement of biosecurity can only be introduced following direct example of benefit after a serious disease outbreak. Increasing awareness of the risks associated with the movement of live fish, internationally, including aquarium fish, has led to concern for improvements in biosecurity at international and national level, at farm level there is still great need for training and establishment of robust biosecurity arrangements that will be both applied and monitored. Currently, however, there is a lack of adequate information on the efficacy of the various disinfectants used in terms of the fish pathogens and, in particular, the toxicity of many of the disinfectants used both in relation to the fish and the environment. A start has been made to resolving these issues (Scarfe et al., 2006; Graham et al., 2007) but inadequate knowledge and application of biosecurity is still a significant factor in the overall assurance of welfare in farmed species.

6.9. Mortality

Council Directive 2006/88/EC contains obligations to report "increased mortality". At the moment most farms do not currently have any formal means to differentiate between expected mortalities and unexpected or increased mortalities, although this is a feature of some of the larger companies and aids biosecurity monitoring and medicines control as well as advanced mortality awareness. The presence of a named veterinary surgeon and regular and detailed veterinary audit are important to the management of disease in the aquatic environment, just as in terrestrial conditions, to support welfare as well as health. Mortalities of fish during the production cycle can result from a variety of causes, including, disease, damage, predation and adverse environmental conditions. Since any population of animals suffers from mortalities it would be unreasonable to aim for zero mortality (NB human mortality in Europe is approximately 1 % of the population per year). At present there are limited data on what levels of mortality are experienced in the various farming systems or what levels of mortality might be considered acceptable for the various farming systems and life stages. Very poor welfare (e.g. disease, poor growth and mortalities) is not cost-effective for the farmer, so even farms that have relatively poor fish welfare have found a balance between welfare and productivity. However, in many cases high or increasing mortalities are an indication of disease problems with serious economic and welfare implications. At present many farms rely on the experience of the farm manager to decide when mortalities require additional action. This is not a simple task since mortalities vary over time depending on factors such as life stage, temperature, farming system, presence of endemic diseases and others.

7. Risk assessment

7.1. Introduction

Problems of poor welfare in farmed salmon are generally the consequence of animal environment changes resulting from management or production factors as well as environmental, genetic and disease factors and their interactions. Presently there are no standards for animal welfare risk assessment, but previous studies exist where risk assessment for animal welfare has been explored (Anonymous, 2001)(EFSA, 2006). In the following the risk assessment terminology in animal welfare is introduced. It would be useful to evaluate benefits as well as risks in this analysis. However, since most of the scientific evidence on salmon welfare that is available refers to adverse effects, this is just a risk analysis. In some places, absence of a beneficial effect is included as a risk.

Risk assessment is a systematic, scientific-based process to estimate the magnitude of and exposure to a hazard impact and include 4 steps: hazard identification; hazard characterisation; exposure assessment and risk characterisation.

In food risk assessment terminology (*Codex alimentarius*), a hazard is a biological, chemical or physical agent in, or condition of, food with the potential to cause an adverse health effect. The risk is a function of the probability of an adverse health effect and the severity of that effect, consequential to a hazard(s) in food.

Making a parallel to the *Codex alimentarius* risk assessment methodology, a hazard in animal welfare risk assessment is a factor with a potential to cause negative animal welfare effect (adverse effect).

A risk in animal welfare is a function of the probability of a negative animal welfare effect and the severity of that effect, consequential to the exposure to a hazard(s). The probability of a given target population to be exposed to a particular hazard was scored as frequency of exposure. Once exposed, the proportion of the population affected will vary and was assessed as the likelihood of effect. Consequences of exposure have been scored by severity of the effect in the individual and duration of the effect.

While hazards and risks usually relate to negative welfare impacts, the risk assessment approach could be also extended to include positive welfare consequences (resulting in risk-benefit analysis). This aspect was not taken into account in this assessment.

The degree of confidence in the final estimation of risk depends on the uncertainty and variability

Uncertainty arises from the evaluation and extrapolation of information obtained from epidemiological, experimental, and laboratory animal studies and whenever attempts are made to use data concerning the occurrence of certain phenomena obtained under one set of conditions to make estimations or predictions about phenomena likely to occur under other sets of conditions for which data are not available. Uncertainty also arises from incomplete knowledge. Uncertainty can be evaluated by carrying out further studies to obtain the necessary data or quasi-formally by using expert opinion or by simply making a judgment. Uncertainty could be treated formally in conducting more studies or quasi-formally in using expert opinions or informally by making judgment.

Variability is a biological phenomenon (inherent dispersion) and is not reducible. However, it is not always easy to separate it from uncertainty. Uncertainty combined with variability is generally referred as total uncertainty.

7.2. Steps of risk assessment

For risk assessment of welfare of farmed Atlantic salmon the different production systems, as well as the different life stages were identified.

The different life stages cosidered were: eggs and alevins, fry, parr, smolt, ongrowing and broodstock (Table 10). The different production systems considered are summarised in

Table 10. **Life stages of farmed Atlantic salmon**

	Duration	Average weight (g)	Estimated % of the total life cycle
Broodstock			
Eggs	480-510 d/d		5
Alevins	780 -810 d/d		10
Fry		0.16 –1	10
Parr		Up to 15	10
Smolt		Up to 70 – 90	5
Ongrowers		Between 4000 to 5000	65

Table 11. **Production systems by life stages**

PRODUCTION SYSTEMS	PRODUCTION LIFE STAGES						
	Eggs	Alevins	Fry	Parr	Smoltification	Ongrowing	Broodstock
Trays	**X**	**X**					
Cylinders	**X**						
Tanks (recirculated)			**X**	**X**	**X**		
Tanks (flow-through)			**X**	**X**	**X**		**X**
Freshwater cages				**X**	**X**		
Sea-water cages						**X**	**X**

7.3. Hazard identification

The aim of this step is to identify causes or factors that affect animals' needs and that have a potential to change the animals' welfare. Although (both negative or positive changes) can be accessed only negative impacts were considered.

A list of potential categories of hazards to fish welfare and health of Atlantic salmon was drawn up. The identified hazards were grouped in different categories such as abiotic, biotic, genetic, management and disease. The hazard tables referred to the different life stages of the fish as well as to the different types of production systems.

Different factors that may affect the welfare of farmed fish are for example, water temperature or stocking density. Those factors may also more broadly be described as conditions that may have a direct impact on the welfare and health of salmon. Subsequently, hazard (a detrimental factor) identification (clinical signs and physiological changes), its character, and the consequences of it occurring, are all important issues to be taken into account when making a Risk Assessment.

The list of potential hazards was discussed by experts in the field (Table 12).

Table 12. **Factors or hazards**

HAZARD IDENTIFICATION	HAZARD SPECIFICATION
ABIOTIC	
Water flow	too low / too high
Light	period / intensity
Water depth	
Water temperature	rapid change/ high /low
Shape of tank / distortion of cage	
Suspended solids	
Storm impact / water vessel impact	
Salinity	too high / fluctuations
pH	too high or low in combination with Al
Oxygen content	too low
Metals other than Al	too high, pH dependent
Environmental complexity	
Carbon dioxide content	too high
Ammonia content	too high, pH dependent
Aluminium content	too high, pH dependent
BIOTIC	
Stocking density	high/low
Intra-specific interaction	
Predators	
Other invasive species (e.g. algae)	
Mixing fish from different origins	
Inter-specific interactions	
FEEDING	
Nutrients	Surplus/deficiency
Not typical salmon diet (e.g. vegetable protein)	

Lack of food	short time/long time
Dietary toxins	
Feed additives for fish (e.g. glucans)	
MANAGEMENT	
Sorting of fish	Frequency /Methods
Lack of staff training	
Lack of biosecurity	
Impact of lack of monitoring	Health /Biomass
Handling	
Genetic Selection	Growth/Disease
DISEASES	
Furunculosis	
Winter ulcers	
Saprolegnia infection	
Infectious pancreatic necrosis	
Infectious salmon anaemia	
Sea lice infestation	
Pathology as a result of jellyfish	
Eye lesions	

Production factors (hazards) could have direct effects on animal or indirect effects that change the animals' environment in ways that affect their abilities to fulfil their basic needs which can also lead to animal welfare problems Due to the already complex tables we concentrated on single factors without interactions and on the negative effects. However, since production factors can interact and welfare problems are generally due to multiple exposures to different factors, any positive or negative interactions with other factors should be reviewed. Interactions and positive effects are described in the text if deemed necessary.

7.4. Hazard characterisation

The objectives of this step are:

- to examine and describe the consequences of an exposure to one or several hazards; and
- to assess the relationship between the level of the hazard in terms of frequency and duration and the likelihood and magnitude of the adverse effect.

The severity of adverse effect is described and scored in the following ways. They were scored according to scientific evidence of the level of physiological and behavioural responses.

Table 13. **Severity of adverse effect**

Evaluation	Score	Explanation
Negligible	0	No pain, malaise, frustration, fear or anxiety as evidenced by measures of the normal range of behavioural observations, physiological measures and clinical signs for >95% of the species or strain/breed
Mild	1	Minor changes from normality and indicative of pain, malaise, fear or anxiety
Moderate	2	Moderate changes from normality and indicative of pain, malaise, fear or anxiety
Substantial	3	Substantial changes from normality and indicative of pain, malaise, fear or anxiety.
Severe	4	Extreme changes from normality and indicative of pain, malaise, fear or anxiety, that if persist would be incompatible with life.

The duration of the adverse effects, i.e. the consequences of the hazard, were scored on a 0 to 100% scale considering the rest of the life of the fish and not just the particular life stage mentioned.

A problem in scoring the “duration of adverse effect” arises when the animal dies as a consequence of a particular hazard. This can be described in two different ways it depends on how the concept of “life time” is considered.

Death may not be considered as a primary welfare problem, If the adverse effect is fatal then the duration before death (i.e. an animal would not be susceptible to suffering) would be the key welfare issue, even though death itself might indicate a prior welfare problem. Life time can be judged as the “potential life time”: if an animal immediately dies of a certain hazard, than the duration of the effect over the potential life time is very short. However, life time can also be the “real or actual absolute life time”: if the effect of the hazard over the real life time of that particular animal is considered than the duration would be 100%. In the case of the fish welfare, it was decided to score the duration of the effect over the “potential life time” of the animal, but indicating if a hazard was so severe that it could lead to instant death.

A hazard is not only described by the magnitude of its adverse effect, but also by the likelihood of the adverse effect occurring which equates to the proportion of the population affected.

Table 14: **Likelihood of adverse effect occurring (i.e. proportion of population affected)**

Evaluation	Score	Explanation
Negligible	0	The event would almost certainly not occur
Extremely low	1	The event would be extremely unlikely to occur
Very low	2	The event would be very unlikely to occur
Low	3	The event would be unlikely to occur
Moderate	4	The event would occur with an even probability
High	5	The event would be very likely to occur

The uncertainty value is an indication of the type of information available, whether there are different studies with differing conclusions, but also whether the scientific information has been published or not. The uncertainty value (low, medium and high) gives an estimate of how much confidence one has in the information. The qualitative assessment of uncertainty for each assessment according to the availability of scientific evidence was also scored (Table 15).

Table 15: **Uncertainty**

Evaluation	Score	Explanation
low	1	Solid and complete data available: strong evidence in multiple references with most authors coming to the same conclusions (e.g. in a meta-analysis).
medium	2	Some or only incomplete data available: evidence provided in small number of references; authors' conclusions vary.
		Solid and complete data available from other species which can be extrapolated to the species considered.
high	3	Scarce or no data available: evidence provided in unpublished reports, or based on observation or personal communications; authors' conclusions vary considerably

7.5. Exposure Assessment

Exposure assessment is the qualitative, semi-quantitative or quantitative evaluation of the probability of a specific scenario of exposure.

The scenario here takes into account the frequency and duration of exposure to one or several hazards during the life stage of the fish. First of all the frequency of exposure was considered (Table 16), that is, how often a particular hazard would be encountered.

Table 16: **Frequency of exposure**

Evaluation	Score	Explanation
Negligible	0	The exposure would almost certainly not occur
Extremely low	1	The exposure would be extremely unlikely to occur
Very low	2	The exposure would be very unlikely to occur
Low	3	The exposure would be unlikely to occur
Moderate	4	The exposure would occur with an even probability
High	5	The exposure would be very likely to occur

The duration of the hazard for a given life stage was described, that is, for how long the hazard would occur and for how long it would last within that life stage of the fish. For instance a predator attack could only last a short period of time while a temperature change could last for much longer. The duration of the hazard during a life stage will be indicated on a value from 0% to 100%. However, to indicate that certain hazard would lead to instant death (and therefore some risk scores may be counterintuitive to experience, because large mortality is also considered a welfare problem) and to ensure comparability with other risk assessments, this was noted next to the risk score column.

The uncertainty of the information was judged as well using the criteria as above.

Experts were asked individually to fill in the tables, based on current scientific knowledge and published data. Due to the low number of experts in relation to the large number of tables on average two experts filled in each table. Their scores were compared and if no consensus was found between their values, they were discussed in the working group, taking into account the published literature. In numerous cases this appeared to be a problem of different scaling of the risk scores or interpretation of the risk factor. This was improved in discussions among the experts. These scores served as a basis for the overall risk scoring.

7.6. Risk characterisation

Risk characterisation integrates hazard characterisation and exposure assessment into a risk score. In the case of the fish welfare risk assessment that included a semi-quantitative risk score for each life stage in all of the production systems employed during this life stage.

This step aims to estimate the likelihood of occurrence of the adverse effect in a specific production system at a specific life stage of the fish. It aims to give information to the risk manager to evaluate a specific situation regarding maximising good welfare. The risk estimate was calculated for each hazard, and expresses its animal welfare burden in the considered population.

Risk score = (severity of adverse effect)*(duration of the adverse effects) *(likelihood of adverse effect)* (frequency of hazard)*(duration of hazard)

The scores of frequency of hazard, severity and likelihood of effect were standardized to give even weighting to the scores (frequency of hazard /5, severity / 4, and likelihood of hazard / 5). Duration of hazard and duration of effect were divided by 100. Eventually, the risk score was multiplied by 100 to make it easier to read.

Interactions of the hazards cannot easily be considered with this approach and each hazard is looked at individually.

As exact quantitative figures were not available due to the limited amount of data of the hazards on adverse welfare effects, a semi-quantitative risk assessment has been used. Furthermore, the risk assessment was mainly based on expert opinion. The methodology used does not give a precise numerical estimate of the risk attributed to certain hazards. However, the output can be used to rank the problems and designate areas of concern, as well as provide guidance for future research.

Uncertainty scores could not used in the risk estimate directly but are indicated in the final column to give an idea of the overall certainty of the data. This can also point to areas where more research is needed to give more certainty to the scientific data. Two uncertainty scores are in the original tables. To simply the presentation they were summed up in a single figure according to an uncertainty classification matrix Table 17.

Table 17. **Combined uncertainty scores**

		Uncertainty (exposure assessment)		
		High (3)	Medium (2)	Low (1)
Uncertainty (Hazard characterization)	High (3)	High (3)	High (3)	High (3)
	Medium (2)	High (3)	Medium (2)	Medium (2)
	Low (1)	High (3)	Medium (2)	Low (1)

The risk score gives a ranking that allows looking at the importance of some of the risks. This allows predominantly the comparison of hazards in different production systems at the same life stage. Risk scores have been summed to show this comparison between the different production systems.

All values agreed by the experts of the WG for the assessment of the various identified factors in different production systems for the various life stages of farmed Atlantic salmon.are predated in tables in Appendix B. The tables were arranged in a way to cover the four essential steps of risk assessment such as hazard specification, hazard characterisation and exposure assessment.

7.7. Discussion of risk assessment

The risk scores based on expert advice were used to compile a risk ranking by category such as abiotic or biotic to obtain an idea which hazards are the more important for each life stage in the various production systems considered, and also to enable the comparison of the different production systems.

7.7.1. Welfare risks associated with eggs incubation

Only hazards belonging to the abiotic factors category were assessed. Welfare impact on subsequent life stages was considered. The adverse effect considered was the development of deformities which would lead to life long poor welfare consequences. The ranking by order of the highest risk scores is summarised in (Table 18).The combined uncertainty scores were high for all abiotic factors.

No considerable differences between the 2 production systems, cylinders and trays, were found with regards to potential risks to welfare.

Table 18. **Welfare risks ranking - Eggs**

	Trays	**Cylinders**
Abiotic	Rapid change of water temperature	Rapid change of water temperature
	Too high water temperature	To high water temperature
	Too high water flow	Too high water flow

7.7.2. Welfare risks associated with farming of Alevins

Only hazards belonging to the diseases and abiotic factors categories were assessed in a single system, trays. The ranking by order of the highest risk scores is summarised in Table 19. The diseases considered for this life stage constituted a high risk of poor welfare since death is usually preceded by severe pathological alterations. Environmental complexity and lack of physical support, was considered an important risk for alevins in trays and although a low exposure was assessed, its adverse effects were considered severe as it could affect the entire life of the salmon. The combined uncertainty scores were high for all abiotic factors and low for diseases.

Table 19. **Welfare risks ranking - Alevins**

	Trays
Disease	*Saprolegnia*
	IPN
Abiotic	Rapid change of water temperature
	Environmental complexity
	High temperature

7.7.3. Welfare risks associated with farming of Fry

The welfare risks associated with diseases constituted high risk of poor welfare in particular conditions such as eye lesions that may continue in other subsequent life stages .For the abiotic hazards category, water oxygen content constituted the most important welfare risk but in recirculated tanks high CO_2 was assessed as the limiting factor. The adverse effects of stocking density were found to be high as well as interspecific interaction (aggression). High stocking density is closely linked with deterioration of water quality but the aspects of interaction are difficult to disentangle. For the feeding, an unbalanced diet and lack of food over long periods were the higher score hazards. Lack of biosecurity and insufficient grading as well as lack of staff training were ranked highest in the husbandry factors category. The combined uncertainty scores were low for both diseases and husbandry factors. The ranking by order of the highest risk scores is summarised in Table 20.

Two production systems were considered, tanks flow-through and tanks with recirculation. For the fry, recirculated tanks showed overall a smaller risk score due to the higher level of biosecurity and reduced risk of disease introduction. However abiotic factors could constitute a greater risk for welfare than in flow-through tanks.

Table 20. **Welfare risks ranking - Fry**

	Tanks flow through	**Tanks recirculated**
Diseases	Eye lesions	Eye lesions
	Furunculosis	Furunculosis
Husbandry	Lack of biosecurity	Lack of grading
	Lack of grading	Lack of biosecurity
	Lack of Staff training	Lack of Staff training
Abiotic	Too low water oxygen content	High carbon dioxide content
	Too low water flow	Too low water oxygen content
	Too high water temperature	Too low water flow/ Water pH too high or low in combination with Al
Feed	Unbalanced diet	Unbalanced diet
	Feed deprivation (long term)	Feed deprivation (long term)
Biotic	Aggression / High stocking density	Aggression / High stocking density

7.7.4. Welfare risks associated with farming of Parr

The welfare risks associated with chronic diseases such as as eye lesions but also IPN infection were important hazards. For the abiotic hazards category, reduced water oxygen content, low water flow and too high a temperature were ranked highly, as for parr. High carbon dioxide levels and high ammonia content were assessed as a risk in recirculated tanks, but much less so for the flow-through tanks and cages. For cages light period and rapid changes in water temperature were more of a risk than for the tanks. High stocking density was an important risk as well as aggression but also low stocking played a more important role than for fry. An unbalanced diet, lack of food over long periods and nutrient deficiency were the highest hazards in the category of feed and feeding. Lack of biosecurity, insufficient sorting, lack of staff training and impact of lack of monitoring were the top hazards for the management issues for all production systems. The ranking by order of the highest risk scores is summarised in Table 21.

Three production systems were considered, tanks flow-through, tanks with recirculation and freshwater cages. Flow-through tanks and cages showed a higher risk due to lower biosecurity and increased risk of disease introduction. Freshwater cages can also be exposed to predators and compared with tanks there is less control of water quality. Cage culture of parr has also particular problems in relation to husbandry practices, handling and fungus control.

Table 21. **Welfare risks ranking - Parr**

	Tanks flow through	**Tanks recirculated**	**Freswater cages**
Diseases	IPN	Eye lesions	Eye lesions / IPN
	Furunculosis /Eye lesions	IPN	*Saprolegnia*
Husbandry	Lack of biosecurity	Lack of grading	Lack of biosecurity
	Lack of grading	Lack of biosecurity	Lack of Staff training
	Lack of Staff training	Lack of Staff training	Lack of monitoring
Abiotic	Too low water oxygen content	High carbon dioxide content	Too low water flow
	Too low water flow	Too low water oxygen content	Water oxygen content
	Too high water temperature	Too low water flow	High or low water pH with Al
			Water temperature rapid change/ Light period
Feed	Unbalanced diet	Unbalanced diet	Unbalanced diet
	Feed deprivation (long term)	Feed deprivation (long term)	Feed deprivation (long term)
Biotic	Aggression / High stocking density	Aggression / High stocking density	Aggression / High stocking density / Predation

7.7.5. Welfare risks associated with farming of Smolts

For smolts the high-ranking abiotic hazards were: water oxygen content too high or too low, reduced water flow and wrong light signals. In recirculated tanks high carbon dioxide content and ammonia content were the high ranking hazards. High stocking density and aggression were the top hazards in the biotic category, for the tanks low stocking density was also a significant risk. Unbalanced diet, lack of food over a long period of time and a deficiency in nutrients were at the top of the feeding hazards. Lack of biosecurity and lack of staff training and monitoring was also important for smolt. Lack of biosecurity was a more serious hazard in the cages than in the tanks. IPN and furunculosis but also *Saprolegnia* infections and eye lesions constituted a high risk. The ranking by order of the highest risk scores is summarised in Table 22.

Three production systems were considered, tanks flow-through, tanks recirculated and freshwater cages. Overall risk score of the three systems did not differ, except for increased management risks in the freshwater cages.

Table 22. **Welfare risks ranking - Smolts**

	Tanks flow through	**Tanks recirculated**	**Freshwater cages**
Diseases	IPN	Eye lesions	*Saprolegnia*
	Furunculosis	IPN	Furunculosis
Husbandry	Lack of biosecurity	Lack of staff training	Lack of biosecurity
	Lack of staff training	Lack of biosecurity	Lack of staff training
Abiotic	Too low water oxygen content	High carbon dioxide content / Too low water oxygen content	Too low water oxygen content
	Too low water flow / Light period	Too high Ammonium / water flow	Too low water flow/ Light period
Feed	Feed deprivation (long term)	Feed deprivation (long term)	Feed deprivation (long term)
	Deficiency of nutrients	Deficiency of nutrients	Deficiency of nutrients
Biotic	High stocking density	High stocking density	High stocking density
	Aggression	Aggression	Aggression

7.7.6. Welfare risks associated with farming of Ongrowing Atlantic salmon

Only sea-water cages were considered as a production system for Atlantic salmon ongrowing. Eye lesions and Sea lice infection were the most important welfare risk factors in the disease category for ongrowing Atlantic salmon. Water oxygen content, low water flow, water temperature (too high) were highest on the list of hazards for abiotic factors. Sea cages are exposed to natural non-controllable water quality and other abiotic factors so site selection and cage design characteristics are of utmost importance in determining the exposure to these hazards. Too high a stocking density and intraspecific interaction (aggression) were followed by mixing fish from different origins in the biotic factors. Sea cages are exposed also to biotic factors like toxic algae, jellyfish, which, although rare, can have serious consequences. Predators were not considered as an important risk since anti-predator control measures are usually in place. An unbalanced diet and protein replacement (vegetable protein) were top hazards for the feeding category but were less importance than for earlier life stages. Lack of biosecurity and lack of staff training were the highest risks score for the husbandry hazards category.

Table 23. **Welfare risks ranking – Ongrowing**

	Sea-water cages
Diseases	Eye lesions
	Sea lice

Husbandry	Lack of biosecurity Lack of Staff training
Biotic	High stocking density Aggression
Abiotic	Low DO Water flow High Temperature
Feed and feeding	Unbalanced diet / Vegetable proteins

7.7.7. Welfare risks associated with farming of Atlantic salmon broodstock

The duration of this life stage is complicated to define. Only a small percentage of the population is designated as broodstock (at their last year of life) and held to become mature. Only then can they really be considered separately. They also may be held for only one year or for two depending on whether they are early or late spawners in addition some farms use a single stripping while others reuse their male population. For the purpose of this RA the same life stage duration than ongrowing was considered.

A lhe lack of biosecurity was by far the most important hazard, especially for sea cages. Several hazards on the disease category were assessed in sea-water cages but not considered relevant for tanks. Handling was the second highest hazard in the husbandry category. In the biotic category intra-specific interactions (aggression), stocking density (both too low and too high) was listed, but the risk of poor welfare from a low stocking density was more important than from too high. Water oxygen content and water flow were the highest abiotic hazards and more relevant for tanks than for sea cages. For sea cages, the water salinity and the correct light period were important risks.

The highest risk for welfare at this life stage from feed and feeding was the presence of dietary toxins. The ranking by order of the highest risk scores is summarised in Table 24.

Atlantic salmon broodstock can be kept in tanks or cages, the final stages of maturation, prior to spawning can only be achieved in freshwater. Biosecurity and disease introduction risks are the more important risks in open systems such as sea cages.

Table 24. **Welfare risks ranking – broodstock**

	Tanks	**Sea cages**
Disease	Eye lesions *Saprolegnia*	Sea lice Eye lesions
Husbandry	Lack of biosecurity Handling	Lack of biosecurity Handling
Biotic	Aggression Low stocking density High stocking density	Aggression Low stocking density High stocking density
Abiotic	Too low water oxygen content / too low water flow	Water salinity

	Tank shape/ Light period	Too low water oxygen content Too low water flow/ Light period
Feeding	Unbalanced diet Feed deprivation (long term)	Unbalanced diet Feed deprivation (long term)

7.7.8. Risk associated with production systems

Overall the production system within life stages seemed not to differ very much. There were higher scores for sea cages than for the other production systems, mainly related to problems with disease. For broodstock sea and brackish cages had higher risk scores with regards to disease. Flow-through tanks had more problems with disease than recirculating tanks for abiotic factors. Overall the highest risk scores were found for disease and welfare impact of disease control measures such as side effects of vaccination across all life stages. Inadequate management followed as a risk, but with considerably lower risk scores. Biotic factors were more a risk for broodstock, and abiotic hazards i.e. mainly water quality which was a concern for all life stages.

7.8. Uncertainty

The combined uncertainty score indicates how certain the experts were about the scientific data knowledge for a particular field and whether this could be backed up with published references.

The uncertainty for certain areas was high, and this reflected the fact that expert opinion had to be used, since few data were available. Information on management issues varied between fairly certain (low uncertainty) to medium uncertainty (for alevins and fry). For feeding, experts gave a low uncertainty score. For biotic factors the whole range of uncertainty scores were given depending on each particular hazard. The uncertainty score for the impact of genetic selection on salmon welfare was high.

7.9. Data gaps

The following are some of the gaps in the data available for this analysis.

- There is insufficient information about the production systems for Atlantic salmon used throughout EEA.
- Key operational data on water quality parameters under commercial conditions is mostly not available.
- Prevalence data on Atlantic salmon diseases are not available
- Effects of many of the environmental hazards on welfare are mostly unknown although tolerance levels have been determined under experimental conditions.

APPENDICES

APPENDIX A - PRODUCTION FIGURES

The information on production data, number of farms/sites and other operational data presented in the following tables was sourced from:

- **Scotland,** "Scottish Fish Farms - Annual production survey 2006", the survey was carried out by the Fisheries Research Services (FRS) and includes responses to questionnaires sent to all companies registered with the Scottish Government. Statistics.
- **Ireland**, Official Reports (OR) produced by the Marine Institute as a result of site inspections / sampling carried out in under Council Directive 91/67/EEC
- **Norway, "**Fish farming 2005, Official statistics from Norway" censuses and surveys filled in by the farmers and collected by the Fisheries Directorate. Additional data from 2006 was available from the official web site of the Fisheries Directorate. Also "A summary of key operational data from Norwegian hatcheries for salmonide (1999/2006)" from the Norwegian institute for water research, the report sums up some key operational data from 160 norwegian hatcheries reported directly from the fish farm
- **Other countries,** results from questionnaire distributed at the consultation meeting (Members states and stakeholders representative) on Animal Welfare aspects of Husbandry Systems for Farmed Fish held on 4 March 2008 in Parma.

Table 1: **Number of companies and sites/licences in freshwater production in 2006**

	No of companies	No. of sites	No of licences
Scotland	39	135	
Norway (a)	153		227
Ireland		20	
Germany		10 (fry and parr for restocking only)	
Finland		13 (fry and parr for restocking only)	

(a) the numbers include Atlantic salmon, rainbow trout and trout production

Scotland: Since 1998 when statistics are available there has been a decrease on the no. of companies and an increase of number of sites per company. Only half of the registered sites are in production.

Table 2. **Freshwater production systems**

	Cages				Tanks Raceways				Total produced
	No of sites	Total capacity m^3	Total no. produced	Stocking density (smolts/ m^3)	No of sites	Total capacity m^3	Total no. produced	Stocking density (smolts/ m^3)	
Scotland 2006	58	365000	18700000	51	77	360000	22127000	615	
Ireland 2006	5				15				7000000
Germany					10				
Finland					10		3-5000000		
Norway									272 946 000

Scotland: The most used production system for production of smolts in freshwater are cages or tanks and raceways freshwater. In 2006 16/84 produced between 1000 -100000 smolts, 58/84 between 100 000 to a million smolts and 10 sites more than a million smolts.

Table 3. **Mortality by life stage (%), Norway 1999-2006**

	Hatching	**Start feeding**	**Production**		**First 4 weeks at sea**	
Year			**S0**	**S1+**	**S0**	**S1**
1999	3.7	6.4	5.0	6.7	2.8	2.9
2000	2.8	4.0	3.3	5.2	4.1	1.4
2001	3.2	5.4	3.8	3.4	3.3	3.4
2002	3.6	10.2	5.4	8.3	2.1	3.8
2003	5.2	3.5	7.5	11.3	2.3	6.0
2004	4.9	2.8	6.7	6.2	1.7	1.2
2005	5.3	4.8	4.0	4.8	1.1	1.3
2006	3.4	3.8	4.1	7.8	1.9	3.1
Avg. 1999/2006	3.6	5.6	4.9	6.7	2.7	3

Source: NIVA 5352-2007

Table 4. **Smolts produced and put to sea in 2006**

	Smolts produced	Smolts put to sea
Scotland	40 827 000	41 090 000
Norway	272 946 000	18 6714000

Table 5. **Smolts put to sea in Scotland farms in 2006 by age group**

	S 0	S1	S1 1/2(Smolting at approximately 18 months from hatch)
Scotland	15 578 000	23 733 000	1 779 000

Source: Scotish Fish Farms – Annual Production Survey 2006 (FRS 2006)
Scotland: The percentage of S0 smolts increased since 1994.

Table 6. **Water exchange rate (l/m^3/min) and total renewal time (min) in fresh water smolt rearing facilities - Norway**

	Water exchange rate (l/m3/min)			Total renewal (min)		
Year	average	SD	Range (min –max)	average	SD	Range (min –max)
2000	12.93	8.7	2.94-42.4	106	70	23-340
2001	12.97	2.8	8.75-18.3	79	16	54-114
2002	12.29	10.7	3.99-55.5	115	59	18-250
2003	13.20	4.1	7.5-18.5	84	30	54-133
2004	13.57	7.7	3.33-45	97	55	22-300
2005	13.78	6.7	3.33-30	90	42	22-175
2006	12.48	5.8	5.71-29.3	96	41	34-175
Avg. 1999/2006	13.79	8.9	1.88-55.5	98.8	60	18-531

(a)The data is collected from 3 smolt rearing tanks one week prior to sea transfer on each of the farms included in the survey
Source: NIVA 5352-2007

Table 7. **Stocking density (kg/m^3) and specific water consumption (l/kg fish /min) in fresh water smolt rearing facilities – Norway**

	Stocking density (kg/m^3)		specific water consumption (l/kg fish /min)	
Year	average	Range	average	Range
1999	41.3	5.5-100	0.50	0.04-3.65
2000	53.75	4-157	0.28	0.019-1.03
2001	50.29	19-97	0.30	0.16-0.87
2002	48.63	7.4-197.4	0.24	0.08-0.67
2003	44.41	7.5-71.4	0.27	0.2-0.51
2004	41.6	3.3-82.5	0.51	0.06-3
2005	41.0	3.3-76.8	0.56	0.06-3.87
2006	33.6	4.2-68.4	0.38	0.14-0.76
Avg. 1999/2006	44.4	2.7-197	0.42	0.019-3.87

(a)The data is collected from 3 smolt rearing tanks one week prior to sea transfer on each of the farms included in the survey
Source: NIVA 5352-2007

Table 8. **DO (mg/l) in freshwater in inlet and outlet and range of original measures (min-max) in freshwater smolt rearing facilities – Norway**

	DO (mg/l) (a)		Range (min-max) (a)	
Year	inlet	outlet	inlet	outlet
1999	15.3	10.7	9.8-25	6.8-14.8
2000	18.9	10.9	9.4-32	6.5-16.5
2001	15.6	9.8	8.4-23.6	6.9-13.2
2002	16.8	10.2	9.8-24.3	6-15.8
2003	18.2	8.9	12.8-27.7	6.2-10.5
2004	16.7	9.5	10.1-28	5.8-13.1
2005	15.6	9.4	10.1-26.9	5.8-10.7
2006	19.7	9.7	13-41.2	6.2-11.4
Avg. 1999/2006	16.6	10.2	8.4-41.2	5.8-16.5

(a)The data is collected from 3 smolt rearing tanks one week prior to sea transfer on each of the farms included in the survey
Source: NIVA 5352-2007

Table 9. **CO_2 (mg/l) and TAN (µg/l) in freshwater smolt rearing facilities - Norway**

	CO_2 (mg/l) (a) (b)		TAN (µg/l) (a)	
Year	average	range	average	range
2000	11.42	1.83-27.5	402.7	5-2110
2001	11.39	2.97-19.45	449.8	111-1940
2002	11.9	3.45-23.4	475.7	5-1496
2003	17.3	7.7-28.6	702.7	33-1800
2004	11.5	3.1-31.5	671.7	2-3150
2005	10.5	2.2-23.8	777.7	106-2450
2006	9.52	1.6-21.2	437.5	30-1600
Avg. 1999/2006	11.2	2.3-28.6	453	2-3150

(a)The data is collected from 3 smolt rearing tanks from 160 different farms one week prior to sea transfer on each of the farms included in the survey. Source: NIVA 5352-2007

Table 10. **Number of companies and sites in production in sea-water 2006**

	No of companies	No. of sites	Produced Tonnes
Scotland	44	252	131847
Norway	226	909	629888
Ireland		54	14000

Source: Scotish Fish Farms – Annual Production Survey 2006 (FRS 2006)
Scotland: In 2006 a total of 28 388 000 fish with a total weight of 131847 were harvested from which 115000 were harvested in year 0 (the same year than put to sea grow out) average weight of 1.8KG, 14036000 were harvested in year 1 , average weight 4.6 Kg and 14237 harvested in year 2 with 4.7 Kg average weight. The statistics show a considerable increase on the average weight of fish harvested in year 1 from 3.4 in 1995 to 4.6 in 2006.

Table 11. **Stock of live salmon (units) in net cages, Norway 2005 and 2006**

	Stock as per 1 Jan	Supplies	Delivered for sale	Loss	Stock as per 31 Dec	Loss %
2005	194032 000	160840 000	123470 000	25111 000	206292 000	7.1
2006		186 714 000		31 045 000	241 042 000	

Source: NIVA 5352-2007

Table 12. **Losses of salmon (units) in net cages by cause, Norway 2005**

	Loss total	disease	escape	other
Norway	25 094 000	19557 000	715 000	4821 000

Table 13. **Smolt survival (% harvested) Scotland, 2006**

	First years at sea	Second year	Total
2003 Input	45.7	32.3	78
2004 Input	39	36.5	75.5

Source: Scotish Fish Farms – Annual Production Survey 2006 (FRS 2006)

Table 14. **Percentage (by weight) of annual production by growth stage harvested during Scotland 1998-2006**

	1998	1999	2000	2001	2002	2003	2004	2005	2006
Input year fish	2	2	2	<1	<1	<1	<1	0	<1
Grilse	35	32	35	30	23	19	17	18	13
PreSalmon	43	34	35	39	39	37	37	34	35
Salmon	20	32	28	30	37	43	45	48	51

Source: Scotish Fish Farms – Annual Production Survey 2006 (FRS 2006)

Table 15. **Number and production (tonnes) of salmon harvested in Scotland 2006 and mean fish weight (kg)**

	Year of smolt input	Number	Production	Mean weight at harvest
Harvest in year 0 (year of input)	2006	115 000	211	1.8
Harvest in year 1	2005	14 036 000	64 099	4.6
Harvest in year 2	2004	14 237 000	67 537	4.7

Source: Scotish Fish Farms – Annual Production Survey 2006 (FRS 2006)

Scotland:. The statistics show a considerable increase on the average weight of fish harvested in year 1 from 3.4 in 1995 to 4.6 in 2006.

APPENDIX B - RISK ASSESSMENT TABLES (MICROSOFT® EXCEL FILE)

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8. Abbreviations

ADNS	Animal Disease Notification System
BKD	Bacterial Kidney disease
DO	Dissolved Oxygen
EEA	European Economic Area
EMEA	The European Medicines Agency
EU-15	The first 15 members of the European Union
EU-25	The first 25 members of the European Union
FEAP	Federation of European Aquaculture Producers
GnRH	Gonadotrophin releasing hormone
HSMI	Heart Skeletal Muscle Inflammation
IPN	Infectious pancreatic necrosis
IPNV	Infectious pancreatic necrosis virus
ISA	Infectious salmon anaemia
ISAV	Infectious salmon anaemia virus
LMG	Lower modal group
OIE	World Organization for Animal Health
PD	Pancreas disease
ppt	parts per thousand
UMG	Upper modal group
VMP	Veterinary Medicinal Product

9. Glossary

Alevin	First stage of the salmonlife-cycle following hatch: the alevin has a very limited swimming ability and is provided with nutrition by an attached yolk sac. In the wild alevins remain within the redd in which they are hatched, and in aquaculture within the container in which they are hatched.
Broodstock	A population of fish selected to provide genetic material for the next generation. In a modern breeding programme, broodstock populations are selected and isolated at the egg stage and grown through all the life stages separately from production stocks. Broodstock are maintained beyond the end of the ongrowing stage in order to reach sexual maturity.
Closed systems	A rearing system with control of inlet and outlet water, e.g. tanks, raceways or closed bags.
Crowding	The situation in which the movements or other activities of individuals in a group are restricted by the physical presence of others
Degree/days	Average temperature in degree centigrades multiplied by the number of days.

Euryhaline	Used for organisms that are capable of osmoregulating in a relatively wide range of salinities.
Eyed Stage	The stage of development of eggs during which the eye is visible.
Fry	Early life stage of salmon beginning from independence of yolk sac as primary source of nutrition and ending when fish begin move from their hatching site: the redd in the wild and hatching container in aquaculture. In aquaculture the term *First Feeding Fry* is often used to describe the stage at which fish have entered the freshwater column and begun to feed.
Grilse	An adult salmon sexually maturing after one winter in sea-water.
Hypercapnia	A condition with elevated carbon dioxide concentration in the water.
Hyperoxia	A condition with oxygen saturation above 100% of the normal atmospheric equilibrium for a given temperature and salinity.
Hypoxia	A condition with low oxygen saturation in the water.
Kelt	Female salmon that survive after spawning (in the wild most adult Atlantic salmon die) and that may migrate back out to sea. Occasionally in aquaculture kelts will be recoveed to obtain a second crop of eggs. Usually this procedure is carried out in aquaculture for restocking
Ongrowing	In salmon farming this is the sea-water stage of the life cycle, beginning at the time when fish are properly adjusted to the sea-water environment and ending at slaughter (usually 13-20 months after sea-water transfer).
Oxygenation	In aquaculture: the mixing of pure oxygen and water; this generally refers to a process by which oxygen pressurized in a gas cylinder is diffused into the water mass to be oxygenated, for example for fish transport.
Parr	Life stage of salmon from dispersion from the redd to migration as a smolt. In aquaculture this is the life stage spent in freshwater tanks and/or cages.
Pin heads	Young fry that do not ingest food sufficiently at first feeding, ending up as slender fry with large heads.
Pre-smolt	The period from the beginning of smoltification to its completion in freshwater.
Redds	Spawning areas, often with a gravel substratum.
Restricted feeding	A reduced ration usually bellow fish appetite
S0	Smolts that are transferred to sea-water in the same year of hatching usually in the autumn
S1	Smolts that are transferred to sea after at least 12 months in freshwater usually in the spring
Smolt	A juvenile salmon during its seaward migration down river. In aquaculture this term refers to a juvenile salmon that has acquired full sea-water tolerance.

Smoltification	Salmon parr are transformed to smolts during the smoltification process. This includes morphological, physiological and behavioural changes that pre-adapt the salmon to life in sea-water.
Starvation	A period of food deprivation such that the animal metabolises tissues that are not food reserves but are functional tissues.
Stocking density	The number of fish per unit volume of water. This term is the reciprocal of the space allowance (the volume of water occupied per fish).
Supersaturation	A condition in which a medium, such as a solvent, contains concentration of a substance higher than it can normally hold at a given temperature and pressure, e.g. oxygen supersaturation in water.
Upper and Lower modal group	Populations of wild parr separate into two groups in autumn, based upon growth rates. The population separates into two size classes, UMG and LMG: UMG which will tend to smolt and migrate to sea the following spring and LMG which will tend to remain in freshwater for at least a further year
Vitellogenesis	The process of yolk production within the ovary of a female fish.
Water quality	The extent of presence in water of any substance that may have an effect on fish in that water.

Risk Analysis Terminology

Exposure Assessment	The quantitative and qualitative evaluation of the likelihood of hazards to welfare occurring in a given fish population.
Hazard Identification	The identification of any factor, from birth to end of life, capable of causing adverse effects on fish health/ welfare.
Hazard characterisation	The qualitative and quantitative evaluation of the nature of the adverse effects associated with the hazard. Considering the scope of the exercise of the working group the concerns relate exclusively to fish/trout welfare.
Risk	A risk in the context of this report is a function of the exposure to an adverse effect, the magnitude and the likelihood, consequent to a hazard for trout health/ welfare.
Risk Characterisation	The process of determining the qualitative or quantitative estimation, including attendant uncertainties, of the probability of occurrence and severity of known or potential adverse effects on welfare in a given fish/ trout population based on hazard identification, hazard characterisation and exposure assessment.
Risk Assessment	A scientifically based process consisting of the following steps: i) hazard identification, ii) hazard characterisation, iii) exposure assessment and iv) risk characterisation.
Quantitative Risk Assessment	A risk assessment that provides numerical expressions of risk and an indication of the attendant uncertainties
Qualitative Risk	A risk assessment based on data which, while forming an inadequate basis for numerical risk estimations, nevertheless, when conditioned by prior

Assessment	expert knowledge and identification of attendant uncertainties, permits risk ranking or separation into descriptive categories of risk.
Risk Analysis	A process consisting of three components: risk assessment, risk management and risk communication.
Uncertainty Analysis	A method used to estimate the uncertainty associated with model inputs, assumptions and structure/form. This includes also uncertainty, due to the lack of reliable publications, uncertainty in the scientific results etc.