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Relationships between the frequency of farmed Atlantic salmon, *Salmo salar* L., in wild salmon populations and fish farming activity in Norway, 1989–2004

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In Norway, there have been restrictions on salmon farming in several fjords to reduce the potential negative impact on important stocks of wild Atlantic salmon. Little is known about the incidence of escaped farmed salmon in fisheries and broodstocks relative to the extent of fish farming in nearby areas. In this study, we analysed data on the incidence of escaped farmed Atlantic salmon in angling catches and broodstock fisheries in rivers for a 16-year period (1989–2004). These data were weighted using official catch statistics and combined at the county level, and the incidence of escapees was correlated with both the stock of farmed salmon in net pens and the reported number of escapees in different Norwegian counties. Our results indicate a significant positive correlation between the incidence of escaped farmed salmon in the rivers at the county level and the intensity of salmon farming, measured as the number of farmed salmon in net pens, suggesting that protection areas may reduce the impact of escapees in salmon populations nearby.

Keywords: escaped, farmed, *Salmo salar*, wild.

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Introduction

During the past 35 years, production of farmed Atlantic salmon (*Salmo salar* L.) in the North Atlantic has increased from less than 5000 t in 1980 to approximately 800 000 t in 2004, with farms in Norway accounting for about 64% of current production (ICES, 2005). The stock of farmed Atlantic salmon greatly exceeds that of wild conspecifics (Gross, 1998). Although a relatively small proportion of farmed salmon escape, the number is large relative to the populations of wild salmon. Reports of escaped farmed salmon in Norwegian salmon rivers first appeared in the 1980s (Gausen and Moen, 1991; Lund *et al.*, 1991), methods for identification of farm escapees were developed (Lund and Hansen, 1991; Fiske *et al.*, 2005), and since 1989, a number of Norwegian rivers have been sampled to estimate the occurrence of fish farm escapees (Lund *et al.*, 1991; Fiske *et al.*, 2001). In recent years, the number of farmed salmon in reported Norwegian salmon catches has been estimated to be between 30 000 and 60 000 annually (Hansen *et al.*, 2005). Spawning of escaped farmed salmon in wild salmon rivers has been documented (Lura and Sægrov, 1991), and introgression of farmed salmon into wild populations may have negative effects (Hindar *et al.*, 1991; Einum and Fleming, 1997; Jonsson, 1997; Fleming *et al.*, 2000; Tufto, 2001; McGinnity *et al.*, 2003; McGinnity *et al.*, 2004).

Farmed smolts released at marine sites tend to return to the area from which they were released (Hansen and Jonsson, 1991), while adult salmon that escape tend to disperse more widely (Hansen, 2006). In other words, if many salmon escape as smolts or early in the post-smolt stage, the incidence of escapees in rivers close to fish farms may be higher than if the farmed fish escape as adults. Furthermore, if salmon move randomly after they escape, they may be "trapped" in the fjord system in which the farm from which they escaped is located and enter rivers within that system. This is one of the reasons that salmon farming in Norway has been restricted or prohibited in some areas close to important salmon rivers (Lund *et al.*, 1994;

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Anon., 1999, 2002). Another reason is to reduce the risk of pathogens and parasites spreading from farmed to wild salmon populations (Finstad *et al.*, 2000; Bjørn and Finstad, 2002).

In this study, we analysed the occurrence of escaped farmed Atlantic salmon in angling catches and broodstock samples from salmon rivers relative to the intensity of salmon farming in different counties in Norway in the period 1989–2004.

Methods

Scale samples from salmon caught in river fisheries were provided by anglers during the legal angling season (1 June–18 August (1989–1994), 1 June–31 August (1995–2004)) and obtained from broodstock fisheries during autumn (September–November). These samples are hereafter referred to as summer and autumn samples, respectively. Anglers also provided a morphological assessment for each fish. Scale readings combined with the morphological assessments were used to estimate the proportion of farmed escapees in the samples (Lund and Hansen, 1991; Fiske *et al.*, 2005). When the origin assigned by scale reading and morphological assessment differed, the origin of the fish was determined based on the scale reading, but when origin could not be determined conclusively from the scale reading, morphological assessment was used to assign the sample. For each river, the proportion of farmed salmon in the samples was calculated annually.

The data were normalized by arcsine square root transformation (Sokal and Rohlf, 1981). The total data set comprised 89 916 scale samples (62 229 summer samples and 27 687 autumn samples). The number of scales analysed in each river varied from 29 to 911 (a mean of 136 and a median of 101) for the summer samples, and from 24 to 449 (a mean of 87 and a median of 74) for the autumn samples. Data from 95 different rivers for periods varying from 1 to 16 years (a mean of 6.8 and a median of 6 years per river) were used. The summer samples represented only a proportion of the total catch in each river. The autumn scale samples were obtained mainly from fish caught by anglers in the period close to spawning after the end of the angling season, but samples were also obtained from fish caught by other methods. Most of the wild salmon in the autumn samples were released after the scale samples were taken, or they were stripped to produce fry or smolts for stocking.

The percentages of farmed salmon in individual rivers in the period 1989–2000 are presented in Fiske *et al.* (2001), but the data for 2001–2004 have not yet been published. Summer samples were not analysed in 2003 because the sampling programme received limited financing that year. As a measure of the incidence of farmed salmon in each river, we computed the mean of the transformed proportion from the summer and autumn samples each year. In some cases, only summer or autumn samples were available, and then the incidence was estimated from the linear regression forced through the origin of the relationship between the observed proportion and incidence. The following were used to estimate the incidence of escapees in cases where only summer or autumn samples were available:

$$\text{incidence} = (\text{transformed summer proportion}) \times 1.283 \quad (t = 38.1,\ p < 0.001);\ \text{or}$$

$$\text{incidence} = (\text{transformed autumn proportion}) \times 0.727 \quad (t = 74.5,\ p < 0.001).$$

From the Statistics Norway website (http://www.ssb.no/), we collected data on salmon stock size in net pens in the sea, available since 1989, and the reported number of escaped farmed salmon, available since 1993. These data are available for different regions in Norway, normally corresponding with counties, except for southern and southeastern parts of Norway, where data from several counties are pooled, probably because there is relatively little fish farming in this region. Hereafter, these geographical units are referred to as "counties". These ten counties are shown in Figure 1. Catch statistics for each river were provided by the Directorate for Nature Management and Statistics Norway. These statistics report the annual nominal catches in numbers of salmon for each river, and include both wild and escaped farmed salmon (Figure 2). The statistics for individual rivers were used to compute the weighted mean incidence of escaped farmed salmon for each county for those rivers for which samples were available. Consequently, our weighting procedure did not include the total catch in each county, but only the catch from rivers for which we had scale samples. Rivers were allocated to county based on the location of their outlet to the sea, and none of the rivers formed the border between counties. Each river was weighted with the reported number of salmon caught in the river annually. In this way, rivers with large catches (large populations of wild salmon) were weighted more heavily than rivers with small catches. As a consequence, our analysis reduced bias caused by overemphasis on small populations with large proportions of farmed salmon.

With "county" as the unit in our analysis for each year, we computed the correlation coefficient between the incidence of escaped farmed salmon in rivers and either the size of farmed salmon stocks or the reported number of escapees. To avoid possible biases caused by time-trends in the data sets, we analysed the data annually. The correlation coefficient for each year was then used in a "bare bones" meta-analysis (Hunter and Schmidt, 1990). We tested the significance of the effect sizes (mean correlation coefficients r) using the z test (Rosenthal, 1984) and used a meta-analytic approach because the number of counties with adequate data varied among years. In the meta-analyses,

Figure 1. Map showing the locations of salmon and/or rainbow trout farms in Norway in 2004 (data from *Havbruksregistret*, Norwegian Directorate for Fisheries). The map shows the localities where farming is permitted, but not all localities were in use in 2004. Only a few sites rear only rainbow trout. The counties used in the analysis are also shown.

the number of "county years" is regarded as the total sample size.

Results

The incidence of farmed salmon in summer and autumn fisheries – patterns over time

The percentage of farmed salmon in autumn samples was higher than in summer samples (Figure 3). The proportion of farmed salmon in the autumn samples has decreased since monitoring began in 1989, while the tendency in the summer samples has increased, with the largest proportion found in 2002. Weighting the incidence of farmed salmon in each river with the catches in individual rivers (a proxy for population size) gave lower percentages than not weighting for both summer and autumn samples (Figure 3).

The incidence of farmed salmon relative to stock size of farmed fish in net pens

The incidence of escaped farmed salmon in the rivers, at the county level, correlated positively and highly significantly with the stock of farmed salmon in net pens in the same areas (mean $r = 0.52$, $n = 157$ county years, $z = 6.54$, $p < 0.001$). The annual correlation coefficients varied from 0.17 to 0.77, and they decreased significantly during 1989–2004 (Figure 4). Analysing summer and autumn data separately provided a similar pattern: summer, mean $r = 0.42$, $n = 145$ county years, $z = 5.02$, $p < 0.001$; autumn, mean $r = 0.24$, $n = 146$ county years, $z = 2.91$, $p < 0.01$.

The incidence of farmed salmon relative to the reported number of escaped farmed salmon

The incidence of escaped farmed salmon in the rivers at the county level correlated positively with the reported number of escaped farmed salmon: mean $r = 0.24$, $n = 119$ county years, $z = 2.49$, $p < 0.02$. The annual correlation coefficients varied from −0.21 to 0.87, and there was no clear pattern with time for the years 1993–2004 (Figure 5). The correlations were not significant when analysing summer and autumn data separately: summer, mean $r = 0.17$, $n = 109$ county years, $z = 1.73$, n.s.; autumn, mean $r = 0.05$, $n = 113$ county years, $z = 0.41$, n.s.

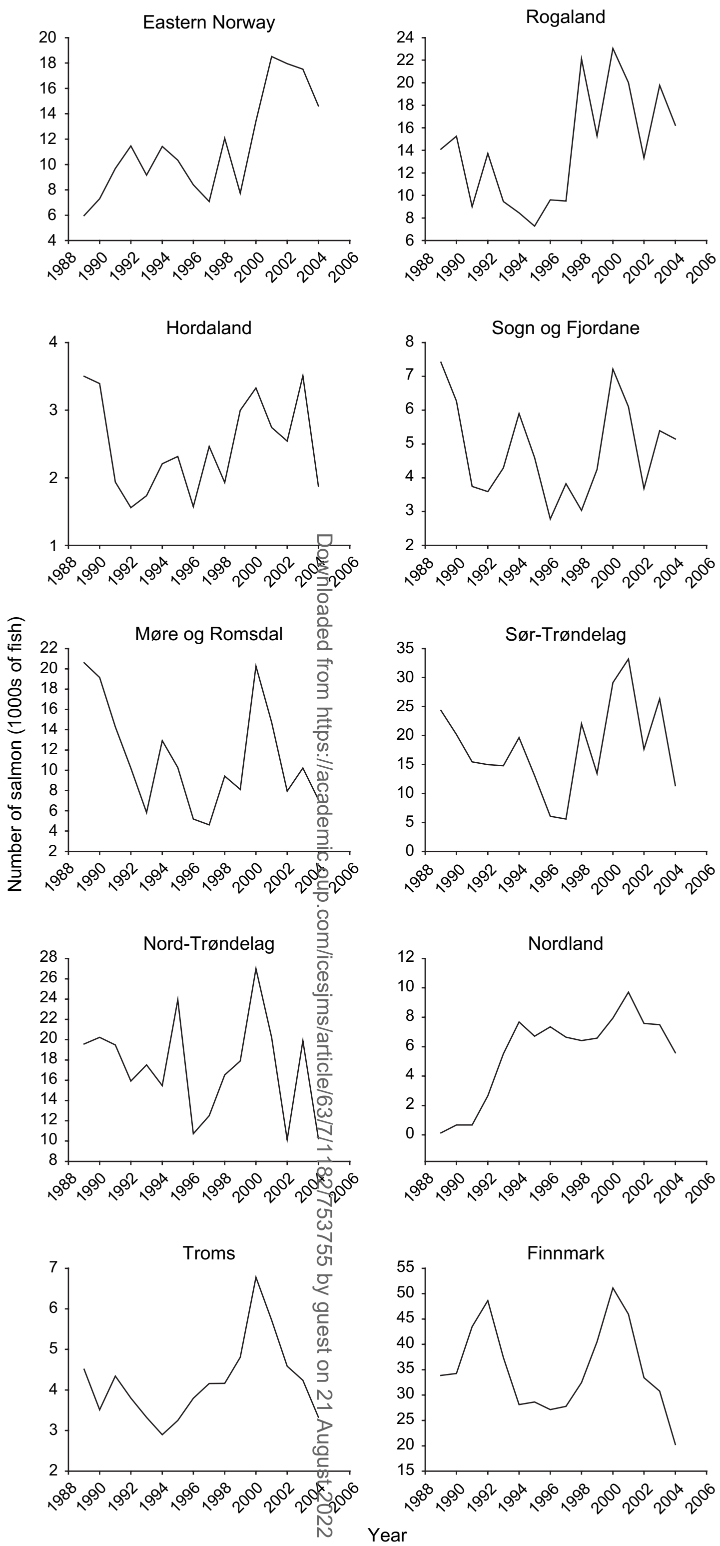

Figure 2. The total annual nominal catch of salmon (number of fish in thousands) in rivers for each county, 1989−2004 (Source: Statistics Norway and Directorate for Nature Management). Catches of escaped farmed salmon in the rivers are included. Note that the scales on the *y*-axes vary.

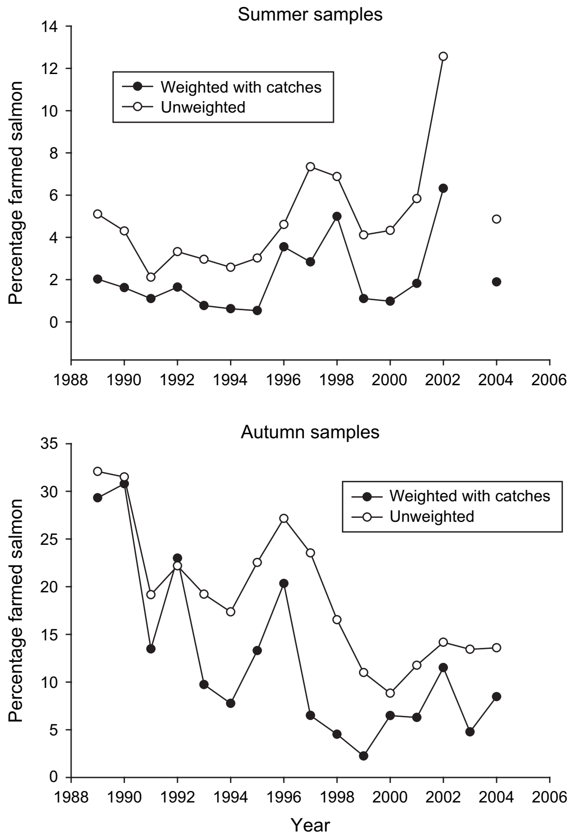

Figure 3. The percentage of escaped farmed salmon in summer and autumn samples in Norwegian rivers, 1989–2004. Data were computed as the mean of the transformed data from individual rivers and then back-transformed to percentages. The means were computed both by weighting and not weighting the percentages from individual rivers with the reported number of salmon caught in the rivers. Note the different scales on the *y*-axes of the two graphs.

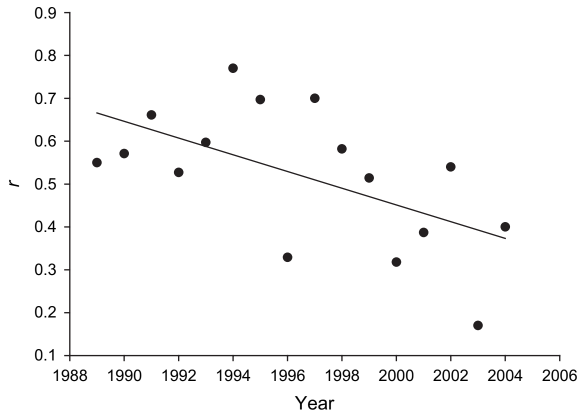

Figure 4. Correlation coefficients for the relationship between the incidence of escaped farmed salmon in rivers and the stock of farmed salmon in net pens plotted against time. There is a significant negative correlation with time, $r = -0.58$, $n = 16$ years, $p = 0.02$.

Discussion

The analysis indicates that farmed salmon escapees are found more commonly in wild salmon rivers in areas with higher levels of salmon farming activity than in other areas. This confirms expectations based on the behaviour of escaped farmed salmon (Hansen and Jonsson, 1991; Hansen, 2006). Similarly in Scotland, a higher frequency of occurrence of farmed salmon was found in rivers on the west coast, where the fish farming industry is located, than on the east coast, which has little salmon farming (Youngson *et al.*, 1997). In Canada, the proportion of farmed salmon entering the Magaguadavic River increased as the aquaculture industry in that area expanded (Carr *et al.*, 1997). A preliminary study suggests that up to 50% of the escaped farmed salmon caught in bag nets on the coast of Norway may have escaped as smolts or post-smolts (Lund, 1998). The positive correlation between the intensity of salmon farming and the incidence of farmed salmon in wild stocks at the county level may be the result of farmed salmon that escaped as smolts or post-smolts returning to the area from which they escaped. This homing behaviour has been demonstrated for hatchery-reared smolts with wild parents released in stocking programmes (e.g. Carlin, 1969; Sutterlin *et al.*, 1982; Hansen *et al.*, 1989; Heggberget *et al.*, 1991; Jonsson *et al.*, 2003). Furthermore, if adult farmed salmon escape relatively close to spawning and move randomly, they may also enter rivers in the fjord system in which the farm from which they escaped is located (Heggberget *et al.*, 1993).

The standing stock of farmed salmon in counties explained the incidence of farmed salmon in nearby rivers better than the reported number of escapees. This suggests that the official statistics underestimate the numbers of

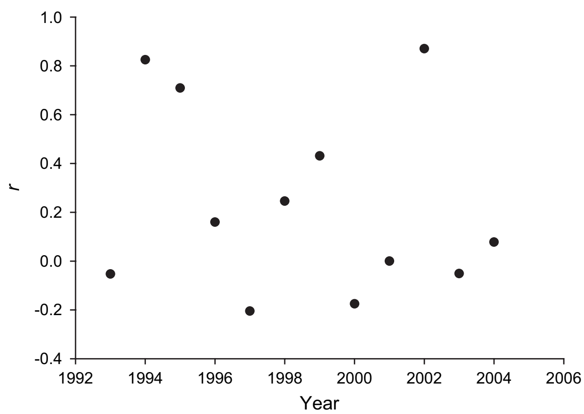

Figure 5. Correlation coefficients for the relationship between the incidence of escaped farmed salmon in rivers and the reported number of escaped farmed salmon plotted against time. The relationship is not significant.

escaped farmed salmon owing to non-reporting or under-reporting of some escape events (e.g. the small-scale trickle losses). However, farmed salmon may not ascend rivers in the same year as they escape, and this may weaken the relationship between the reported number of escaped salmon and farmed salmon in wild populations.

Correlation coefficients between the size of fish farm stocks and the incidence of farmed salmon in wild populations decreased with time. This may be the result of fewer smolts and post-smolts escaping from farms in recent years, leading to a smaller proportion of escaped salmon returning to the area from which they escaped, or as salmon farming activity has increased in Norway, the difference in the stock of farmed salmon between counties has become smaller, leading to less spread in this variable. The coefficient of variation for the size of the stock of farmed salmon among counties has decreased from 63% in 1989 to 50% in 2004, suggesting that, over time, the pattern may be, in part, a statistical artefact.

The proportion of farmed salmon has decreased with time in autumn samples, although it appears to have increased with time in summer samples. This increase with time is probably a consequence of more fish being caught in August in recent years, as a result of an extension to the fishing season established in 1995. Escaped farmed salmon tend to enter the rivers later in the season than wild salmon (Crozier, 1998; Fiske *et al.*, 2001), and therefore, it is more likely that the increase reflects the change in angling season rather than an increased number of escaped farmed salmon entering the rivers. The consistent decline in the proportion of farmed salmon in autumn samples during the study period probably reflects the reduction in the number of escaped farmed salmon in wild populations. It is also possible that changes in fishing seasons, resulting in more effort late in the season in both the sea and rivers, have increased catches of farmed salmon and thus reduced numbers in the spawning populations. A combination of these two explanations probably accounts for the observed pattern.

Limitations of the data set

The number of wild salmon populations used in this study varied among counties. Although the counties varied in size, they were chosen as the unit of analysis because they were the smallest geographical area for which fish farming statistics were available. A county such as Hordaland, which has a large salmon farming industry but small wild salmon populations (Skurdal *et al.*, 2001), probably strengthens the relationship between the stock of farmed salmon and the incidence of farmed salmon in wild populations than it would be if the wild populations in this county were larger. The data were weighted to reduce this effect, but as most wild stocks in Hordaland county are relatively small, it may not have been removed completely.

Rivers in the analysis were grouped at the county level, but a more robust analytical approach might have been to group rivers according to their distance from the nearest salmon farms. Unfortunately, historical data on the location of fish farms are not available. Therefore, our results should be interpreted cautiously, but they do indicate that farmed salmon pose a greater threat to the wild populations in areas with high production of farmed salmon than in low production areas. This is probably partly because areas with high production of farmed salmon coincide with areas with few spawners in the wild salmon populations. A combination of small wild salmon populations and high intensity of salmon farming is likely to have a negative impact on genetic diversity in the wild populations (Tufto, 2001).

The sampling in this study was based mainly on rod catches, and if farmed salmon and wild salmon differ in their catchability, the samples may not accurately reflect the "true" proportion of farmed salmon in wild populations. However, the data were collected in a similar manner in each river and should be comparable. We also used the mean proportion of escapees in summer and autumn samples as the measure of the incidence of farmed salmon in wild populations. The proportion depends on both the size of the wild salmon population and the number of escaped farmed salmon present. Therefore, apparent changes in the samples' proportions of farmed salmon may be the result of changes in the size of wild populations, even if the number of farmed salmon is relatively constant. The survival of wild salmon appears to be correlated over large areas (Friedland *et al.*, 2000). By analysing the data annually, we probably avoided some of the problems caused by proportions depending on the size of wild stocks. If the survival of both escaped farmed salmon and wild salmon are affected by the same factors, the proportions of farmed salmon in the samples may still provide a relatively comparable statistic of the year-to-year variation in escapees from salmon farms. Potential problems caused by variations in the abundance of wild populations on estimates of farmed salmon in the catches were minimized, first, by weighting rivers based on their catch and, second, by computing the correlations annually.

Furthermore, we combined summer and autumn samples to provide one estimate of the incidence of escapees for each year. This increased the sample size and allowed as much information as possible to be used in a single analysis. Analysing the data for summer and autumn samples separately gave similar results when using farmed salmon stock, but resulted in non-significant correlations when using the reported number of escapees. Therefore, our conclusion that the size of the stock of farmed salmon is a better predictor of the incidence of farmed salmon in wild populations than the reported number of fish farm escapees was valid even when summer and autumn samples were analysed separately.

In conclusion, our data suggest that fewer farmed salmon enter rivers in areas with lower salmon farming production.

Therefore, area protection is likely to reduce the impact of escaped farmed salmon in nearby wild salmon populations. However, our analysis is based on a geographical scale (counties) too large to allow detailed advice to be developed about the appropriate size for protected areas as a management approach to reducing the impact of farmed salmon in wild salmon populations.

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