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Stocking of Atlantic salmon in Scotland:

Technical reference paper in relation to RAFTS policy

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Summary of technical reference paper in relation to RAFTS policy paper series 1/2014

Background

Following the publication of numerous general advisory documents on the stocking of Atlantic salmon (*Salmo salar*), more recent research specifically on salmon populations across Scotland has prompted a review of stocking policy guidance for RAFTS members and other fishery management bodies in Scotland. This document summarises the findings of published peer-reviewed scientific papers and other relevant literature that provide further information pertinent to stocking programmes.

Main findings

A salmon stock in a river is made up of a single or multiple separate breeding populations, with heritable life-history and behavioural traits that are adapted to their local environment. It has been clearly demonstrated that the operation of hatcheries can cause loss of fitness through artificial breeding of close relatives (inbreeding depression) and breeding between different populations (outbreeding depression). Salmon and trout raised in hatcheries display different physical, behavioural and genetic properties which result in a lower life-time performance than that of wild counterparts. There is also evidence of damage to wild stocks resulting from increased competition from hatchery fish stocked at larger than natural size for the time of year or at numbers that crowd out the wild fish. Subsequent loss of fitness and performance of wild stocks have been identified as a consequence of mating between wild and hatchery-reared fish. There is good evidence of the poor survival of hatchery fish from their lack of their contribution to fishery catches. Many similar studies on Brown trout (*Salmo trutta*), including sea-run forms have shown similar genetic and other effects from the use of hatcheries.

Conclusions

In response to these findings:

RAFTS policy is that there should be a presumption against stocking practices undertaken to enhance salmon and sea trout fisheries.

This informed policy is aimed at improving management of salmon fisheries in Scotland and the conservation of native stocks. This policy is aimed at protecting the complexity and differentiation of populations within and between rivers, the adaptive traits that promote fitness and their ability to adapt to changes in the environment. The diversity of stocks and associated traits such as run timing underpins the long angling season enjoyed by many Scottish rivers. Additionally, the lack of demonstrable benefit to fisheries further reinforces the position that the potentially damaging consequences arising from stocking is not justified (nor economic). RAFTS acknowledges that there are specific situations where the use of hatcheries can be appropriate in breeding support programmes aimed at restoration and for mitigation for permanent loss of juvenile production. In such cases there needs to be a carefully constructed framework where there is sufficient information and expertise to ensure the risks are minimised. Studies of the resulting performance of both target and neighbouring populations should also be assessed.

There are alternative strategies to hatcheries for optimising fishery performance: ensuring sufficient adults escape the fishery to fill the naturally accessible juvenile habitat to capacity; improving habitat condition; and future-proofing habitats against threats from further climate change. These activities are more likely to achieve the long-term benefits of maximising the number of healthy wild salmon smolts that go to sea; protecting the genetic diversity of the wild Atlantic salmon and conserving the productive capacity of the resource.

The guidance for fishery management of salmon from international bodies (NASCO and ICES) in response to declines and already reduced fishery exploitation is to:

- **Maximise the number of healthy wild salmon that go to sea from their home rivers**, since management options in the ocean are limited. This entails addressing all the impact factors in fresh, estuarine and coastal waters including degraded freshwater habitat, barriers to migration, over-exploitation and salmon farming.
- **The goal is to protect the genetic diversity of the wild Atlantic salmon and sea trout in order to maximise their potential to adapt to the changing environment**.
- Consistent with a precautionary approach, where there are uncertainties there is a need for caution. **The absolute priority should be to conserve the productive capacity of the resource**.

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Introduction & Background

Rivers and Fisheries Trusts of Scotland (RAFTS) represent the network of 25 charitable fishery trusts in Scotland. As a fundamental principle, the trusts operate from a basis of evidence-based management, and from this foundation seek to influence sustainable management practice of Scotland's freshwater habitats, their native fish populations and associated fisheries. Allied to this remit is a wider interest in native freshwater ecology and habitat in view of the interdependent nature of aquatic ecosystems.

RAFTS members collect up-to-date information on fish stocks and utilise appropriate scientific information to provide management advice to District Salmon Fishery Boards (DSFBs) and other fishery management organisations. Primarily it is essential for decision makers to understand salmon and sea trout biology, the constraints on stocks imposed by the environment and how they are exploited by fisheries so that limited resources may be focused on the most beneficial fishery management activities. On the basis of a comprehensive body of scientific evidence, both national and international, RAFTS has developed a principle policy on the use of hatcheries in freshwater fisheries for salmon and sea trout. RAFTS believe that;

- **Enhancement stocking is largely ineffective and potentially harmful.**
- **There should be a general presumption against artificial introductions (stocking) of salmon and sea trout for fishery enhancement purposes.**
- **Alternative strategies such as stock conservation and habitat enhancement are likely to provide more effective, cost-efficient and sustainable solutions.**

The concept of stocking programmes designed to enhance salmon and trout fisheries can appear attractive to fishery managers, owners and fishermen alike. The maths suggest that a hatchery can simply convert a relatively small number of broodstock into what appears to be a significant number of juveniles, taking advantage of the potentially high rates of juvenile survival in the hatchery unit. However, notwithstanding the widespread and long term use of hatcheries in salmonid fisheries based on wild stocks (Aprahamian et al. 2003; Fraser 2008), very few of the many studies undertaken have found them to be successful in improving the performance of a fishery. With all the effort and expense spent on hatchery-based initiatives, why is it the case that there appears to be no demonstrable benefit?

The published scientific knowledge provides much information on the biology and ecology of Atlantic salmon including the key points in their life-cycle at which hatcheries intervene. While there remains much still to be learnt, there is now sufficient information to assess the implications of artificial breeding and subsequent release of hatchery-reared salmon on wild populations.

This document primarily seeks to summarise the current knowledge that has been gathered on Atlantic salmon from Britain and Ireland, but also draws on studies undertaken further afield and on other closely related salmonid species. New information will no doubt be forthcoming and those involved in policy development, management and users of salmon fisheries are encouraged to become and remain aware of current knowledge. It is essential that RAFTS policy remains informed by current knowledge and it will therefore undergo regular review as and when new information is available.

The use of technical terminology in this report has been minimised, but where it has been used the terms are explained further in the glossary. Full references to scientific studies cited in the text are given at the end of the document along with recommended further reading.

Aspects of salmon and trout biology relevant to stocking

The Atlantic salmon (*Salmo salar*) and sea-run trout (*Salmo trutta*) in Scotland both have similar and complex life cycles, utilising many different habitat niches at various life-stages, and operates across a large geographical range. Therefore, to thrive, salmon and migratory trout must perform adequately in each of a predictable sequence of different environments (McCormick *et al*. 1998).

2.1 Stock structuring and adaptation to local conditions

The Atlantic salmon, along with other salmonid fish, shows life-history variations both within and between locations, and has evolved significant behavioural diversity and morphological adaptation for reproduction success. Studies of behaviour (reviewed in Fleming 1996, 1998; Fleming and Reynolds 2004) and molecular genetic markers have begun to uncover aspects of the mating system and the social structures which influence the amount and distribution of genetic variation within a population.

The mating systems of salmon (summarised by Jordan *et al.* 2007) include aspects of competition for mates and resources (i.e. spawning redds), courtship, mate choice and number of mates acquired. Genetic studies have ascertained that females will spawn with multiple males (Garant *et al*. 2001, 2003b, 2005; Taggart *et al*. 2001) with most eggs being fertilised by larger dominant males with contributions from a mixture of subordinate sea-run males and mature male parr (average of 45% of eggs in one study) through 'sneaky' mating to avoid confrontation with larger males (Jones and Hutchings 2001; Garant *et al*. 2002).

The homing behaviour of salmon and trout to the stream they come from makes the chances of breeding with close relatives high, but negative effects of this strategy may be mitigated by multiple mating, multiple redd construction and by mate choice by females. This strategy appears to have fitness benefits for reproductive success as it ensures more genetically varied offspring and decreases the risk of the loss of all a females eggs if there is poor survival in one of the redds. Odours (and possibly other senses) are used to determine a mate that has a genotype that is dissimilar to their own in order to avoid breeding with close relatives and this appears to promote a range of fitness-related traits (reviewed by Jordan *et al*. 2007). Discrimination in mate choice is also apparent in brown trout (Forsberg *et al*. 2007).

As a result of their ability to home to natal rivers, Atlantic salmon demonstrate a considerable degree of population structuring on wide-range scales (e.g. King et al. 2001; Verspoor et al. 2005), between different river systems, (e.g. Fontaine et al. 1997; Dillane et al.2007), and within river systems (e.g. Verspoor et al. 1991; Jordan et al. 2005, Dionne et al. 2008). These distinct breeding units are reproductively separated to varying degrees (reviewed by King *et al*. 2007).

Recent studies by the Focusing Atlantic Salmon Management On Populations (FASMOP) project has shown significant complexity in the genetic structuring within and between salmon populations in both large (e.g. Coulson et al. 2013) and relatively small Scottish rivers (Coulson et al. 2012). Breeding groups are separated by distance or channel features such as waterfalls, lochs or tributaries (Vaha *et al*. 2007, Dillane *et al*. 2008; Dionne *et al*. 2008). Similar studies have also identified genetic structuring of wild brown trout populations, (Griffiths *et al*. 2009a; Ferguson and Taggart, 1991; Griffiths *et al*. 2009b) of which the sea-run form 'sea trout' forms a part (Cauwelier *et al*. 2011).

Central to the local management of salmon and trout populations is the recognition of how they are structured in space, within and between catchments. Recognising and maintaining this very high degree of genetic structuring and adaptation to local conditions is fundamental to both conservation and fishery management.

2.2 Factors affecting survival and abundance

A salmon population in a river can be visualised as a pyramid shape, with a broad base of eggs, with fewer surviving to smolt and a narrow pyramid tip of returning mature adults (see Appendix 1). The reproductive strategy of salmon, unlike birds and mammals, is to produce a very large numbers of eggs (1500-1800 per kg) that are subsequently able to exploit large areas of habitat as fry and parr to overcome the effects of predation by other animals. Hence, if a pair of salmon produces 5,000 fertilised eggs, then if the population is stable only two will survive as returning adults to spawn. Those that do not survive show less suitable characteristics for that environment compared to those that do survive through natural selection.

The fertilisation and subsequent hatching success of eggs is usually very high, but may be reduced where habitat has become less suitable (Montgomery and Buffington 1998; Lapointe *et al*. 2000; Malcolm *et al*. 2003; Sayer *et al*. 1993)., Locally derived data are required to evaluate the effect of potential losses on a population. The use of multiple redd sites by females can compensate for localised losses, although fry emerging in high numbers can have high losses as they compete intensively for space and resources (Einum et. a., 2005; reviewed by Webb et. al. 2007). If egg or fry numbers are reduced, a higher rate of survival and growth (Imre *et al*. 2005) of the remaining fry often occurs as there is reduced competition for habitat and food. Consequently wild production of salmon and trout can recover very quickly after reductions in the number of returning adults or egg survival as long as the habitat remains suitable. Losses of parr occur at the over-winter stage when survival can be size dependent (Aubin-Horth *et al*. 2005). Juveniles remain territorial, which limits population size, density and subsequent smolt production in a complex interplay between the various density-dependant and density-independent factors affecting survival and growth (Armstrong *et al*. 2003).

Unlike freshwater habitats, factors influencing the survival of European stocks of salmon at sea are currently thought to be largely independent of salmon numbers. Losses are thought to be principally due to variability in effects of predation, food availability, parasites and disease, though freshwater influences also impact marine survival (reviewed by Webb *et al*. 2007). Estimates of the Pre Fishery Abundance (PFA) of salmon at sea have fallen from 10 million in 1970 to 3.6 million in 2010. The PFA of southern European stocks (of which Scottish fish are a component) are estimated to have declined by 66% for 1 sea-winter salmon (grilse) and 81% for multi sea-winter salmon over this time (Windsor *et al*. 2012).

Variation found in the environment (e.g. river flow, competition, and predation from other species) favours some individual fish over others and hence has an influence on the genetic variation found among and within populations. This results in natural selection for characteristics (i.e. morphology, life history and behaviour) that improve fitness, promoting survival of individuals and population abundance.

There is now very clear evidence of local adaptation for a number of environmental pressures acting on salmon populations (e.g. disease, parasites and water chemistry). There is also a growing understanding of the differences found between populations in morphology (body size, shape and composition), physiology (growth efficiency and rates of digestion, growth and health condition), timing of important life-history events (spawning, hatching of ova, emergence of fry) that affect juvenile survival, return rate and adult survival (reviewed by Garcia de Leániz *et al.* 2007). More obvious outward displays of genetic-based adaptation in salmon in Scotland are seen in the run timing of adults (Stewart *et al*. 2002, 2006), the timing of smolt runs (Englund *et al*. 1999) and sea age at maturity (Niemela, 2006) which influence the size of fish present in a fishery.

The size of a population and the genetic variation (and associated adaptation and fitness) found within it influence how effectively individuals and the population adapt to changes in the environment over time such as those expected as a result of climate change. Small populations are more prone to local extinction due to loss of genetic variation that can reduce the ability of populations to respond to the changes in the environment, such as water temperature or other factors related to climate change (McGinnity et al. 2009*)* .

It is essential to preserve the genetic variation and fitness of each population at their largest possible size so that the inherent robustness to environmental change is maintained. This requires protection of their habitats, and where necessary to restore natural conditions to which populations are adapted.

The effect of hatchery reared salmonids on wild populations

The use of hatcheries in fishery management generally seeks to avoid the losses suffered in the wild and increase the survival of young fish through their freshwater life-stages. Typically, intervention begins with the removal of mature adults from the wild prior to spawning which are then, when ripe, used for the artificial fertilisation of eggs. The subsequent rearing of the resulting juveniles can potentially take a shorter time than in the wild.

3.1 Broodstock selection and artificial breeding

There are inherent risks in removing fish from the wild, which include both reduction of natural production in the wild and unintended mortality of broodfish whilst held in the hatchery through water supply or equipment failure, human error, physical damage to fish during capture or stress-induced disease. In practice, the collection of broodstock is often determined by logistical and practical concerns including accessibility and suitability of sites for capture of fish, while the geographical structuring of stocks is rarely considered or possible to determine in practice. Broodfish collection may capture members of more than one population if undertaken in the main channel, or a number of close relatives,if made in a small tributary. Breeding of close relatives (inbreeding) and mixing of different breeding groups (outbreeding) can have long term negative effects on population viability by reducing survival of salmon and reduce the degree of local adaptation (Hansen *et al*. 2009). There is also a risk of accidentally incorporating salmon of farm origin (or hybrids of these) into hatchery programmes which would substantially reduce lifetime success of their progeny (McGinnity *et al.* 2003; Ferguson *et al*. 2007). Recent genetic studies of salmon populations have also shown that a significant proportion (average 25.1 %) of juvenile salmon in Scottish west coast rivers have some genes that are of farm origin (Coulson 2013).

Once in the hatchery, unintentional biases arise (Fleming *et al*. 2002) as it is impossible to mimic the mating choices that occur in wild populations where mating with close relatives is avoided. The subsequent negative effects of this on individual and population performance come when the fish are released into nature (Jonnson and Jonnson, 2006) though they might not be noticed within the easy and protected environment of a hatchery. A study of brown trout concluded that the necessarily unselective artificial mixing of milt and eggs from wild broodstock generates offspring that differ significantly from any that are produced by natural pairings that arise by free mate-choice (Griffiths *et al*. 2009). This is likely to reduce fitness of the hatchery fish (and their progeny) and has been demonstrated to occur over just a single generation (Griffiths, Bright & Stevens, 2009).

3.2 Hatchery rearing and domestication

Use of a hatchery involves an alteration or relaxation of natural selective pressures on the fish grown there. Compared to wild fish, hatchery-reared juveniles are usually fed to excess and live in a low exercise environment protected against predators and if required, treated for disease. Hatchery fish are subject to unintentional artificial selection, which is a form of domestication, similar to that found in intensively farmed animals, as the environments experienced differ significantly from the wild. Thus, hatchery-reared fish are best adapted to this artificial environment and are therefore less well adapted to the environment into which they are ultimately placed. While the process of divergence of hatchery-reared fish from their wild origin is firstly environmental (phenotypic), there can also be undesirable genetic consequences over the long term. Genetic adaptation to captivity has been observed in as little as a single generation (Christie et al. 2012).

Studies indicate that the lack of sensory stimulation for fish grown in the hatchery influence subsequent performance in nature, such as homing precision, feeding, migration, and spawning behaviour (reviewed by Jonsson and Jonsson 2006). Hatchery salmon have also been shown to display raised stress and aggression levels as a result of the unnaturally high densities at which they live, which also leads to an increased vulnerability to certain diseases (Huntingford, 2004).

Direct comparisons of the swimming ability of both salmon and trout smolts of the same size taken from the wild and a hatchery (which had wild parents from the same population) found that wild smolts performed 30 % and 25 % better than the hatchery-reared salmon and trout smolts respectively (Pedersen *et al*. 2008*)*. The poorer swimming performance of hatchery fish was attributed to diet and poorer fin condition which occurs as a result of aggression (fin nipping), netting and other forms of handling and abrasion from tanks. This study also noted that the wild salmon and trout smolts had been exposed to natural selective pressures prior to the experiment which may also have given them other immeasurable advantages over hatchery smolts. Swimming performance is likely to have an effect on an array of ecologically relevant functions such as feeding, predator avoidance and migration and therefore have some bearing on the poorer post-stocking survival of hatchery fish (despite their wild parentage) compared to those of wild origin.

Evidence indicates that the hatchery environment induces body shape and behavioural changes as a result of a relaxation of natural selective pressures. The longer that a fish spends within the hatchery environment, the less likely it is to survive in the wild.

3.3 Post-stocking interactions

When hatchery-reared salmon and trout are released into the wild they compete with wild fish for food, space, and eventually breeding partners.

At stocking sites where wild fish are present, competition from hatchery salmon has been found to increase energy expenditure and exposure to predators of wild juveniles (Peery *et al*. 2004). Growth reductions in wild fish caused by the release of hatchery fish has been observed in wild Atlantic salmon (Imre *et al*. 2005) as well as in brown trout (Bohlin *et al*. 2002): growth reduction can decrease survival and influence other life history traits (Jonsson and Jonsson, 2004).

Other than the effects of direct competition, impacts of interbreeding have also been tested, since some stocked fish will survive to maturity and so subsequently some of the wild production will be converted to ‘hybrids’ (wild x hatchery origin) in the next generation. In terms of survival and other aspects of performance, such hybrids are intermediate between wild and hatchery stocks, resulting in an overall reduction in survival for the population, producing fewer fish and lower production of juveniles. Repeated stocking of salmon results in a cumulative reduction in recruitment over generations (reviewed by Cross *et al*. 2007). A decrease rather than an increase in total population size may also be the result of a genetic change (Ryman & Laikre 1991), with the introduction of inappropriate characteristics or loss of genetic variation (Wang and Ryman, 2001).

Hatchery populations do not experience the continuous evolutionary adjustment to changing environmental conditions that occurs in the wild, and therefore do not have the benefit of the history of natural selection experienced by a wild population. This disrupts the capacity of natural populations to adapt to changes in the environment such as higher winter water temperatures associated with projected climate change variability (McGinnity *et al*. 2009).

Release of hatchery-reared salmon increases competition for limited resources and has been shown to affect growth and survival of wild juveniles in stocked waters. Since some hatchery fish will survive to spawn, subsequent progeny will have acquired disadvantageous characteristics and loss of genetic variation. This has longer term potential to undermine the ability of salmon populations to adapt to changes in the environment.

RAFTS policy on different types of stocking

Driven by a desire to 'improve' the fishing, salmon and trout have been moved within and between catchments with often little consideration given to the effects of competition and interbreeding on native populations or benefits to angling resulting from the process. The four principle reasons for stocking are (Cross *et al.* 2007):-

1. **Reintroduction where a population(s) has become extinct;**
2. **Restoration (or rehabilitation) to increase abundance in a population in danger of extinction;**
3. **Mitigation of loss of freshwater production (compensation) and;**
4. **Enhancement of population(s) above natural levels to allow for increased fishery exploitation.**

The major differences between the outcomes of these strategies are that enhancement and mitigation stocking require an on-going annual investment of resources and are unlikely to lead to the establishment or permanent enhancement of a self-sustaining natural population because the underlying reason for the damage to the population has not been or cannot be addressed. Reintroduction of an extinct population or restoration of a remnant stock is intended to be a more short-term management response to loss or acute decline in a population and aims to produce a self-sustaining population.

Reintroduction

This approach has been to establish that there are no remaining native juveniles or adults present that represent future breeding stock. The loss of all juveniles caused by a short term event (e.g. a pollution incident) might in some cases be mitigated by adults that are out at sea.

Where there is no stock remaining, natural straying of salmon may allow a habitat to be recolonised if the abundance of local stock elsewhere is sufficient. Where salmon have been lost from a complete catchment, natural re-colonisation has resulted in reestablishment of a population in the River Mersey (Mawle and Milner, 2003), River Dove (Milner *et al*. 2004) and River Clyde (Coulson *et al.* 2012).

Despite high profile attempts to re-establish salmon to the River Thames using Irish stocks, the few fish found recently were identified as mostly originating from nearby stocks in Southern England (Griffiths *et al*. 2011); the Thames Salmon Stocking Programme has now been discontinued. Other attempts to reintroduce salmon such as that on a tributary of the upper River Tay upstream of a hydroelectric dam are thought to have failed primarily due to the late run timing of smolts and their inability to migrate through a large loch (Youngson *et al*. 2002). Studies in Norway where six donor stocks were used to establish a lost population found that one stock eventually predominated (Gjedrem, 1999), but this approach may take a similar amount of time to natural recolonisation. There are risks associated with a hatchery-based approach to reintroduction which include removal of broodfish from wild donor populations with the subsequent potential to reduce smolt production from those populations (Reisenbichler *et al*. 2003), from unintended introduction of new pathogens (Bakke *et al*. 1990) or introduction of stock that is unsuited to the habitat that will compete with the natural colonisation by a more suitable population.

Rebuilding of an extinct population should ideally be allowed to occur naturally once the factors causing the decline have been addressed. The closer and more abundant other stocks are, the shorter the time for natural colonisation is likely to occur. Where necessary, a robust and transparent process need to be undertaken to identify site specific risks associated with introductions of new stock which need to be weighed against the potential benefits of reducing the time taken to re-establish a population and likelihood of success.

Restoration (or rehabilitation) stocking

Where remnant populations are present, hatchery-based restoration primarily aims to maintain existing genetic variation found in a small population threatened with extinction and has the prerequisite of removal or easing of pressures on the population that have caused the severe decline. The general consensus among salmon geneticists is that inbreeding is a tangible and serious threat to population fitness. Genetic populations consisting of over 100 individuals (given equal numbers of males and females) are probably at minimal risk of short-term inbreeding depression, although a more cautious minimum number of 200 individuals to prevent a loss of population fitness (reviewed by O'Reilly and Doyle 2007). In such cases, the introduction of new genetic material has been shown to have undermined genetic variation of native salmon stocks in Spain (Allyon *et al*. 2006), France, (Perrier *et al*. 2013) and Sweden (Nilsson *et al*. 2008).

Introductions of new non-native genetic material through stocking of salmon and trout from other rivers should not be undertaken for purposes of restoration where a remnant of the native stock is present.

Hatchery-based restoration programmes may utilise native salmon or trout populations with either supportive or captive breeding programmes, but these should only be considered as a conservation measure when the population is in danger of going extinct (Webb *et al.* 2009).

Supportive breeding programmes are primarily aimed at maintaining the limited genetic variation found in small, threatened populations as one part of a suite of measures that ease pressures acting on all life-stages. It is a prerequisite that there is sufficient quantitative and genetic information on the target population(s) upon which informed decisions can be made. For this technique to be effective, it is essential to maximise the number of families created (multiple crosses of broodfish) while avoiding mating of close relatives (inbreeding), and selection within a hatchery (domestication) by utilising genetic information and planting out eyed eggs or releasing unfed fry as early as possible to allow natural selection to act, ultimately allowing well adapted individuals to survive in the population and those less so to perish.

As river-specific scenarios vary widely, specialist advice needs to be sought when supportive breeding programmes are being considered to establish if a hatchery-based approach is appropriate.

Captive breeding programmes have similar aims to supportive breeding programmes, but differ in that juveniles are captured prior to migration and subsequently grown-on in the hatchery to maturity and may be used to produce progeny on more than one occasion. Their progeny are used not only to stock into the wild but also to produce the next generation of broodfish in the hatchery. This approach has significant potential to reduce fitness of hatchery reared salmon and trout through domestication, longer term detrimental effects of inbreeding within the captive stock and subsequent undesirable effects on future generations. These genetic effects may be a factor in the limited success of such recovery programmes (reviewed by O'Reilly and Doyle 2007). Longer-term effects on performance of captive breeding programmes have been described in other salmonid species with migratory life-histories in the U.S.A (Araki, 2008). This genetic study highlighted that the subsequent ability of hatchery reared steelhead trout to reproduce is lower than that of wild spawned fish. Future generations that are produced by hatchery fish have been shown to be less well adapted to life in the wild with a reduction of reproductive success of around 40 % per generation, indicating negative effects are both cumulative and heritable.

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Captive breeding and rearing, despite the best of intentions, will bring about physiological, behavioural and genetic changes that will lower the fitness of released individuals in the wild.

4.3 Mitigation stocking

There are a number of examples of mitigation stocking in the UK and abroad which are often undertaken as result of legal and economic commitments by developers to 'mitigate' for loss of freshwater production upstream of dams built as part of hydroelectric generation schemes. Other interpretations of mitigation stocking are attributed to attempts to overcome high losses during the marine life-phase currently being experienced by Southern European stocks .However all mitigation hatchery programmes are subject to all the same realities as other stocking strategies and much lower sea-return rates for hatchery stock should be expected when compared to their wild counterparts, and their potential to effect other non-target populations close by remain.

For example, in the case of the hydro dam on the River Conon, although fish passes allow fish to migrate upstream of dams, stream habitat required for spawning and juvenile nursery life-stages is reduced by a reservoir. To minimise the undesirable effects of the mitigation stocking programme broodfish are collected from a trap on the fish pass at the hydroelectric dam which avoid incorporating wild spawned fish from downriver. Their progeny are planted out as eyed ova where there is available habitat to ensure that natural selection retains fitness in the population.

It has been claimed that the mitigation stocking programme on the River Tyne (developed for loss of habitat upstream of the Kielder dam) has been responsible for the restoration of salmon stocks throughout the catchment and re-establishment of fisheries. However, a study of the stocking and tagging data (Milner *et al*. 2004) found that simultaneous improvement in water quality in the tidal waters and recovery in the sea trout (of which very few were stocked) accompanied the recovery in salmon stocks (see Appendix 2). Data suggest that 80% contribution of the recovery was as a result of self-regeneration of the remnant native populations. As much of the original stock for this hatchery was brought from other rivers (e.g. the River Shin and the River Tweed) it is possible that the first years of stocking actually hindered the recovery of local populations through outbreeding depression.

Mitigation stocking activities can be undertaken to overcome human-derived permanent or long-term loss or impairment of freshwater habitat. However, these programmes are subject to the same undesirable effects as other hatchery operations. Where carried out, it is essential that detrimental effects of domestication and inter-breeding between hatchery and wild fish are minimised and monitored to inform management.

Enhancement stocking

Typically, enhancement stocking is used where those exploiting the fishery have expressed dissatisfaction with the quality of fishing or a desire to increase catches for economic benefit. Hatcheries to enhance fisheries utilise artificial production to produce fish in excess of the natural potential with the aim of increasing population size above natural carrying capacity to allow for increased harvest. Enhancement stocking can take a number of forms which include:

Utilising progeny of non-native broodfish by the translocation of stock from other rivers to improve a native stock was perhaps once the most common form of stocking. Direct comparison between the life-time survival of introduced fish and native fish was undertaken using wild stock from the native River Burrishoole and a donor population from the neighbouring Owenmore River in the west of Ireland. Despite close proximity of the two populations and similar habitat characteristics of the rivers, this study found that the overall lifetime success of the donor stock, from fertilised egg to returning adult, was only 35% of that found in the native Burrishoole stock (McGinnity *et al*. 2004). These findings, and observations made in respect to the genetic-based considerations, demonstrate that the use of non-native broodfish stock is not sustainable and should be avoided.

Introductions of new non-native genetic material through stocking of salmon and trout from other rivers should not be undertaken to enhance fishery catches.

Utilising progeny of native broodfish assumes that there is a surplus of spawning stock each year for use in the hatchery over and above that required to repopulate all naturally available habitats with juveniles to carrying capacity. Attempts to increase juvenile abundance where stock strength is perceived to be less than desirable are currently the most commonly used hatchery programmes. However, two recent studies have highlighted the lack of demonstrable benefit of stocking to fishery performance;

Examination of fishery catches over a 15 year period in 42 stocked rivers and 20 rivers where no stocking was undertaken in England and Wales (Young 2013) found no detectable benefit to catches in catchments with stocking programmes compared to those that were not stocked. Not only was there no demonstrable benefit to the fishery, there were also slight declines in the catches of stocked fisheries, more so where stocking of older juveniles (parr and smolts) was carried out.

Genetic studies of the outcomes of enhancement stocking have shown that returns of hatchery-origin adult salmon are much lower than expected by fishery managers. A comprehensive genetic study of a stock enhancement programme on the River Spey in Scotland (Coulson, 2013) examined the contribution of 2,803 salmon used as broodfish (2004-2010) and the 13 million progeny stocked (2004-2012) at different life stages through assigning parentage of 1,057 rod caught salmon in the fishery and another 868 caught as broodfish for the hatchery (2008-2012). Accurate parentage analysis of the 1,925 adult tested over the five year period, found that 17 of these could be verified as being of hatchery origin. The contribution of this large-scale stocking programme to the fishery was clearly less than expected (range 0 to 1.8 % of stocked fish caught in the fishery) and the significant resources expended to operate such a programme is now being re-assessed.

The scientific evidence is clear that the lack of demonstrable benefit to fisheries resulting from stock enhancement of salmon and trout indicate that it is likely to be detrimental to wild populations and a poor use of resources and therefore should not be undertaken.

Some stock enhancement programmes have artificially increased freshwater habitat availability by trans-locating progeny of hatchery broodstock to habitat upstream of impassable waterfalls. This practice has recently been curtailed through legislation in Scotland (Wildlife and Natural Environment (Scotland) Act 2011) that make it an offence to release or to allow to escape from captivity any animal to a place outside its native range. This is to prevent any detrimental effect on resident brown trout through hybridisation and increased competition for food and habitat resources.

Translocation of hatchery-reared fish outside of their natural range is illegal and therefore should not be undertaken.

The overall effect of hatchery fish may depend on the relative numbers of stocked and wild salmon and trout present and how much lower the fitness is of introduced fish relative to wild fish (Cross *et al*. 2007). Hence, a large stocking programme in a small catchment is likely to have a greater impact and therefore more damaging to the fitness of the wild population, while a similar programme in a large catchment may be less successful in terms of fishery catch, but may be relatively less damaging to native stocks. Although it is not possible to quantify these effects after the event, every effort should be made to avoid such effects.

Ranching of smolts avoids the use of freshwater habitat altogether by completing all juvenile life-stages in the hatchery environment. The two main types of smolt release programme used to enhance fisheries differ in that some have developed a line-bred ranching stock (developed originally from native stock), while others utilise stock collected from the wild each year (or a combination of both). Ranching poses a threat to the genetic fitness of wild populations over and above that of other stocking strategies in that there is no natural selection imposed during the juvenile life-stage. The relative ability of a fishery to prevent or minimise cross-breeding between ranched and wild stock is therefore critical to the management of ranching programmes.

The ranching programme of the River Ranga in Iceland is frequently held to be a successful model for a ‘put and take’ salmon fishery managed as a commercial operation at the expense of protecting the genetic identity of the remnant and possibly neighbouring wild salmon populations. Unlike Scottish rivers, the River Ranga currently has little natural production of salmon due to the smothering of its spawning gravels by ash from a volcanic eruption. The return rates of ranched smolts in the Ranga fishery is sufficient to operate a fishery, but are still far lower than those of smolts of wild Icelandic populations. The higher smolt to adult survival and higher catch rate of returning fish in Icelandic rod fisheries mean that direct translation of the Ranga ‘model’ to the Scottish situation is highly unlikely to be commercially viable (see Appendix 3). Differences in Icelandic catches compared to that found in Scotland may be attributed to genetic traits that are associated with local populations (reviewed by King *et al*. 2007) as well as different marine feeding grounds and survival rates for northern compared to Scottish and other southern European stocks (Windsor *et al.* 2012). The Ranga, similar to most Icelandic catches, consist mainly of grilse which return over a short season (3 months), while Scottish stocks are more complex and return over a much longer period (10 months) on larger rivers, a diversity that has not yet been reproduced in a hatchery.

Other simultaneous studies of both hatchery and wild smolts in the same rivers in Norway found sea survival of wild salmon is 3–5 times higher than that of stocked salmon released into rivers (Jonsson *et al*. 2003; Saloniemi *et al*. 2004; McGinnity *et al*. 2004). The difference in sea survival was more pronounced in low- than in high-survival years. The poor survival of stocked smolts may be linked to the phenotypic divergences of hatchery fish from wild fish (Jonsson and Fleming, 1993; Reisenbichler and Rubin, 1999; Ford, 2002). Ranched smolts also have a higher rate of straying and a later time of year of return, which has implications for fishery performance and interbreeding with neighbouring populations (McGinnity *et al*. 2004).

In Scotland there have been a number of attempts to assess the viability of smolt release programmes. A study on the River Lochy between 1987 and 1989 found returns of ranched smolts to the river was less than 1 % (Struthers *et al*. 1991). There have been other attempts to enhance fisheries through ranching, but collection of robust data on the performance of both ranched and wild smolts is scarce. Comparison of wild and ranched smolt returns are summarised in Appendix 3.

Irrespective of the poor performance of ranched compared to wild smolts where ranched salmon are able to spawn with wild salmon, resulting hybridisation and loss of fitness in the wild population may be as serious a threat to fitness of wild populations as fish farm escapes or more serious when ranching is continued over a long period (Chilcote, 2003; McGinnity *et al*. 2004).

Given the clearly defined risks associated with causing harm to wild populations, ranching should not be undertaken for fishery enhancement purposes in Scotland.

Alternative Strategies

The aim of fishery management are to ensure that there are sufficient numbers of spawning adults in each breeding population to optimise egg deposition, that all available habitat is accessible and in the best possible condition to promote survival of juveniles and to maximise subsequent wild smolt production.

The development of a fishery management plan is an essential component of ensuring management activities are targeted at the most significant bottlenecks acting on smolt production. Such plans need to be based on accurate and up-to-date information that is able to describe the character of fish populations and the natural limitations of the habitat, fisheries and other factors that influence recruitment of juveniles (see IFM, 2012 for further guidance). The expectations of fishery owners and managers also need to be realistic and founded in the natural productivity of freshwater habitat and current returns of smolts as adults from the sea.

Managing exploitation

At times when the sea survival of smolts is relatively low or variable there is no surplus of returning adults that should be harvested by fisheries. Preventing or reducing exploitation of the stock in the fishery will maximise spawning escapement and subsequent egg deposition and juvenile recruitment. This may be accomplished by reducing fishing effort, curtailing the use of the most effective fishing techniques or releasing all or part of the catch. Returning rod-caught fish has been shown to be an effective means of maximising spawning escapement from the fishery. Catch & Release (C&R) recreational fisheries provide an intermediate management strategy (ICES, 2009) between a full retention fishery and fishery closure for populations that are below conservation limits. Rules governing the release of rod caught fish can differ through the season or by fish size and is therefore a very flexible means of directing conservation efforts to the most vulnerable parts of a stock.

Recycling of fish can also increase the overall catch with studies of salmon fisheries indicating that a number of released fish are caught again with similar rates of post-release survival. Curtailing fishing effort at warmer water temperatures (above 18 ºC) ensures high rates of survival of released fish are maintained (ICES, 2009). Further benefits of catch and release of sea trout are likely as a higher proportion may return to spawn several times and be available to be caught in fisheries over a number of years.

Maximising habitat accessibility

To maximise benefit from the increased spawning escapement from the fishery, it is essential to maintain and, where possible, increase the current productive capacity of Atlantic salmon habitat (NASCO 2010). Removing or easing obstacles to fish passage will ensure that all naturally accessible habitats are potentially productive. There has been demonstrable benefit as a result of the removal of 59 barriers on the River Tweed and subsequent natural re-colonisation of salmon (Campbell 2010). While removal and easing of man-made barriers are generally beneficial, however, changes to naturally accessible barriers have the potential to disrupt existing genetic structuring by increased mixing and merging of populations and consequentially promoting outbreeding depression (Verspoor *et al.* 2007).

In-stream structures have generally been considered in relation to the upstream migration of adults but it is now clear that they also need to be thought about in terms of downstream smolt migration as well. Recent work (Gauld *et al.* 2013) has shown that losses of smolts during their downriver migration during low flows can be very high and is made worse by barriers that pond back rivers creating areas of slow water in which predators can be more efficient. It is possible that losses during downstream smolt migration might be more significant than many factors earlier in the life cycle.

Optimising habitat condition

While many factors may act to generate losses and limit numbers of smolts produced, the quality of habitat and food availability are amongst the most influential factors. Human-derived pressures have affected the condition and productivity of juvenile habitat. Pressures include catchment wide use of land and water resources and more direct disturbance of habitat from realignment (usually straightening) of the river channel which reduce habitat area and complexity.

Salmon fry and parr utilise riffle areas containing gravel or cobble substrate, and higher densities are usually associated with complex channels containing coarser grade substrates. Juveniles shelter from predators and floods and over-winter within the stream bed substrates, therefore there are implications for survival if the gaps between bed substrates become filled by fine sediment as a result of forestry, agriculture and other land use activities. Quality of water chemistry and both in-stream and riparian habitat diversity are also influential on growth and survival. Historically natural rivers, streams and their floodplains across most of the UK were more densely wooded, but much of this tree cover has been lost. Organic inputs from the riparian zone in the form of leaf litter and insects can account for up to 50% of the energy in a river system (reviewed by Lanene 2012). Woody debris would also have been a common feature in river channels which increase habitat diversity and storage of leaf litter and associated food items.

Climate change predictions indicate that the temperature of freshwater habitats are set to rise, potentially changing growth and survival of juveniles and threaten some populations. It is vital that freshwater habitats are managed to both maximize the smolt output and to minimize the impact of factors acting on salmon in freshwater that may compromise them once they migrate to sea (Russell *et al.* 2012). Riparian trees and shrubs can help to keep rivers cool on hot summer days. Average and maximum summer water temperatures are on average 2-3ºC lower in shaded areas than in open rivers. Planting the banks of the headwater streams is likely to offer the greatest benefits to water temperature within a river basin and combat effects of predicted climate change on salmon and trout production (reviewed by Lanene 2012).

It is important that managers understand factors affecting aquatic habitats on a catchment-wide scale and are able to focus on protecting the habitat that is in good condition and restoring damaged habitat.

6. Conclusion

Stocking information provided by the Association of Salmon Fishery Boards to NASCO as recently as 2010 declared that 42 hatcheries were operated by 25 district salmon fishery boards, stocking 12,758,000 salmon and 127,000 sea trout. While stocking may be a legitimate management tool in the appropriate situation, managers often look at stocking as the first tool in the box when fishery catches are lower than desired. Variation in the numbers of salmon and trout returning to spawn in Scottish rivers each year is largely determined by changes in the marine environment that influence the survival of smolts at sea. Atlantic salmon and sea trout have a successful strategy to cope with short-term changes in their numbers by producing a large number of eggs that can restock freshwater habitat from relatively few adults.

Recent dramatic technological advances in genetics have marked quantum leaps in our understanding of Atlantic salmon and sea trout as organisms and species. Genetic information that RAFTS and Marine Scotland found during the Focusing Atlantic Salmon Management On Populations (FASMOP) programme highlighted that there are numerous, genetically discrete salmon populations throughout Scotland. There are several populations within most river systems, some of which may be small and vulnerable to over exploitation, habitat loss and effects of inappropriate management intervention, such as stocking.

Much of the variation in catches in salmon fisheries is related to marine survival of salmon at sea. Current and future changes in the North Atlantic Ocean, probably exacerbated as a result of climate change, will further test the resilience of salmon and sea trout populations. There are further indications that warmer winter temperatures will pose further selective pressures on over-wintering parr and summer high temperatures may also affect juvenile growth and survival where critical limits are reached. The research data tell us that hatchery intervention is highly likely to diminish the fish's ability to adapt to these changes.

While the concept of hatcheries in salmon and trout fisheries is generally a popular vehicle for management in response to declines or a desire to increase catches, there is now clear scientific evidence that most hatchery programmes aimed at improving catches in rod and line fisheries are mostly ineffective due to inherent and largely unavoidable factors related to the unnatural selection of hatchery-reared fish that are less well adapted to survive once released compared to their wild counterparts. Hence, even in large-scale expensive and well managed hatchery programmes, the numbers of stocked fish that return to freshwater are not usually large enough to make a significant difference to the fishery catch as the proportion of the stock caught in the fishery is generally relatively small. The subsequent effect of the hatchery fish that do return to spawn on the fitness of the wild stock depend on their relative number compared to the wild spawners, the suitability of the parent stock and length of time spent in the hatchery as juveniles. Hence, hatchery programmes based on a relatively small stock in a small catchment may appear beneficial to a fishery if a higher proportion of the stock is exploited by the fishery, but removal of wild spawners as broodstock and reduction in the fitness of the wild population through domestication in the hatchery is likely to be more acute, undermining any potential benefit. Continued stocking aimed at fishery enhancement is likely to exacerbate these effects and create longer-term consequences that erode the genetic and phenotypic variations in wild Scottish populations. These variations underpin the diversity of salmon and trout found in Scottish fisheries and their ability to adapt to changes in the environment.

There are conservation and economic cases for stocking to mitigate for loss of freshwater habitat upstream of man-made obstacles, or assist recovery of small populations under threat of extinction. Hatchery programmes need to be carefully managed to avoid deleterious effects of inbreeding and outbreeding depression and progeny need to be exposed to natural selection in the wild to minimise effects of domestication. Such programmes need to operate within a carefully constructed framework where there is sufficient information and expertise that ensure risks are minimised.

On the basis of the evidence of multiple scientific studies, future fisheries management needs to focus on activities that make better use of the limited resources available by protecting the variety and abundance of wild salmon and trout in fisheries and investing in improvements to the condition of fish habitat, rather than the year-on-year spending on ineffective and damaging stocking programmes.

In response to declines and already reduced fishery exploitation, the guidance for fishery management of salmon from international bodies (NASCO and ICES) is to *maximise the number of healthy wild salmon that go to sea from their home rivers*, since management options in the ocean are limited. This entails addressing all the impact factors in fresh, estuarine and coastal waters including degraded freshwater habitat, barriers to migration, over-exploitation and salmon farming. *The goal is to protect the genetic diversity of the wild Atlantic salmon and sea trout in order to maximise their potential to adapt to the changing environment.* Consistent with a precautionary approach, where there are uncertainties, there is a need for caution. *The absolute priority should be to conserve the productive capacity of the resource*.

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8. Glossary

Adaptation – the process of genetic adjustment of the character of a population to its environment which results in increased survival and reproductive success.

Artificial selection – includes hatchery-based domestication and selective breeding leading to genetic and phenotypic change of traits in the progeny generation (as opposed to natural selection.

Bottleneck - a short, temporary decrease in the size of a population usually lasting one or a few generations.

Broodstock – mature fish captured and reared to provide eggs and sperm (milt) for artificial breeding.

Captive breeding – breeding of fish maintained in captivity.

Conservation limit (CL) – demarcation of undesirable stock levels.

Domestication – the process whereby inadvertent selection in culture changes the genetic character of a population or inadvertent adaptation to the culture environment.

Fitness – the ability of an individual or population in a given environment to survive and produce offspring.

Fry – young salmon from when they cease to be dependent on the yolk sac as primary source of nutrition until they have dispersed and become territorial.

Genes – internal molecular elements responsible for controlling inheritance, reproduction and development.

Genetic diversity – differences among genetic populations within species.

Genetic population – a group of sexually reproducing individuals and their relatives, within which mating is more or less random but among which interbreeding is constrained so that they constitute a distinct gene pool.

Genotype – the hereditary or genetic constitution of an individual.

Hybridisation – crossing of two individuals from different genetic populations (or species).

Inbreeding – the successful mating of closely related individuals (i.e. siblings or first cousins) or of individuals more closely related to each other than the average within the population.

Inbreeding depression – a decline in the fitness of the individuals, with regard to either survival or reproductive success, due to inbreeding.

Life history trait – a trait which relates to the way that an organism lives its life.

Local adaptation – the evolutionary adjustment of the genetic character of a population which increases fitness in its local environment.

Natural selection – the natural process by which the genotypes in a population best suited to their environment survive better and leave more descendents than those less well suited.

Outbreeding – the mating of genetically different organisms from different populations.

Outbreeding depression – a reduction in fitness arising from outbreeding

Parr – juvenile salmon after the fry stage.

Phenotype – the overall character of an individual. Phenotypic trait – an observable feature of an individual that results from the interaction between its genotype and the environment.

Precautionary approach – Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

Recruitment – the addition to a population of new individuals as a result of reproduction.

Smolt – fully silvered juvenile salmon migrating or about to migrate to sea.

Spawner escapement – numbers of salmon that survive to spawn, usually calculated after the removal effects of fisheries, predation and disease have occurred.

Stock – a group of individuals of a species defined on the basis of arbitrary management criteria, such as river of origin, area or time of capture.

Strain – a cultured population of individuals showing a particular phenotype as a result of its unique genetic character.

Sustainable use – the use of components of biological diversity in a way and at a rate that maintains biological diversity in the long term so it can meet the needs and aspirations of present and future generations.

Wild salmon – having spent its entire life cycle in the wild

Further Reading

Code of Good Practice for Freshwater Fisheries Management (Part 1: Salmon and Brown trout. Institute of Fisheries Management (Scottish Branch).

Natural breeding = healthier stocks! Fisheries Research Services. Topic sheet No. 21.

Salmon and sea trout - To Stock or Not? Fisheries Research Services. Scottish Fisheries Information Pamphlet No. 22.

Scotland's Freshwater Fish Populations: stocking, genetics and broodstock management. Fisheries Research Services. Topic sheet No. 41. V1.

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Appendix 1 – Structure of a typical salmon or trout population

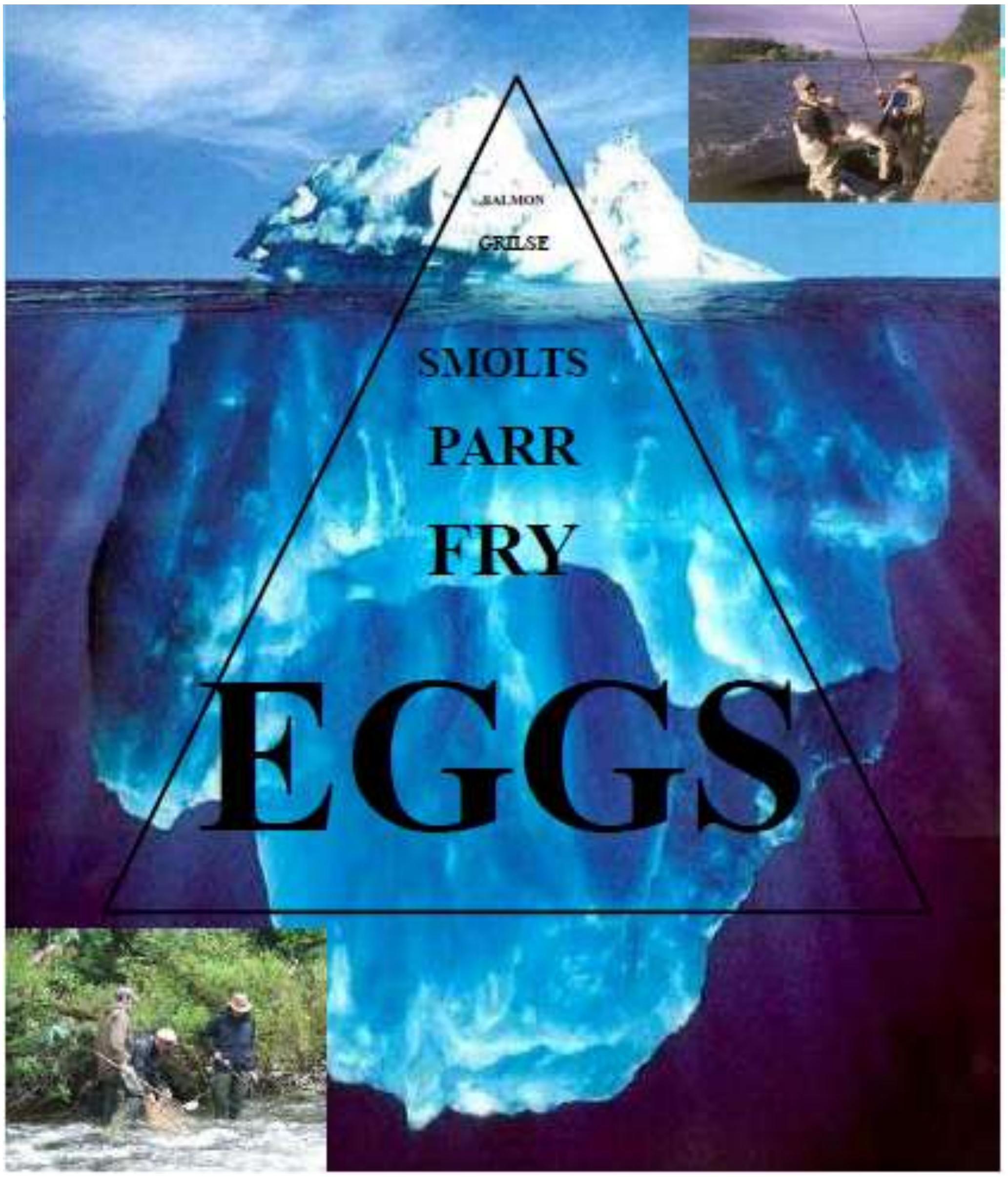
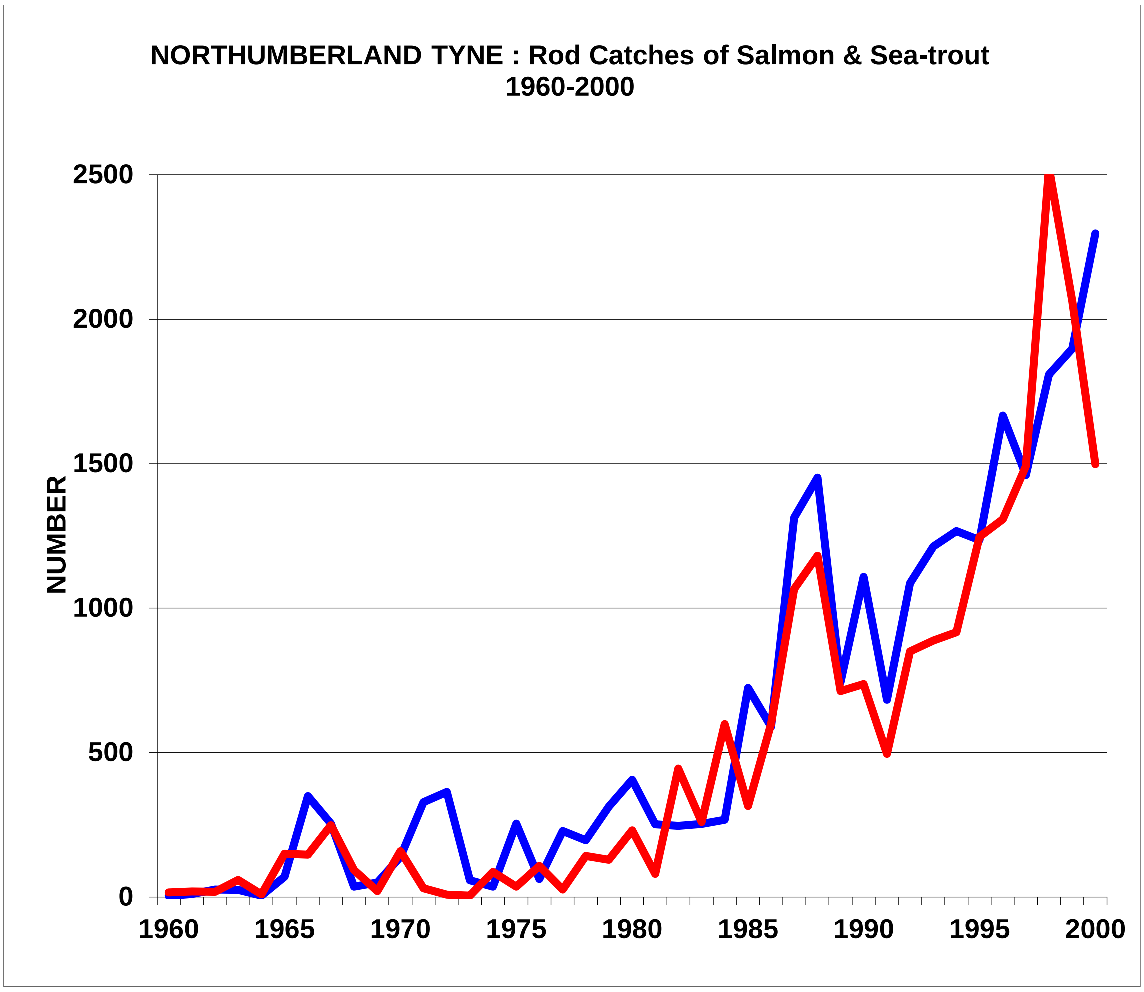


Diagram representing the structure of salmon and trout populations in freshwater with a high number of eggs and decreasing number of fry, parr, smolts and adult returns from the sea (Taken from the Institute of Fisheries Management (Scottish Branch); Code of Good Practice for Freshwater Fisheries Management (2012).

Appendix 2 – Comparison of catches of salmon and sea trout from the River Tyne (1960 to 2000)



1960-1990 data fromfrom Table 20 in Salmon Net Fisheries 1991 (MAFF & SO); Later data from annual statistical bulletins.

The species represented by the two colours of lines are not named in this graph so a guess can be made as to which is the Salmon, which had the benefit of an extensive and expensive stocking programme and which is the Sea-trout, which did not.

Appendix 3 - Summary table of the performance of ranched and wild smolts

River (country)	Time Period		Marine survival % (smolt to adult return to river)						No. smolts per adult return to rod (10% catch of stock)						Notes
			Ranched			Wild			Ranched			Wild			
	years	No.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	
Burrishoole (Ireland)	1970-1998	29	0.5	2.4	6.7	3.1	7.7	12.3	149	589	2000	81	149	323	Cross et al. 2007 (ranched strain)
Ranga (Iceland)	1989-2009	21	4.0*	13.5*	31.0*	-	-	-	323	1125	2500	-	-	-	* calc from catch % (= > 10 % catch rate)
Ellidaar (Iceland)	1975-2008	23	-	-	-	4.5*	8.8*	21.0*				48	136	222	*actual measured % survival
Tay (Scotland)	1989-1997	9	0.2	0.4	0.6	5.1			1667	3856	5000			196	FRS Report no.22 2003
Lochy (Scotland)	1987-1989	3	0	0.4	0.8	-	-	-	1250	2883	4900	-	-	-	Struthers *et al*. 1991 (wild origin)
Carron (Scotland)	2002-2004	3	1.3*		3.5*				286	527	769				*actual recapture rate probably > 10 %
Esk (England)	1998-1994	7		0. 4			4.7			2500			213		
Tyne (England)	1980-2002	22	0.4		1.0				1000		2500				Milner *et al*. (2004)