Atlantic salmon in the Baltic Sea -
the world’s second most disturbed salmon populations

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Abstract

The Baltic Sea supports genetically distinct populations of Atlantic salmon (*Salmo salar* L.) that do not migrate to the Atlantic Ocean. Over the course of the 20th century, the two major salmon producing nations in the Baltic (Sweden and Finland) have exchanged wild salmon production for hydroelectric power generation. Salmon production lost to dams has been mitigated by hatchery production systems in both countries. In 1996, hatchery production was thought to account for 90% of all smolts entering the Baltic Sea. Coincident with the shift from wild to hatchery production, the fishery shifted from targeting migrating spawners in rivermouths and coastal locations to offshore driftnet fisheries on mixed stocks of feeding salmon. Total salmon catches have remained high for the past 50 years (~9 generations). Despite fishery exploitation rates that exceed 90%, reproductive disorders that destroy up to 90% alevins, destruction of 82% of salmon spawning habitat, wild salmon still remain and plans are being implemented to protect them. Many features of Baltic salmon population dynamics are positively correlated among populations. Marine survival of reared salmon is correlated among Baltic hatcheries but not with the west coast, annual catches of wild salmon in Gulf of Bothnia rivers are correlated, as is the annual recruitment of wild salmon parr in Gulf of Bothnia rivers. The high degree of correlation over reasonably large distances was not expected based on recently published results and probably makes the job of managing Baltic salmon a little easier.
Introduction

Although over 100 rivers supported Baltic salmon (*Salmo salar* L.) populations in the 19th century (HELCOM web page 1997), there were concerns about overfishing (Lundberg 1886). By the end of the 19th century, salmon had been extirpated from some smaller Finnish rivers (Christensen and Johansson 1975). At the end of the 20th century, the current count of rivers with salmon is, optimistically, about 40 (Figure 1). Even this number may be overestimated as it is based on the 'faint hope' that sightings of salmon in some rivers indicates self-sustaining populations (ICES 1997). This is particularly true in the southeastern Baltic where the data on salmon abundance are of uncertain quality. Hydroelectric power developments have been the primary agent of salmon population extirpation, although pollution, hatchery production, and intensive mixed stock fisheries have also contributed to their demise.

Experimental releases of salmon and sea-trout fry in the early 19th century suggested that fisheries could be improved by artificial hatching of eggs (Lundberg 1886). The first salmon hatcheries in the Baltic were built during the 1860's (Lindroth 1965). By the late 19th century, Swedish releases of fry averaged 1,000,000 annually. Fry releases grew slowly until the mid 1930s when they increased to a peak of 8,000,000. Releases of parr began in the early 1930s and peaked at 1,200,000 in 1950. Smolt releases began in the early 1950's and rose very quickly to greater than 1 million. By 1970, annual Swedish smolt releases totaled about 1.9 million and have remained near 2 million ever since. Most of these releases were due to Water Court decisions that required the state power companies to compensate for the loss of spawning and freshwater rearing habitat when the dams were built. Finnish and other Baltic countries increased smolt releases beginning in the 1980s. Currently, about 5 million smolts are released annually (Karlsson and Karlström 1994).

This paper is primarily concerned with scale; the temporal and geographic scale of factors affecting Baltic salmon survival. The scale of potential impacts is an important component of modeling the risks of population extinction. Myers et al. (1997) concluded that the spatial correlation scale of recruitment success for anadromous species was intermediate between that of freshwater species (50 km) and marine species (500 km). Their model examines the relationship between population covariance and the geographic distance among populations. Neighbouring populations were shown to covary more than widely separated populations. As neighbouring populations are likely to have more in common, they may also exhibit similar responses to perturbation. The important questions to consider with regard to spatial effects (what is close? and what is distant?) is a function of the scale of the potential impact.
Methods and Materials

Swedish and Finnish salmon hatcheries have been tagging and releasing salmon smolts since the 1950s, primarily to assess the contribution of each hatchery to the fishery. There is no designed sampling plan to recover tags from the fishery, however, rewards are offered to stimulate fishermen to return them. The annual rates of tag recapture are frequently used as surrogates for marine survival. Survivals computed from these tag recaptures will represent the minimum survival because there is a greater likelihood of underreporting (tags not being turned in by fishermen) and little opportunity for overreporting.
The estimates of total survival for all Swedish hatcheries to the entire Baltic Sea in any year was computed as the total number of tag recaptures divided by the total number of tag releases in a given year. These estimates will therefore reflect the recovery rates of the largest hatcheries. The historical record of individual hatchery recovery rates is substantial in some hatcheries, although there are some hatcheries (e.g., Ljungan) where about 50% of the years were reported. To maximize the use of available data, pairwise deletion was used to compute the correlations among hatcheries. Multiple dimensional scaling was used to examine the correlation pattern among hatcheries.

Historical salmon catch data at the Svartö weir (1804-1953) were taken from Lundberg (1886) and Svärdson (1955). Catch data for the R. Oulujoki were taken from Hagman and Kukkamäki (1938).

To determine the spatial correlation scale of survival among hatcheries, I followed Myers (1997) and attempted to estimate the e-folding scale. This measures the distance required for the correlation among hatcheries to decrease by a factor of \( e^{-1} \). Hatchery location was approximated using a large scale map. Pearson product moment correlations were computed among all pairwise comparisons of hatchery survival time series. For a similar analysis with wild parr recruitment, the point describing the location of a river containing wild salmon parr was determined as the midpoint along the length of a river.

**Equation 1. Exponential decay model (Myers et al. 1997)**

\[
\rho(d) = \rho_0 e^{-d/v}
\]

where \( d \) is the great circle distance between 2 locations,
\( \rho_0 \) is a parameter for the estimated correlation between 2 populations at zero separation,
and \( v \) is the e-folding scale (km) estimated from the data.

A number of steps were taken to estimate the total annual catch of Baltic salmon (excluding the Gulf of Finland), between 1804 and 1971. Total catches since 1971 are available (ICES 1997). Regression methods were used to extend time series of catches using those periods where the different catch series spanned similar years. The total reported catch of the combined annual Danish and Finnish catches extends from 1903 to the present (Christensen and Johansson 1975, ICES 1997). The Danish/Finnish series of catches shares a considerable number of years in common with the reported rivers catches at the Svartö weir (R. Lule älv) and with the R. Oulujoki. The Danish/Finnish series was extended backwards in time using the catch from each river, independently. This provided two series of estimates of total Danish/Finnish catch, one dating from 1804 based on the Svartö data and one from 1860 based on the Oulujoki series. Once these series had been developed, both estimates of the Danish/Finnish catch series were used to estimate the total Baltic salmon catch.
Results

**Marine survival trends - reared salmon**

The grand mean survival to the fishery in the Baltic Sea is 9.8% compared with 7.2% for Swedish hatchery fish released to the North Sea (Figure 2). There is no significant correlation (r=0.11) between survivals of salmon released on from west coast hatcheries and those released within the Baltic Sea.

![Graph showing survival rates](image)

**Figure 2 Tag recapture rates for all Swedish hatcheries combined (Data provided by Mr. Curt Insulander (Salmon Research Institute, Älvkarleby, Sweden)).**

The mean survival values for individual hatcheries, including two from Finland, varied from 6.5% at the Iijoki hatchery (Finland) to 11.8% at the hatchery on the river Dalälven (Figure 3). A common feature of the Swedish hatcheries is that the most recent smolt year-classes have the lowest recapture rates in the history of the record. These low survivals appear to follow a long trend of declining survival.
Figure 3 Tag recapture rates for 8 Swedish and 1 Finnish (Oulu) hatcheries in the Baltic Sea.

Salmon population synchrony

One of the dominant characteristics of the history of salmon in the Baltic Sea is that catches have fluctuated synchronously among rivers over long time scales (Alm 1928, Hagman and Kukkamäki 1938, Lindroth 1965). Recent data indicate that the recruitment of wild age 0+ parr among some northern rivers is highly correlated (Figure 4) as are the catches of migrating wild salmon in rivers (Figure 5).
Figure 4. Correlations in annual recruitment of wild age 0+ salmon parr in Gulf of Bothnia rivers.

Figure 5. Correlations in annual catches of wild salmon among Swedish rivers.

Since the 1950’s, the offshore fishery has been so intense that it is possible to speculate that the recent synchrony is driven entirely by the fishery. Annual salmon catches in different locations within the Baltic have been correlated since the 19th century (Figure 6) suggesting that it is an inherent property of the Baltic. The synchronous collapse of populations in 1900 was one of the first major events that focused research on this issue.
Figure 6 Salmon catch (tonnes) in the River Oulujoki, Finland versus the salmon catch (deci-tons) at the Svärto Weir (Lule älv, Sweden) from 1860 to 1944 on log10 scales.

**Correlations - reared salmon**

Recapture rates (minimum survival) of hatchery reared salmon in the Baltic Sea are positively correlated indicating a substantial degree of synchrony in interannual smolt survival. Multivariate analyses of the correlation matrix indicated that there is geographic structure in the correlations (Figure 8). The most similar hatcheries are those of central Sweden (Indals, Ume, Ångerman). The ranking of hatcheries on Dimension 1 is similar to the ranking that would be obtained if a line was traced northward along the coast from the southernmost Finnish hatchery (II), around the Swedish coastline and out to the west coast hatchery on the River Lagan. The Spearman rank correlation of the hatchery position on the line I've just described and the hatchery rank on Dimension 1 is 0.95. The second dimension with Lule and Dal at one extreme and Skellefte and Ljungan at the other is more difficult to interpret but it does tend to separate populations with more unique survival histories.
Figure 7. Multiple dimensional scaling of the survival correlation among hatcheries in the Baltic Sea.

Spatial correlation scale

The mean correlation in marine survival among all pairwise comparisons of salmon hatcheries within the Baltic Sea is \( r = 0.45 \) (range: 0.20 - 0.82). The relationship between correlation and geographic distance between hatcheries is weak. The survival correlations among hatcheries did not decrease rapidly with increasing distance between the hatcheries (Figure 8). This resulted in problems estimating the e-folding scale parameter, \( v \). When a hatchery from the west coast of Sweden (River Lagan) was added to the analysis, it added sufficient decay in the correlation-distance relationship that the estimate of \( v \) stabilized at 329 km. This suggests that the e-folding rate for survival of reared Baltic salmon (within the Baltic Sea) is greater than 329 km.
The spatial correlation scale of wild parr (age 0+) recruitment in six Swedish and one Finish river is large. The non-linear regression search algorithm in SYSTAT was unable to converge to a solution, suggesting that there is insufficient information in the data to estimate the e-folding scale. The mean correlation of all pairwise comparisons of recruitment in rivers was $r=0.73$ and it decays very little with geographic distance between rivers.

Figure 8. Pairwise correlations in hatchery survival versus distance (km) among Baltic salmon hatcheries.

Figure 9. Pairwise correlations in wild age 0+ salmon parr versus pairwise distances among seven rivers in the northern Baltic Sea.
Although the number of rivers is few, wild salmon catches in the rivers Torne, Kalix, Byske, and Vindelälven indicate that the spatial correlation in the annual number of wild spawners is high (Figure 10).

![Figure 10. Pairwise correlations in annual wild salmon catch versus distance among four rivers in the northern Baltic.](image)

**Reconstructed salmon catches**

Reconstructing total salmon catches prior to 1972 (excluding Gulf of Finland) from either the Svartö weir (R. Lule älv) or the R. Oulujoki time series produced comparable estimates of total salmon catch. The average annual catches was about 1,000 tonnes for most of the 19th century. At the turn of the century, catches dropped by about 40% and remained at low levels until 1945 when they increased dramatically. The two series differ significantly over an eight year period during the mid-1940s to the early 1950s. During this period the Oulujoki time series suggests that total salmon catches were much higher than predicted by the R. Lule älv series. There is general agreement that salmon were significantly more abundant during the late 1940s (Lindroth 1965, Karlsson and Karlström 1994) so the Oulujoki series likely provides a better prediction of this period.
Figure 11. Total catches of Baltic salmon (excluding Gulf of Finland). Catches after 1971 are taken from the 1997 ICES WGBAST report. Values before 1972 were estimated independently from historical weir catches on the Lule älv and the Oulujoki.

Discussion

The theory of salmon population extinction was put into practice in the Baltic Sea. At some point during the last 100 years, almost every human and natural threat to salmon abundance has been applied, and with vigor. The good news is that something approaching half the rivers with wild populations still remain after such an onslaught. The bad news is that half the rivers and their wild populations are gone and will probably never return in our lifetimes. Despite the elimination of many wild salmon populations, the catches of salmon in the Baltic Sea have continued at historically high levels since the mid 1940's. The increase cannot be attributed entirely to hatcheries because it occurred before hatcheries were producing current levels of smolt production.

The high correlation structure in recruitment and abundance of wild and reared salmon populations in the Baltic Sea can be exploited to study longterm changes in salmon abundance. Although the catch histories at the Svartö weir and the Oulujoki ended at the middle of the present century, they are of sufficient length that they extend continuously back in time to the early 19th century and they overlap with other, more complete catch time series that extend to the present. Reconstructed Baltic salmon catches for the past two centuries suggest that the dominant changes have been major shifts in salmon production that occur rapidly. Two shifts have occurred in the period of record: a decrease in 1900 and an increase in 1945 (Lindroth 1965). Interannual effects are a minor component of the variation compared with the shifts between one production regime and another. Although these changes have sparked considerable scientific interest, their causes have not been entirely understood. Most studies suggest that, because of the scale, climate must be the regulating factor but no convincing arguments have been promulgated. The recent
experience with M74 suggests that other large-scale phenomena have to potential to regulate abundance of salmon in the Baltic Sea.

Since the mid 1940's, Baltic salmon production has remained high due to hatchery stocking, and perhaps due to increased abundance of wild fish since the 1940s. Current high production levels cannot be attributed to increasing hatchery smolt releases or higher hatchery survivals. Tag recapture data suggest that many hatcheries have decreasing survival. If this is true, increased wild production must have contributed to the increased catches. If one assumes an average annual release from the 1950s to the present of approximately three million smolts with an average survival of 10% and an average weight at catch of 4.5 kg, one can only account for 1,350 t of hatchery fish in the catch. This number is substantially less than the average catches over that same period. Either hatchery survivals are markedly underestimated or wild salmon abundance is considerably higher. Evidence from scale pattern analysis suggests that wild salmon abundance may be underestimated (Ikonen and Torvi 1997). Taking this to the extreme, it may be possible to speed the achievement of IBSFC Salmon Action Plan goals in some rivers simply by doing a better job of estimating salmon abundance and origin. Unfortunately, smolt production capacities are not that well determined in rivers so it will take some time before sufficient data are available to determine productive capacities. Where the wild salmon are being counted accurately in the River Vindelälven, the number of spawners has been increasing since the early 1980s (Figure 12).

![Figure 12. Number of spawners passing the Norrfors fish trap on the River Vindelälven.](image)

Myers et al. (1997) suggested that interannual recruitment variation in marine species has spatial correlation scales of approximately 500 km while freshwater species have spatial correlation scales of approximately 50 km and that the spatial correlation scales of recruitment in anadromous species are intermediate. The spatial correlation scales of Baltic salmon are not consistent with those results. The e-folding scale for both freshwater and marine survival in
Baltic salmon is greater than 400 km. It seems likely that it may be as large as the entire Baltic Sea although it might be possible to refine the scale if similar data were available for the Gulf of Finland and the southeastern Baltic. The spatial correlation scale of Baltic salmon does not appear to extend beyond the Baltic as there is no significant longterm correlation in tag recapture rates between the west coast hatcheries and the Baltic Sea hatcheries. Perhaps this suggests that the ultimate cause of large-scale variations in survival may not be climatic in origin.

The high correlation among important population characteristics of salmon (abundance, recruitment, survival, size-at-age) within the Baltic Sea suggests that the geographic scale of the marine system determines the complexity of factors affecting population abundance. If management actions affect mixed stock fisheries in the Baltic Sea, the impacts will likely benefit most populations because the e-folding scale is approximately the same magnitude as the geographic scale of the Baltic. If the correlation scale were much smaller, any management actions aimed at restoration would need consider a more spatially complex environment.

Low frequency shifts in salmon production are not unique to the Baltic Sea. Recent findings (Beamish and Boullion 1993, Beamish et al. 1995, Adkison et al. 1996) have shown that Pacific salmon undergo shifts in productivity that are generally hypothesized to be related to climatic variations. Adkison et al. (1996) found significant covariation in the productivity of sockeye populations in Bristol Bay, Alaska (the world’s largest producer of sockeye salmon) but not for Fraser River (Canada) populations. Only recently has an hypothesis by which climatic variations might affect salmon productivity through ecosystem effects been formulated (Gargett 1997). A similar exercise is required for the Baltic salmon.

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