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Antti Siira

MIXED-STOCK EXPLOITATION OF ATLANTIC SALMON (*SALMO SALAR* L.) AND SEAL-INDUCED DAMAGE IN THE COASTAL TRAP-NET FISHERY OF THE GULF OF BOTHNIA

CHALLENGES AND POTENTIAL SOLUTIONS

FACULTY OF SCIENCE,
DEPARTMENT OF BIOLOGY,
UNIVERSITY OF OULU;
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Challenges and potential solutions

Academic dissertation to be presented, with the assent of the Faculty of Science of the University of Oulu, for public defence in Kuusamonsali (Auditorium YB210), Linnanmaa, on October 6th, 2007, at 12 noon

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Abstract

The aims of this thesis included identifying ways to mitigate the economic losses of the commercial fishery in the Gulf of Bothnia resulting from fishery regulation enforced to protect wild Atlantic salmon stocks, the recent decline in survival of hatchery-reared salmon, and the dramatically increased seal-induced catch and gear damage. In addition, these solutions should facilitate safeguarding the recently-recovered wild salmon stocks and seal populations. Other goals included adding to and updating basic knowledge on the effects of increased seal populations, migrating salmon stocks, the coastal trap-net fishery, and their interactions.

Seal-induced damage to the commercial fishery was found to be a significant problem throughout the Gulf of Bothnia. Catch and gear damage varied considerably among regions, fishing periods, target species and trap-net models. The regional patterns in seal-induced damage depended on the number of seals in the region and the type of gear, which is strongly associated with the netting materials. Strong and thick materials are more resistant to the attacks of hunting seals. Finer materials and larger mesh sizes that entangle fish are most prone to seal damage. Besides careful selection of the netting material it is also possible to markedly reduce damage by appropriate gear modifications. Three modified trap-net models showed promising results in terms of seal protection, with the pontoon trap being the most successful design.

The total size of the spawning salmon population in the Gulf of Bothnia was c. 230 000 in the first two years of the 2000s. The proportions of wild salmon and hatchery-reared salmon, however, appeared to markedly change between years. The survival rate of cultured smolts seems to be considerably lower than that of wild smolts.

Large variation in the returning migration patterns and run timing of salmon was found between sea age groups, stock components, and among and within regions. Run timing estimates revealed that the temporal regulation effectively safeguards the wild salmon, but, at the same time, a substantial proportion of the reared salmon escape the coastal fisheries in different regions.

The likelihood of survival of wild salmon captured with trap-nets and then released was high, and the cumulative mortality even after several capture-and-release events was estimated to below. Trap-net capture and release did not lead to considerable changes in the normal migration behaviour of Atlantic salmon. This result suggests the potential for a selective harvesting strategy; a system where exploitable (e.g. hatchery-reared fish) and safeguarded (e.g. wild vulnerable stocks) fractions of a fish population complex could be separated in a mixed-stock fishery. However, before introducing a practical and successful selective trap-net fishery, several preconditions should be fulfilled.

Keywords: Atlantic salmon, Grey seal, Gulf of Bothnia, migration, seal-damage, selective fishery

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List of original papers

This thesis is based on the following original papers, which are referred to in the text by their Roman numerals:

I Kauppinen T, Siira A & Suuronen P (2005) Temporal and regional patterns in seal induced catch and gear damage in the coastal trap-net fishery in the northern Baltic Sea: effect of netting material on damage. Fisheries Research 73: 99–106.

II Suuronen P, Siira A, Kauppinen T, Riikonen R, Lehtonen E & Harjunpää H (2006) Reduction of seal-induced catch and gear damage by modification of trap-net design: design principles for a seal-safe trap-net. Fisheries Research 79: 129–138.

III Siira A, Suuronen P, Kreivi P & Erkinaro J (2006) Size of wild and hatchery-reared Atlantic salmon populations in the northern Baltic Sea estimated by a stratified mark-recapture method. ICES Journal of Marine Science 63: 1477–1487.

IV Siira A, Suuronen P, Erkinaro J & Jounela P (2007) Run timing and migration routes of returning Atlantic salmon in the Northern Baltic Sea; implications for fisheries management. Manuscript.

V Siira A, Suuronen P, Ikonen E & Erkinaro J (2006) Survival of Atlantic salmon captured in and released from a commercial trap-net: potential for selective harvesting of stocked salmon. Fisheries Research 80: 280–294.

Contents

1 Introduction

In mixed-stock fisheries, the target populations often show differences in their status that may lead to the serious reduction and extinction of weak populations through high exploitation rates (e.g. Hilborn 1985). A mixed-stock fishery may also include hatchery-reared stocks that are released to be effectively exploited and, furthermore, should not mix with natural populations. Another factor affecting both the fish stocks and the fishery may be piscivorous marine mammals, mostly seals (e.g. Harwood 1992, BIM 2001, Moore 2003). Fishermen and mammals compete for the same resources and may further reduce threatened fish stocks or species (see Chouinard *et al.* 2004). The conflicting interactions between fish stocks, seals and humans pose considerable challenges for fisheries management to produce reliable information and find practical solutions to the conflicts. How can a balance be reached between the protection and exploitation of different fish stocks and the simultaneous safeguarding of seal populations and mitigation of the economic drawbacks for the fishery?

Growing seal populations are causing increasing problems to fisheries in many areas along the northern Atlantic coast (e.g. Haug & Nilssen 1995, Morris 1996, Cairns *et al.* 2000, Moore 2003) and in the Baltic Sea (e.g. Baltscheffsky 1997, Lunneryd & Westerberg 1997, Lunneryd 2001). In the northern part of the Baltic Sea, the Gulf of Bothnia, seal-induced damage in the trap-net fishery has dramatically increased since the mid-1990s (Westerberg *et al.* 2000, Kreivi *et al.* 2002) and coastal fishermen consider seals to be a serious threat to their livelihoods.

Baltic salmon have been heavily exploited during recent decades by the offshore and coastal commercial fishery as well as by the recreational fishery that mainly takes place in the rivers (e.g. Rappe *et al.* 1999, ICES 2006). Since the late 1990s, the main wild Atlantic salmon (*Salmo salar* L.) stocks in the northern Baltic Sea have recovered, largely due to a reduction in the total allowable catches of the offshore fishery and due to the strict seasonal closures (delayed openings) along the Finnish coast of the Gulf of Bothnia (Romakkaniemi *et al.* 2003, ICES 2006). From 1996 to 2003 the abundance of juvenile salmon in rivers increased about 10-fold and a marked increase in wild salmon was observed in commercial catches in the sea areas (ICES 2006, Koljonen 2006). Simultaneously, a substantial increase occurred in the recreational fishery for salmon in major spawning rivers. Clearly, from the perspective of conservation, management of the Baltic salmon fishery has recently been successful. However, the strict seasonal fishing restrictions that safeguard the spawning migration of wild salmon may have effectively prevented salmon fishing during the peak migration along the coast (see Jounela *et al.* 2006). About half of migrating salmon are produced in hatcheries and stocked as smolts in the sea to mitigate for lost salmon production in rivers that have been dammed for hydropower production (Rappe *et al.* 1999, ICES 2006). They are specifically stocked for harvest in the sea areas and in the mouths of dammed rivers; the returning adults of these stockings do not have spawning areas.

The restrictions enforced to protect wild Atlantic salmon stocks together with the recent decrease in the survival of cultured salmon (ICES 2006) and the dramatically increased seal-induced catch damage (Fjälling 2005) have had severe socio-economic impacts on the commercial fishery along the coastal areas of the Gulf of Bothnia. In addition, the coastal commercial fishery has faced considerable changes in recent decades due to changes in fish markets, the environment and fish stocks (Hudd & Leskelä 1998). Larger trap-nets have been introduced and coastal fishing activities in the Gulf of Bothnia have partly been moved from near-shore regions to the open sea.

To allow the harvesting of stocked fish while simultaneously protecting the wild stocks, one alternative possibility is to introduce a fishery where stocked fish can be selectively harvested. Such selective fisheries have been tested for Pacific salmon (*Oncorhynchus sp.*) on the west coast of North America using hook and line (Anon. 2005) and in the Columbia River using tangle-nets (Vander Haegen *et al.* 2004).

Fisheries scientists have sought solutions to the growing seal problem by developing methods to scare away those seals that have become experts at feeding on fish caught in fishing gear (e.g. Westerberg *et al.* 2000). It soon became clear, however, that scaring seals away from fishing gear was not an easy task, especially in remote and exposed off-shore areas. It appeared that a more effective and practical way to reduce the seal-induced damage may be, at least in the trap-net fishery, to prevent seals from entering the fish bag and thereby protect the fish already caught in the bag (Lunneryd & Westerberg 1997, Lunneryd 2001, Lehtonen & Suuronen 2004).

One of the aims of this thesis included identifying ways to mitigate the recent economic losses of the commercial fishery in the Gulf of Bothnia. These solutions should also facilitate safeguarding the recently recovered wild salmon stocks and seal populations. Other goals included adding to and updating basic knowledge on the effects of increased seal populations, migrating salmon stocks, the coastal commercial trap-net fishery, and their interactions (Fig. 1).

The first two papers (I, II) focus on damage caused by growing seal populations to the coastal commercial trap-net fishery of the Gulf of Bothnia, their temporal and regional patterns, and possibilities to reduce the damage. The main questions addressed in these papers were: How do the different regional fishing strategies affect the extent of damage? Is it possible to prevent the entanglement of salmon and reduce the damage by changing trap-net fishing procedures and gear design?

A considerable challenge in salmon stock assessment has been the estimation of the total size of the Baltic salmon population complex and the proportion of the different stock components. This information would be of great value to fisheries managers. In addition, the recent recovery of wild salmon and decrease in the survival of hatchery-reared salmon (ICES 2006) has called for better estimates of the population sizes that enter the Gulf of Bothnia. Questions addressed in paper III include: What was the total size of the salmon population complex and the proportion of the different stock components migrating in the Gulf of Bothnia in the early 2000s? Were there any differences in the marine survival and spawning escapement between wild and reared salmon smolts? How well did the produced estimates correspond with other monitored population indicators and reference points?

The main intention behind the regional temporal closures is to reduce the fishing mortality of the wild migrating salmon, especially of older females, which are the most valuable fish for natural reproduction and tend to migrate earlier in the season than the reared fish (e.g. Karlsson *et al.* 1994). Furthermore, the temporal regulations have aimed at enabling targeting of the fishery on later migrating reared salmon. The temporal regulation has also been based on the belief that the different timing of wild and reared salmon persists and the migration is linear and continuous from south to north in the Gulf of Bothnia. Several factors, however, may have influenced the returning migration behaviour. Questions addressed in the next paper (IV) were: What are the current routes, run timing, and catch accumulation of the migrating Atlantic salmon stocks in the Gulf of Bothnia after marked changes in the wild stock status, wild-to-reared ratio, and fisheries. Are the assumptions of the present temporal regulations valid under current circumstances?

In the final paper (V), selective fishing practices of the commercial salmon trap-net fishery were simulated in a full-scale tagging experiment. Salmon were captured, tagged, released and re-released in different parts of their return migration in the Gulf of Bothnia The main question addressed here was: Is it possible to catch and release wild salmon in a commercial trap-net fishery, even several times, and assume high survival and normal migration behaviour? In other words, is there potential for a biologically-feasible selective fishery, where wild salmon can be released while hatchery-reared fish are harvested?

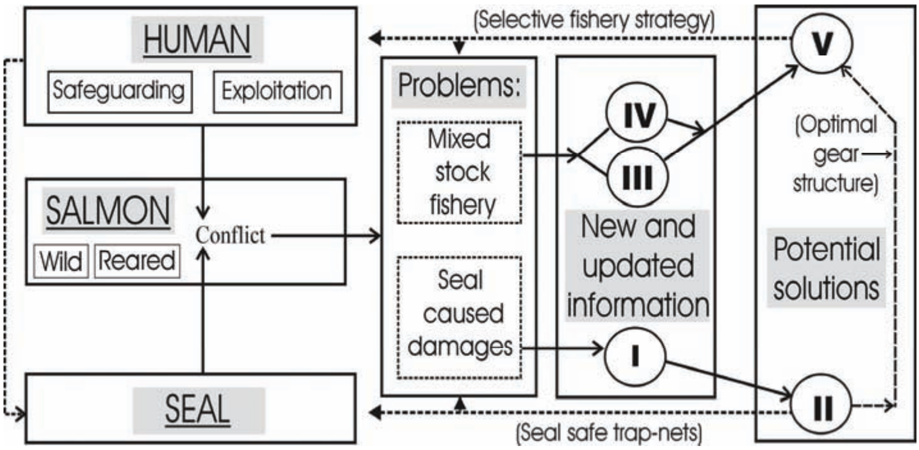

Fig. 1. Schematic diagram of interactions between humans, salmon and seals in the Gulf of Bothnia. Roman numbers refer to the original papers of this thesis.

2 Material and methods

2.1 Study area, species and fishery

The Gulf of Bothnia (60ºN - 65ºN) is the northernmost and most isolated part of the Baltic Sea (Fig. 2). There is virtually no tide and salinity and temperature discontinuities are weak. Salinity in its northernmost parts is especially low (0–0.4‰). In most winters the gulf is ice-covered. Freezing begins in the north in November and the ice cover reaches its greatest extent in February. The ice thaws in April to May. In this thesis, the Gulf of the Bothnia was divided into five regions (Fig. 2). These regions almost overlap with those defining coastal temporal closure dates (delayed openings) in the Finnish salmon fishery (ICES 2006, specific spring fishery allowed in the Åland Sea, which is thus separated from the Bothnian Sea). The regions, from south to north, are here referred to as the Åland Sea, the Bothnian Sea, the Northern Quark, the Bothnian Bay and the northern Bothnian Bay. In addition, in paper I, the Bothnian Bay is referred to as the Central Bothnian Bay and the Northern Quark is divided into two regions: the Northern Bothnian Sea and the southern Bothnian Bay.

Two seal species are regularly found in the Gulf of Bothnia: the grey seal (*Halichoerus grypus*) and the ringed seal (*Phoca hispida botnica*). Grey seals cause most of the damage in the Baltic Sea (Westerberg *et al.* 2000, Kreivi *et al.* 2002, Lunneryd *et al.* 2003). Ringed seals are smaller and cause less damage (Westerberg *et al.* 2000). Seals cause problems to fisheries and fish farmers by damaging fish and fishing gears and scaring fish away (e.g. Westerberg *et al.* 2000, Kreivi *et al.* 2002, Lunneryd *et al.* 2003, Lehtonen & Suuronen 2004). Grey seals are found throughout the Baltic Sea, but are mainly distributed in the Gulf of Bothnia and the Åland Sea (Sjöberg 1999). Due to favourable ice conditions in winter, the northern Bothnian Bay is the main range of the Baltic ringed seal. Seal populations of the Baltic Sea started to increase in the 1980s, after hunting of seals was prohibited and environmental conditions improved (Helle 1999). In overflight censuses that covered the whole Baltic Sea in 2006, c. 21 000 grey seals were found (Finnish Game and Fisheries Research Institute, FGFRI, unpublished data). As grey seals have high mobility (Sjöberg 1999) and diving seals cannot be seen, the estimate is only approximate (Helle 1999). The ringed seal population in the Baltic Sea has been estimated to be around 6500 individuals (FGFRI, unpublished data). The estimated yearly growth rate for the grey seal population in the Baltic Sea is 10% and that of the ringed seal 6% (Halkka *et al.* 2005, Stenman *et al.* 2005).

The feeding migration of stocks of Baltic salmon (the name given to Atlantic salmon in the Baltic Sea) extends to the central and southern parts of the Baltic Main Basin; fish do not migrate out of the Baltic Sea (Christensen & Larsson 1979, Karlsson & Karlström 1994). The main return migration of the Baltic salmon is directed to the northern part of the Baltic Sea, the Gulf of the Bothnia. This is because most salmon in the Baltic Sea originate in the Gulf of Bothnia (Rappe *et al.* 1999, ICES 2006). Twelve of the 13 rivers still having wild salmon stocks in the Gulf of Bothnia are located in its northernmost part, the Bothnian Bay. The annual production of wild salmon smolts in the salmon rivers of the Gulf of Bothnia has in recent years been about one million smolts (ICES 2006). About 3.4 –3.8 million hatchery-reared salmon smolts are released annually into the Gulf of Bothnia, mainly to compensate for the lost salmon production in rivers that have been dammed for hydropower production (Rappe *et al.* 1999, ICES 2006). In addition, substantial numbers of smolts and parr have been released in some rivers in the Gulf of Bothnia to supplement wild production (e.g. Romakkaniemi *et al.* 2003). Finland enforced an early-season closure of the coastal fishery in 1986. In 1996, the restrictions were strengthened and since then temporal regulation on the Finnish coast of the Gulf of the Bothnia has been based on four different regions divided according to latitude (ICES 2006). In contrast to Finnish coastal regulation, there are no temporal restrictions in especially specified areas in the estuaries of the rivers Oulujoki, Iijoki and Kemijoki. These terminal fishing areas allow the capture of hatchery-reared salmon returning to the outlets of the dammed rivers outside of the migration routes of the returning wild salmon. These areas, however, were founded at a time when wild stocks were close to extinction and the migration routes of wild salmon were largely unknown.

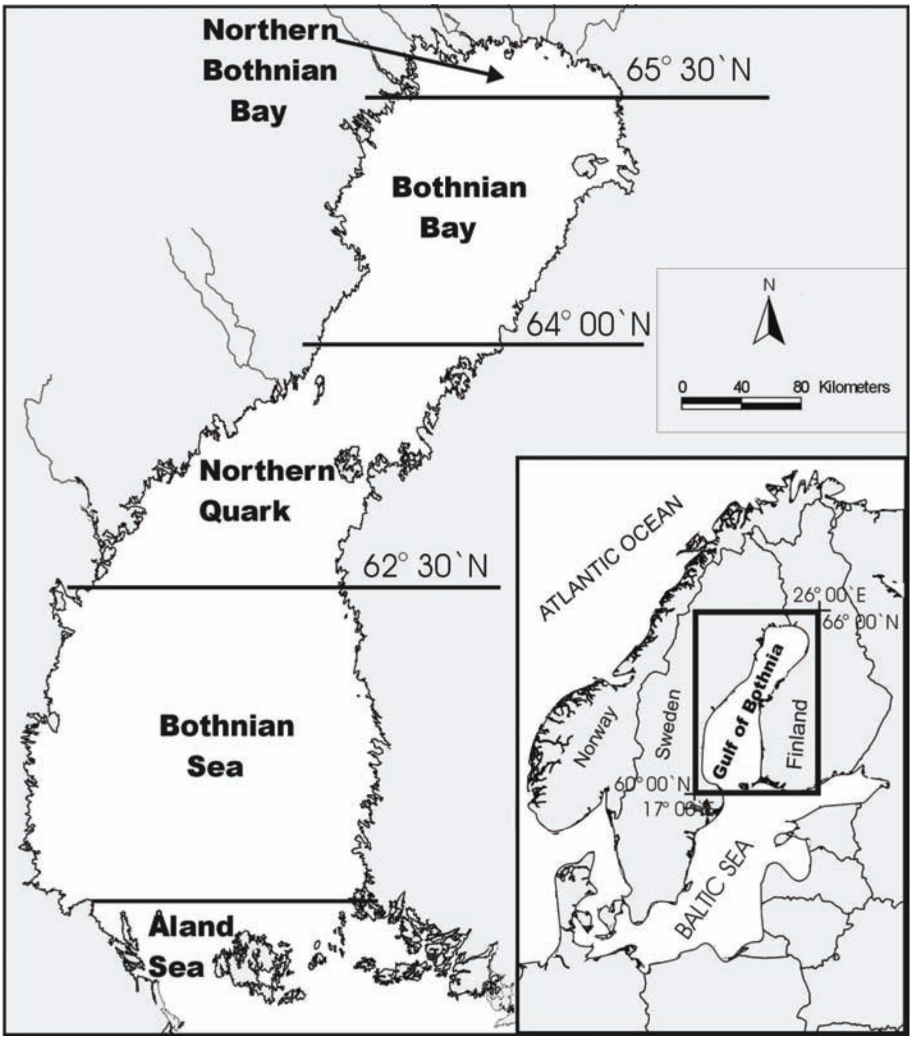

Fig. 2. Location of the study in area the Gulf of Bothnia and the regions defined for this study.

2.2 Seal-induced catch and gear damage evaluation (I)

Data were collected along the Finnish coast of the Gulf of Bothnia during the fishing season of 2002. A total of 136 trap-nets of different types were included.

The catch and damage to catch and gear were recorded in detail for each gear and each haul once a day.

It was tested whether the observations of catch and gear damage made by fishermen and FGFRI employees were consistent within each region and fish species. As the catch and gear damage observations made by fishermen proved to be similar to those of the FGFRI personnel in every region during the same time span, their data were combined.

Catch and gear damage was compared between regions. Moreover, the total catches of each fish species in each region were summed and calculated as a proportion of the number of trap emptyings. Gear-damage frequencies were calculated from the weekly data. Gear damage was also compared among different netting materials and different mesh sizes and twine thicknesses and related to the proportion of fish entangled in different parts of the trap-nets. Separate gear-damage categories (0-3) were summed for each trap and for the whole fishing season to obtain a minimum total number of gear damage events. In the Bothnian Sea, the number of these damage events (FGFRI observations only) was then related to the total number of salmon entangled in the mesh per trap-net.

The relationship between the number of salmon caught and the number of damaged salmon (per one emptying), as well as the number of salmon caught and the percentage of damaged salmon (per one emptying), was separately examined in each region.

2.3 Experimental comparison of traditional and modified trap-nets (II)

In 2003, six types of trap-net were tested during the salmon spawning migration on the coast of the Bothnian Sea, near Merikarvia. All experiments were performed under commercial fishing conditions in co-operation with four local fishermen. Each fisherman had all six trap-net models, which were located randomly within his fishing grounds. Two of the trap-nets represented the traditional non-protected traps that are in common use along the Finnish coast of the Gulf of Bothnia (model A and B). Four models were modified and were equipped with a wire-grid in the funnel and a particular type of fish bag made of strong seal-safe Dyneema netting (model C. Pipe-trap, model D. Protection-net trap, model E. Large-mesh trap and model F. Pontoon trap). All trap-nets had a similar type of leader netting made of stiff orange polyethylene (~2 mm PE) netting of 300 mm full mesh size. The differences between experimental gears were in the design and/or material of the wings, middle chamber, funnel and fish bag (described in paper II). Further experiments were carried out in 2004 in Merikarvia in co-operation with the same fishermen as in 2003. Two of the three experimental trap-net models were similar to those in the 2003 trials (models B and F) and the third trap model was a new design (model G. Folded-hoop trap). In the 2004 trials, each of the four fishermen had the traditional model B and the folded-hoop model. In addition, two fishermen had the pontoon trap.

Catch, catch and gear damage, and entangling or gilling of fish was recorded in detail for each experimental gear for each haul. The 2003 data were analysed when all experimental gears were set out simultaneously. No statistically significant difference in catch rates and seal-induced catch damage was observed between different locations ($p > 0.05$) for any particular trap-net model. This enabled analysis of the differences in measured parameters between the gear models.

2.4 Salmon capture, tagging, recapture and re-release procedures (III, IV, V)

Mark-recapture and catch record data were collected during the salmon spawning migration season along the coast of the Gulf of Bothnia by using commercial trap-nets. The number of trap-nets was 61 in 2001 and 148 in 2002 and traps were distributed among different regions off the Finnish coast of the Gulf (III). Most of the salmon tagging (87% in 2001 and 65% in 2002) and catch recording (86% in 2001 and 88% in 2002) was carried out by fishermen (the rest was performed by the staff of FGFRI). These fishermen were part of the research team and were given permission to start fishing immediately after the break-up of the ice cover in the spring, earlier than the present regulations allow. Part of the experimental catch was tagged and the rest was landed. The special permission was not in effect on the Swedish side, where normal temporal regulations were followed. Catch records included the total salmon catch in numbers per day and per trap net. Salmon catch records made by the fishermen and FGFRI staff were consistent ($p > 0.05$).

The number of salmon tagged in different regions varied substantially between 2001 and 2002. In 2001, tagging sites covered the whole Finnish side of the Gulf of Bothnia, although they were mainly in the central and northern areas. In 2002, tagging was conducted in the central and southern areas; no tagging took place in the north. Salmon were tagged with arrow tags (Hallprint) that allowed individual recognition. The tag was hitched by a steel-made applicator below the dorsal fin so that the fluke of the tag was attached to the supporting bones of the dorsal fin. The number code was printed on four consecutive sections of the tag so that when a tagged salmon was caught, fishermen could cut off one section of the tag and re-release the fish to continue the migration. A reward of 18 EUR was offered for each returned tag. However, the fishermen who assisted in the study were not entitled to the reward.

A total of 1364 salmon in 2001 and 639 in 2002 were tagged from mid-May to the end of July, during the main spawning migration of salmon. Anaesthetic was not used. Fish were carefully lifted one by one from the back of the trap-net to the boat where tagging was performed. Fish were not selected for tagging on the basis of their condition. In 2001, the size range of tagged salmon corresponded well with that of commercial salmon caught in trap-nets. In 2002, only a few first-sea-winter salmon (1SW) were tagged; these fish are not included in paper V. In 2002, FGFRI staff collected scale samples from tagged salmon. In both years, tagging ceased at the end of July but monitoring of salmon catches by the fishermen continued to the end of the fishing season.

2.5 Size of migrating wild and hatchery-reared salmon populations (III)

Estimation of the population size of returning salmon was based on tag recoveries only from those fishermen who were directly involved in the study (see 2.4). In addition to experimental trap-net catches, brood stock fisheries in rivers or salmon passing fish ladders were also screened for tags. This enabled evaluation of the ratios between recovered tags and the known total number of salmon screened. Recoveries from rivers where salmon catch statistics were available were also included in the analyses. The size of the spawning migration population was calculated with a 2-sample stratified mark-recapture method (Seber 1982, Arnason *et al.* 1996). Before calculations, certain tagging and recovery strata were either pooled or deleted. The details and justification for this procedure are presented in paper III. After this, the size of the population was calculated by using the Darroch/Plante maximum likelihood (ML) estimator included in the SPAS program (Stratifed Population Analysis System; Arnason *et al.* 1996). In addition, the pooled Petersen estimator (PPE) was calculated for comparison. The suitability of the ML was examined with the G^2 test, and the

PPE was evaluated by two chi-squared tests, tests labelled for complete mixing and for equal proportions (see Arnason *et al.* 1996).

The total salmon population was divided into wild and hatchery-reared components based on scale samples collected from daily trap-net and drift-net catches from the Åland Sea during the main salmon run. In 2002, microsatellite DNA analysis was used to divide the hatchery-reared component into country of origin. According to this analysis, 57% of the cultured salmon originated from Finnish hatcheries and the rest from Swedish hatcheries (ICES 2006). These estimated country-of-origin proportions were applied to the hatchery component of the population estimate to obtain hatchery abundance estimates according to the country of origin.

2.6 Run timing and migration routes of salmon (IV)

Catch accumulation was used as an approximation of the timing of the spawning run. The same mark-recapture and catch record data were used as in papers III and V (see 2.4). In the modelling of salmon-run timing, only the first observation (tagging or recapture) of tagged fish in each region was taken into consideration. Because the main wild salmon rivers and stocking (and thereby homing) places of hatchery reared salmon are located in the Bothnian Bay and Northern Bothnian Bay, tag recoveries and catches of these two regions underwent more detailed examination in five specific sub-regions: west of Hailuoto Island, the sea area off Maksniemi, and the terminal areas of the rivers Oulujoki (no data collection in 2001), Iijoki and Kemijoki. Catch record data from the terminal area of river Iijoki were obtained from the regional fishery authority.

Neural networks (NNs, see Bishop 1995) were used in modelling the run timing of salmon. Probabilistic neural networks (PNN; Specht 1990) provide a general solution to pattern classification problems. The model uses the nonparametric Parzen windows (Parzen 1962) estimation technique, which made it possible to extrapolate mark-recapture data to the entire fish population. The network constructs a class-dependent probability density function (p.d.f., see Berthold & Diamond 1998) for each classification category and follows a Bayesian classifier, which takes into account the relative likelihood of events and uses a priori information to improve predictions. Two dependent variables were used in run timing analyses. For catch data the dependent variable was the Julian day. The daily sample size was low in the mark-recapture data and hence

Julian day was replaced with Julian week. The PNN procedure splits data into sub-sets and requires several samples (cases) for both training and testing of how well it predicts the known output values. The PNN analyses were performed using NeuralTools software (www.palisade.com).

2.7 Survival of salmon captured and released from trap-nets: potential for a selective fishery (V)

The overall mortality caused by trap-net capture and release was estimated by taking into consideration all potential destinies (fates) of tagged salmon (see 2.4). Estimation was carried out separately for different salmon tagging groups. The model was constructed using a conservative approach in that all parameters were estimated using information that results in maximum values for the capture-and-release induced mortality. The destination of tagged fish was divided into six categories. First, the model took into consideration all re-captured tagged fish by deducting tag-recoveries and by estimating tags not returned from the total number of tagged fish. Second, from the remaining tagged fish, the model deduced estimates of those tagged salmon that had lost the tag, that were eaten by seal from fishing gear, or that entered rivers but were not captured. Finally, after all these deductions, the model divided the remained tagged fish in two categories of handling mortality. The model parameters and justification for the selected values are presented in more detail in paper V.

To estimate tag loss and mortality factors, a controlled experiment was carried out in 2002 in freshwater conditions in the Taivalkoski fish farm of the FGFRI. Tag loss, tagging-induced mortality and capture-and-release induced mortality were experimentally assessed in three treatment groups.

Cumulative mortality caused by repeated trap-net capture-and-release was estimated for two groups: (1) for the tagged salmon of this study and (2) for the total spawning migration population in the Gulf of Bothnia. Mortality estimations for the total population were analyzed for two time periods: for the study years when specific mortality and capture efficiency estimates were obtained, and for future scenarios with varying overall fishing efficiencies. Estimates for the study years included only the Finnish coastal area and only those trap-nets that were used by the fishermen who participated in this study. Moreover, the time scope of this analysis was restricted to the time of regional salmon fishing closures. Cumulative mortality estimates were obtained by using observed maximum values for capture-and-release mortality and for the capture efficiency of the experimental traps. In addition, simulations for future scenarios were performed using two capture and release mortality levels, 5% and 25% (i.e., values within the range of the observed levels), and three capture efficiency levels, 25%, 50% and 75% (where 25% is the maximum observed level and 50% and 75% are hypothetical levels). Each mortality and capture efficiency level was used in all combinations.

3 Results and discussion

3.1 Temporal and regional patterns in seal-induced damage (I)

In the Gulf of Bothnia, considerable variation in catch and gear damage was observed among regions, fishing periods, target species and trap-net models. The most severe catch damage was suffered by the salmon fishery. The regional patterns in seal-induced damage depended on the number of seals in the region and the type of gear, which is strongly associated with the netting materials.

The association between the extent of damage and the number of seals was clearly demonstrated by examining the seal censuses in May 2002: some 4800 grey seals were observed in the southern Bothnian Sea (FGFRI unpublished data) where the corresponding damage was 37% of the total salmon catch (by number). In contrast, about 200 grey seals were observed in the three northern regions (FGFRI unpublished data) where damage percentages were less than 10%. However, the high mobility of grey seals (Sjöberg 1999) and possible influence of ringed seals complicates the argumentation. Observed catch losses (by number) in the whitefish fishery varied between regions from 5 to 7%.

Gear damage frequencies varied between 2 to 25% of emptyings in different regions. Damage was most common in the northern Bothnian Bay and Bothnian Sea, and was significantly rarer in the central Bothnian Bay. Gear damage varied temporally in line with catch damage in each region. The set-up and design of a trap and the netting materials used affect the location and severity of the catch and gear damage. Seals damage those sections of a trap where the fish are entangled. Strong and thick materials are more resistant to the attacks of hunting seals. Materials that fish become entangled or enmeshed in are most prone to seal damage. Traps that catch fish by means of their meshes have fine and large-meshed monofilament and nylon nettings. These materials suffer damage significantly more often than thick polyethylene and also more easily used than small-meshed nylon nettings in traps designed not to entangle fish. Correlation analysis based on the Bothnian Sea data showed that increasing amounts of fish entanglement in a trap result in an increased volume of gear damage.

A significant correlation was observed between the number of salmon caught and number of salmon damaged per hauling. However, there was a significant negative correlation between the number of salmon caught and the percentage of damaged salmon per emptying in all regions. In other words, the more salmon there were in a trap, the smaller was the proportion of them that were damaged. Changes in fish size during the fishing season may lead to bias: small salmon (especially 1 SW) are more common in the later part of the fishing season (Niva 2001, paper IV) and they entangle themselves in meshes more easily than the larger fish. This partly explains why gear damage increased at the end of the fishing season. Estimates of catch damage caused by seals should not only be based on fish numbers. The total catch weight should be taken into account as well. If the catch consists of small-sized fish (e.g. 1 SW salmon), the percentage of damaged fish might increase considerably without any real change in the fish biomass eaten by seals within a certain period. One of the essential prerequisites for protecting trap-nets from seals and thus mitigating seal-induced damage would be to encourage the use of gear structures and netting materials that guide fish straight into the fish-bag and prevent the fish from becoming entangled in the netting.

There were no significant differences in either the catch- or gear-damage frequencies recorded by the fishermen and FGFRI employees in the same time span. In survey studies there is a risk of results being biased. Fishermen might exaggerate the damage they have experienced, or those fishermen that have experienced serious damage might answer the queries more readily than those with minor damage (Lunneryd & Westerberg 1997, Cairns *et al.* 2000). An experimental study with a similarly collected smaller data set in 2001 (Kreivi *et al.* 2002) and a survey of seal-induced fishing damage directed to fishermen in 1997-1999 (Helle 1999) revealed results that were consistent with this study.

3.2 Reduction of seal-induced damage by trap-net modification (II)

The experiments conducted revealed possibilities to markedly reduce seal-induced catch and gear damage by appropriate gear modifications and by the careful choice of proper netting materials (see also Lunneryd 2001, Lehtonen & Suuronen 2004). Three out of five modified trap-net models showed promising results in terms of seal protection. The pontoon trap was the most successful design; seal-induced catch damage was almost non-existent, the capture efficiency of salmon was very good and the hauling of the gear was very easy. The folded-hoop trap (Model G) also showed promising results, although it was a prototype tested for the first time in 2004. Seal protection was almost as good as in the pontoon trap, but catching efficiency was only about half as good. The advantage of the folded-hoop trap is that it can be manufactured by fishermen and is markedly cheaper than the pontoon trap. On the contrary, hauling of the folded-hoop trap, especially in poor weather conditions, was more difficult than that of the pontoon trap. It is likely, however, that catching efficiency and hauling technology of the folded-hoop trap can be improved by further testing. The non-rigid pipe trap showed some promising results, but its seal protection capability was not as good as that of the first two models. The experimental results for the two other modified models, a large-meshed trap and a protection-net trap, were not very encouraging. By comparison, 30 to 54% of the total observed salmon catch (in numbers) was damaged by seals in the traditional non-protected traps (models A and B).

The netting material also affected the location and severity of damage caused to the gear by seals. Strong and thick materials were more resistant to the attacks of hunting seals. There was very little seal-induced gear damage in the fish bags made of Dyneema netting. Likewise, there was no gear damage in the middle chambers and wings made of PE netting. Seals mainly damaged those sections of a trap where the fish were entangled or gilled. The most frequent gear damage was observed in trap model A, which was made of elastic multi-monofilament nylon. In 2003, a total of 84% of all salmon caught in the traditional trap-net model A were observed in the middle chambers and wings and most of these salmon were entangled or gilled in the net before reaching the fish bag. The netting material in various parts of a trap-net clearly played a marked role in the capture process and seal protection. Our results demonstrate that stiff and thick netting material should be used in all those parts of the trap where fish could be gilled or entangled in the netting. Materials in which fish become entangled are most prone to seal-induced damage. This is in line with the observations of Lehtonen and Suuronen (2004) and paper I. In addition, the rigging of wings, middle chambers and funnels should be designed so that there are no steep netting angles that may disturb fish when avoiding an attacking seal.

The observations with the pontoon trap and folded-hoop trap support the view that marked improvements in seal protection can be obtained by building the fish bag of double-layer netting that is held under tension. This tension can most easily be attained using rigid hoops. The upper large-mesh protection net has to be made of strong Dyneema netting or netting material of the same strength. The design of a wire grid installed in the funnel of a trap-net is critical for a seal-safe trap-net to work properly. It seems that it is not possible to completely prevent the passage of the smallest grey seals (typically pups) through the wire grid without dramatically reducing the capture efficiency of the gear, at least in the case of salmon. Visual observations during the study suggest that the wire grid should be as stable as possible. If the grid moves too abruptly, for instance due to waves, it apparently frightens fish, making them reluctant to swim through the wires (see also Lehtonen & Suuronen 2004). In the pontoon trap the vertical movement of the fish bag and grid is greatly dampened by the large pontoons below the bag. Moreover, the rigid frame further helps to keep the system stable and the funnels open. The high stability in rough sea conditions is likely one of the major reasons for the high capture efficiency of this gear type. The colour and the contrast of the wire grid may also play a marked role in the capture efficiency of a trap-net.

3.3 Size of migrating wild and hatchery-reared salmon populations (III)

The total size of the migrating salmon population of Gulf of Bothnia in 2001 and 2002 was estimated at *c.* 230 000 salmon in both years. These estimates are in accordance with those of Jounela *et al.* (2006) on the annual spawning run that approached the Finnish coast of the Gulf of Bothnia in 2001 and 2002.

The estimates suggest that the total size of the Gulf of Bothnia salmon population was stable between years. Further evidence that the population sizes were at similar levels in both years is that no marked changes in fishing effort took place between 2001 and 2002 and the reported total salmon catches from the Gulf of Bothnia in Finland and Sweden were almost similar between years (ICES 2006). The proportions of wild and hatchery-reared salmon, however, appeared to markedly change, doubling between 2001 and 2002. This difference reflects the recent increase in the wild salmon stocks in the Baltic Sea (Romakkaniemi *et al.* 2003, ICES 2006). In addition, the change in estimated numbers of wild salmon in this study was in accordance with the increase in wild smolt production for the corresponding smolt cohorts from 1999 to 2000 (ICES 2006). Increased densities of 0+ salmon parr in electrofishing surveys across all large salmon rivers in the Gulf of Bothnia in 2002 and 2003 (ICES 2006) were reflective of the increased spawning escapement of wild fish between 2001 and 2002, since most of the hatchery-reared salmon do not contribute to natural reproduction in the rivers (Karlsson & Karlström, 1994, Romakkaniemi *et al.* 2003). Another potential reason for the increasing proportion of wild salmon may have been a decrease in the hatchery-reared stock component, despite constant stocking levels. This is consistent with the decreasing trend in cultured salmon survival in late 1990s and early 2000s (ICES 2006, Koljonen 2006).

Estimation results suggest that in 2002, *c.* 50 000 of the hatchery-reared salmon originated from Finnish hatcheries and the remaining *c.* 38 000 fish were from Swedish hatcheries. The estimated abundance of Swedish cultured salmon was in accordance with earlier estimates of cultured salmon abundance on the Swedish coast of the Gulf of Bothnia (ICES 2002).

In addition, estimation results suggest that in both years about 10% of wild smolts survived the feeding migration and returned to the Gulf of Bothnia. Corresponding figures for hatchery-reared smolts were only 4% and 2% in 2001 and 2002, respectively. This translates into a survival rate between 2.5 and 4.5 times lower in hatchery-reared smolts than that of wild smolts. Similar estimates for hatchery-reared smolts have been obtained on the Swedish side of Gulf of Bothnia (ICES 2002). Additionally, survival estimates were in line with the recent estimates of post-smolt survival and annual mortality of salmon in the Baltic Sea (Michielsens *et al.* 2006).

According to rough estimates from 2001, 30–42% of the migrating wild salmon population and 23–38% of the hatchery-reared salmon population escaped both coastal and river fisheries. In 2002, the corresponding figures were 36–50% for wild salmon and 8–20% for hatchery-reared salmon. This suggests that a substantial proportion of the hatchery-reared salmon returning to the Gulf of Bothnia remain unexploited (see also ICES 2002, IV).

3.4 Run timing and migration routes of salmon (IV)

In contrast to the underlying assumptions in the temporal regulation of the Gulf of Bothnia coastal fishery, neural network models indicated that the return migration along the coast of the Gulf of Bothnia does not progress in a unidirectional, linear manner, step by step from one coastal regulation region to another. In all, the results revealed large variation in salmon migration patterns and run timing between sea age groups, wild and reared stock components, and among and within regions.

The estimated run timing of salmon in the Gulf of Bothnia indicated a tendency towards earlier migration of wild salmon compared to the reared ones. In general, the run timing estimates between wild and reared salmon are in line with earlier studies in the Gulf of Bothnia (Ikonen & Kallio-Nyberg 1993, Karlsson *et al.* 1994, McKinnell *et al.* 1994). However, in 2002 in the Åland Sea the reared salmon arrived earlier than wild fish in all age groups (see also ICES 2006). In addition, salmon approaching the wild salmon rivers and terminal fishery areas in the outlets of dammed rivers showed differences in run timing only in the Bothnian Bay, not on their way to the Southern Gulf of Bothnia. Furthermore, the run timing estimates between sea age groups confirm the findings of Niva (2001), who stated that older salmon migrated earlier than younger ones. In addition, this difference in timing increased towards the north. There was only slight variation in the estimated run timing between the years 2001 and 2002 in different sea age classes and regions. In 2002, no clear differences were observed in the tag recovery distribution and general migration pattern between the wild and reared fish.

The tagging data revealed comparable patterns in salmon run timing with the extensive catch data. However, in most of the regions tagging only covered the peak migration or spawning run, excluding possible feeding fish, for instance, and did not continue until the end of run (especially for 1SW salmon) and fishing season. This resulted in a faster increase and earlier end for the accumulation estimates based on tagging data.

The catch accumulation started at roughly one week intervals in successive regions, but almost simultaneously in the two northernmost regions, the Bothnian Bay and Northern Bothnian Bay. This suggests that the majority of salmon were migrating very rapidly in the northernmost areas of the Gulf and/or that a substantial proportion of the early migrants were not recruited at all into the coastal trap-net fishery in the Northern Quark and Bothnian Bay. In contrast to all other regions, the salmon run in the Northern Quark and Bothnian Bay continued until September. There were no marked differences between years in different regions in the estimated catch accumulations.

Salmon may use both Swedish and Finnish coastal areas for migration, with two main crossing places between the Finnish and Swedish coasts: the Åland Sea and Northern Quark. Karlsson *et al.* (1999) presented similar information on salmon migratory behaviour based on data storage tags (DST) and Carlin tags in the Gulf of Bothnia from 1995 to 1997. Some of the DST-tagged salmon also crossed the Northern Quark from the Swedish to the Finnish side.

Catch data and tagging results revealed late migration for salmon entering the terminal areas of the rivers Kemijoki and Oulujoki compared to other salmon returning to the various rivers and areas of the Bothnian Bay. However, there were only slight differences in the estimated run timing between the groups during the migration in the southern Gulf of Bothnia. In contrast, when the same tagged individuals were accumulating in the sub-regions, a clear difference in the estimated run timing between the groups was revealed. Carlin-tag recoveries from 1959 to 1999 have also indicated that salmon originating from compensatory releases at the terminal fishing areas of the rivers Oulujoki and Kemijoki show a later run timing in the Gulf of Bothnia than other stocks (Niva 2001).

A notable proportion of salmon on their way to the terminal areas of the rivers Iijoki and Oulujoki first visited the Northern Bothnian Bay before turning back south. Further analyses of historical Carlin-tag returns from the FGFRI's Carlin-tag database provided supporting findings, confirming the novel information on this migration pattern. The number of days taken by tagged salmon released in one sub-region to be recaptured in another was not consistent with the distances between the sub-regions. Similarly, the hatchery-reared salmon of the River Kemijoki show late river entry, whereas wild salmon of the rivers Torniojoki and Kalixälven seem to enter the rivers directly after reaching the northernmost Gulf of Bothnia. Possible reasons behind the north-south migration of Iijoki and Oulujoki salmon may include the shallow coastal areas off the river outlets and principal northward flow of sea and river waters (Alasaarela 1980, Atlas of Finland 1986). The difference between wild and dammed rivers could be attributed to the differences in water quality (see Alasaarela 1980) and homing instinct between wild and hatchery-reared salmon (Clifford *et al.* 1998, Jonsson *et al.* 2003).

When monitoring the stock or sea age composition of salmon returning to the Gulf of Bothnia, the best sampling area is the Åland Sea. However, the estimates suggest that the Åland sea samples may not be reliable in assessing the recruitment, catch accumulation and run timing of salmon in coastal fisheries further north on the Gulf of Bothnia coast. In addition, it should be noted that some salmon use the Bothnian Sea as a feeding area, (Salminen et al., 1994; Kallio-Nyberg et al., 1999), either staying there for the entire growing period or feeding in the area on their migration from the main basin to the Bothnian Bay. According to Koljonen (2006), the locally released Neva salmon stock that does not usually migrate to the Main Basin comprised 7-27% of the Bothnian Sea salmon catches in 2000 to 2005. Anecdotal, unpublished information further supports the importance of the Bothnian Sea as a feeding ground in that a large majority of captured salmon in that area regularly had prey fishes, mainly herring (*Clupea harengus*), in their stomachs, whereas those of salmon captured in the Bothnian Bay are practically always empty. In addition, recreational trolling for salmon has become popular from the Åland Sea to the Northern Quark, but almost non-existing north of that.

The main salmon fishery areas on the northern Finnish coast of the Bothnian Bay can be divided in two categories, pass-through and accumulation areas. This division plays an important role in planning salmon stock monitoring and catch sampling because of differences in run timing as well as the proportions of different stock components and age classes between these areas.

3.5 Potential for a selective trap-net fishery (V)

The maximum capture-and-release mortality of salmon after release from trap-nets was estimated to vary from 4% to 21% between the different tagging groups, with an average of 11%. Mortality estimates of wild MSW salmon were lower than those of fish with unclassified origin (mixture of wild and reared fish). The result of a tagging experiment conducted at a fish farm corresponded well with the capture-and-release induced estimates obtained in the full-scale field experiment. No immediate deaths were observed after the tagging and release of fish either in the sea experiment or in the tank experiment on the fish farm. The maximum cumulative mortality caused by the capture and release of tagged fish after three consecutive capture events was estimated at less than 7% in both years. The wild MSW salmon, the specific group to be safeguarded by the selective fishery, showed less than 2% cumulative mortality after two captures.

When extrapolating the mortality estimates to the total salmon population entering the Gulf of Bothnia it appears that the maximum cumulative mortality after several capture and release events in the study trap nets during the fishery closure period would have been less than 2% in both years.

Present results indicate that the likelihood of survival of a trap-net captured and released wild salmon is high, and the cumulative mortality even after several capture and release events is remarkably low. The number of tagged fish in this study, however, allowed direct mortality estimation only for the first two to three capture-and-release events. On the other hand, simulations of possible future scenarios reveal that the role of the first 2-4 capture events is significant in determining the level of cumulative mortality, which will not increase considerably with higher number of capture-and-release events, and remains relatively independent of the capture efficiency and capture-and-release mortality.

Capture and release has been observed to cause stress and atypical behaviour in fish over a certain time after release (e.g. Mellas & Haynes 1985). The tag-recovery data of this study indicate that trap-net capture and release would not lead to considerable changes in the normal migration behaviour of Atlantic salmon. In both years the great majority of tagged fish were recovered north of the tagging or re-releasing location, suggesting that most fish continued their expected spawning migration towards the northern rivers.

4 Conclusions

Seal-induced damage to the commercial fishery is a significant problem throughout the Gulf of Bothnia (Westerberg *et al.* 2000, Kreivi *et al.* 2002, I). With the current expansion of seal populations there may soon be no coastal areas in the Baltic Sea where static fishing gears are safe from seal attacks. If effective mitigation measures for seal-induced damage are not found, the conflict between the protection of seal stocks and the existence of the coastal fishery will become very serious. My results demonstrate that it is possible to markedly reduce seal-induced catch and gear damage by appropriate gear modifications and by careful selection of the netting material (I, II). The seal problem requires rapid, practical and sustainable solutions, and gear modification appears one of the most promising mitigation tools in this conflict (I, II). However, further research is needed to develop designs that keep (or scare) seals away from the wings and middle chambers of trap-nets, or allow fish to take other safer routes to the bag. It is notable that replacing gill-nets by seal-safe trap-nets may solve at least some of the problems faced by the coastal gill-net fishery, where seal damage is extremely difficult or impossible to prevent. Functional gear modifications may also mitigate fishermen's attitudes towards seals and play a part in seal conservation by reducing illegal hunting and the deliberate drowning of seals in fishing gear.

The results revealed in papers III, IV and V provide fisheries managers with additional new information to establish a balance between the protection of wild salmon and exploitation of hatchery-reared fish. They also provide useful reference points for the future for various indices and estimates of wild and reared salmon in the area.

The findings of paper IV indicate large variation in salmon migration patterns and run timing between sea age groups, stock components, and among and within regions. Run timing estimates revealed that temporal regulation effectively safeguards the wild salmon, but, at the same time, a substantial proportion of the potential catches of reared salmon is not utilized by the coastal fisheries in different regions. The results of paper IV facilitate assessment of the success of stocking programmes in providing information on migration routes and, for instance, recognizing possible areas of more or less effective exploitation. The findings of this paper can also be used in directing sampling when monitoring salmon of different sea-age groups, stocks and origin. Finally, assessing the need for an update to the temporal regulation of coastal salmon fisheries in the Gulf of Bothnia should be based on understanding of the migration patterns of different salmon stock components.

A selective harvesting strategy has been presented as one possible alternative and as a parallel solution to the conflict in the coastal salmon fishery of the Gulf of Bothnia. This strategy could enable the separation of exploitable (e.g. hatchery-reared fish) and safeguarded (e.g. wild vulnerable stocks) fractions of a population complex in a mixed-stock fishery. The results of my thesis (V) suggest the potential for this kind of fishery. Any plans to introduce a selective fishery strategy should include close monitoring of its impacts on safeguarded populations. A practical and successful concept of a selective trap-net fishery must fulfil several conditions. For example, fish should be caught with undamaged non-meshing fishing gear and should also be protected from seals. Results of the first two papers (I, II) are highly valuable when defining optimal trap-net models for the selective fishery (see also Lunneryd *et al.* 2003, Lehtonen & Suuronen). In addition, released fish should survive and continue their spawning migration (V), fishermen should be able to easily identify wild and stocked fish by some external mark, and the overall fishing effort must be adjusted to fluctuations in the proportion of wild and reared Baltic salmon stocks (III). In the selective fishery, there would be less need to regulate the coastal salmon fishery with strict temporal closures. From 2005 to 2007, Finnish commercial fishermen are being allowed to start the Gulf of Bothnia coastal fishery with a maximum of two seal-protected trap-nets 7, 10 and 14 days earlier in 2005, 2006 and 2007, respectively, than the opening dates enforced since 1998. During this period, fishermen must release salmon longer than 85 cm. However, this experimental management action cannot be regarded as true selective fishery in that there is no method to easily identify stock origin. Furthermore, the differences in run timing between wild and reared fish and between corresponding sea-age classes (less or more than 85 cm) revealed in the present study were too small to support catch selection based on fish length. It is also noteworthy that the number of pontoon traps has recently increased in the Gulf of Bothnia. However, positive results supporting a potential selective fishery do not include practical experience and capture-release events with pontoon traps, and the results should therefore not be directly applied to the use of pontoon traps.

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