Interdisciplinary probabilistic network to examine the possibility to restore potential Baltic salmon rivers

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Abstract

Restoration projects of potential Atlantic salmon (*Salmo salar*) rivers in the Baltic Sea have known relatively limited success. In order to identify the possible factors currently limiting the re-establishment of salmon populations in potential salmon rivers, we compare a wild salmon river with potential salmon rivers in terms of the biological characteristics of the salmon population, the fishing pressure on the population and the river's socio-economic and biological environment. The differences in biological and socio-economical circumstances between rivers can be examined through separate biological, economical and socio-economic studies. The results from the different disciplines can later be linked together within one single probabilistic or Bayesian network model. The probabilistic network has the advantage that the different conditional relationships can be obtained through different methodologies. In the case of Baltic salmon, the biological estimates within the Bayesian network are obtained through a probabilistic mark-recapture model of tagging data, the economic dependencies are obtained through bio-economic models and contingent valuation, while the social dependencies come from questionnaires and in-depth interviews with key people. Network modelling allows us to examine not only what has happened in the past but through the expression of causal relationships within the model structure, it also allows us to examine what would happen to the salmon populations if certain biological, economical and social conditions in potential salmon rivers would be different. It is therefore possible to examine the effect of different management actions on the fishing behaviour of the fishermen in the different rivers and to examine for each river which combination of management actions has the highest probability of successfully restoring the salmon stocks.

Keywords: potential salmon rivers, interdisciplinary, Bayesian network

Introduction

In order to prevent extinction of wild Altantic salmon (Salmon salar) populations in the Baltic Sea area, the International Baltic Sea Fishery Commission (IBSFC) adopted long term management goals which resulted in the launch of the Baltic Salmon Action Plan (SAP) in 1997 (IBSFC and HELCOM 1999). The objective of the SAP is to increase the natural production of wild Baltic salmon stocks to at least 50% of the natural smolt production capacity and to re-establish wild salmon populations in potential salmon rivers i.e. rivers where salmon were extirpated but where it would be possible to re-introduce them after improving the river habitat. At the same time, catch levels should be retained as high as possible. This objective should be met by 2010.

Since the Salmon Action plan was adopte, the total wild smolt production has increased from 0.5 million smolts to about 1.7 million smolts in most recent years. This is estimated to be around 48% of the overall potential smolt production (ICES 2005). However, this development is not uniform among rivers; the number of smolts increased in the larger salmon rivers, whereas numbers remained low for many weaker stocks. The number of spawners is particularly low in the potential rivers, i.e. rivers where salmon were extirpated and are now being reintroduced.

The possible reasons for differences in stock-recovery could be:

a) the biological characteristics of the salmon stocks used for restocking
   - Origin of the salmon smolts. Unlike wild salmon stocks, potential salmon rivers do not have any initial wild salmon available to aid the rebuilding of the salmon population.
   - Number and stage of released reared salmon. Reared salmon is either stocked at the parr stage or at smolt stage. In case the salmon is stocked as parr, their contribution to the salmon recruitment will be delayed. Once these reared parr reach the smolt stage, however, their probability of survival can be assumed similar to wild salmon (Jutila et al. 2005).
   - Post-smolt mortality. Hatchery-reared salmon experience a higher mortality during the post-smolt stage (Olla et al. 1998; Brown and Laland 2001) and in recent years this mortality has increased (Kallio-Nyberg et al. 2004).

b) the fishing pressure on the salmon stock
   - Sea and coastal exploitation. The catchability of wild and reared salmon by the different fisheries differs because of different growth and maturation rates (Kallio-Nyberg and Koljonen 1997; Jutila et al. 2003) and since 1996, the opening of the coastal fishery has been delayed to increase the probability of wild salmon escaping (Romakkaniemi et al. 2003). In addition the exploitation has decreased over time (ICES 2005)
   - Rivermouth exploitation. The exploitation of the salmon in the river mouth is different for different salmon populations. The river mouth of certain potential salmon rivers

are located close to terminal fishing areas of dammed rivers without spawning grounds (Figure 1).

c) the river environment
   - Spawning grounds. The different rivers differ on the amount of spawning grounds available to the salmon. In the case of potential salmon rivers, the spawning grounds are increased thanks to restoration or construction of spawning grounds or by improving their access (Erkinaro et al. 2003).
   - Quality of the river environment. Differences in river quality mainly exist due to river dredging needed for timber floating. The diversity of dredged rives have been increased e.g. by re-meandering straight channels, reconnecting closed river sections back to the river, building log dams and boulder dams (Mills 1989; Yrjänä 1998).
   - M74 mortality (Vuorinen et al. 1997). Baltic salmon has been affected by the M74 syndrome causing high yolk-sac-fry mortality and this mortality has been variable over the years (ICES 2005).

This paper examines the importance of these different factors on the probability of successful re-establishment of salmon populations in potential salmon rivers and evaluates the impact of different management measures i.e. stocking or fisheries regulations, to increase this probability. Because management measures affect the salmon populations through possible changes in fishermen behaviour, socio-economic factors need to be taken into account when evaluating the impact of different management measures on the salmon stocks. This is further explained in Michielsens et al. (2005).

Methods

In order to evaluate the importance of different factors which could have been limiting successful recovery of potential salmon rivers, we examine the differences between a wild salmon population which has successfully recovered (Simojoki) and potential salmon populations (Kuivajoki, Kiiminkijoki and Pyhäjoki, Figure 1) in terms of their biological characteristics, the fishing pressure on the population and the river environment, and which of those factors are currently limiting the re-establishment. The different factors affecting the survival of the salmon smolts and their probability to produce wild salmon offspring can be represented in a causal Bayesian network (Figure 2).

A Bayesian or probabilistic network (also called Bayes' network or Bayesian belief network) is probabilistic graphical model, representing causal relationships (Jensen 2001). Network modelling allows us to examine not only what has happened in the past but through the expression of causal relationships within the model structure, it also allows us to examine what would happen to the salmon populations if conditions in potential salmon rivers would be different (Pearl 2000). It is therefore possible to examine the effect of different management actions on restoration success in the different rivers and to examine for each river which combination of management actions has the highest probability of successfully restoring the salmon stocks. Unless management measures are very restrictive, fishermen's behaviour is not only determined through fisheries management measures but also by socio-economic factors determining fishermen's commitment towards restoring the potential salmon rivers. These factors need to be taken into account when predicting the effect of different management measures on the salmon stocks. Using a Bayesian network it is therefore possible to examine for each potential salmon river which combination of management actions have the highest probability of successfully restoring the salmon stocks while taking into account economic considerations and fishermen's commitment (Figure 3). The current paper will primarily focus of the construction and results of the network corresponding to Figure 2. A description of the network represented by Figure 3, which includes the management actions, can be found in Michielsens et al. (2005).

The model presented in Figure 2 requires the input of probabilistic estimates for the abundance of wild and hatchery-reared smolts for the rivers Simojoki, Kuivajoki, Kiiminkijoki and Pyhäjoki. In combination with probabilistic estimates for the model parameters described in Table 1, the model allows to calculate estimates for the probability of reaching the SAP management objective i.e. to reach 50% of the smolt production capacity. In order to be able to examine the effect of the SAP on the salmon stocks, the average probability of a salmon smolts before the establishment of SAP (1993-1996) to produce a wild salmon smolt in the next generation, will be compared against those for salmon smolts stocked in 1997-2000 and 2001-2004.

The probabilistic estimates for the model parameters described in Table 1 are obtained through a state-space mark-recapture model similar as the one proposed by Michielsens et al. (In Press). In addition to differentiating between wild, hatchery-reared salmon stocked in dammed rivers and hatchery-reared salmon stocked in rivers where they can reproduce, the mark-recapture model is also adjusted to separately track hatchery-reared salmon stocked as smolts and hatchery-reared salmon stocked as parr (or semi-wild smolts). Because the stocked salmon parr have spent part of their juvenile phase in the wild, it is assumed that, once they reach the smolt stage they are able to survive better than the hatchery-reared salmon released as smolts (Jonsson et al. 1991). Because of the lack of evidence of any difference in post-smolt survival between wild smolts or smolt obtained from hatchery-reared parr releases, it is assumed that survival rates are the same once the smolt stage is reached. The mark-recapture model is also adjusted to separately model the coastal and rivermouth catches. The coastal catches are defined as the catches in the Bothnian Sea and the Bothnia Bay below the river Pyhäjoki. Because the rivers are located close together and the rivermouths overlap, catches in the rivermouhts are defined as all catches along the coastline of the Bothnian Bay area, starting below the river Pyäjoki and going upwards. Because salmon from the different rivers are assumed to show the same migration patterns, the model estimates the same offshore and coastal catches for all stocks. In order to estimate the rivermouth catches, an hierarchical modelling approach has been used whereby it is assumed that the harvest rates in the rivermouths can be different for each wild or potential salmon river stock but that there exist no prior information about the differences in harvest rates (Gelman et al. 1995). Unless the tagging data clearly indicates that the rivermouth exploitation of certain stocks is higher or lower than for other stocks, the exploitation rates will be similar across the stocks.

Data

The model parameters are estimated through the use of tagging data obtained by releasing around 25,000 wild and 260,000 hatchery-reared tagged salmon between 1987-2002. The majority of the information comes from hatchery-reared smolts released in the rivers terminal rivers Kemijoki (63,000), Iijoki (46,000) and Oulujoki (51,000) and the wild salmon rivers Tornionjoki (54,000) and Simojoki (22,000) and only to a limited extent from potential salmon rivers Kuivajoki (4000), Kiiminkijoki (9000) and Pyhäjoki (8500). In addition, about 17,000 and 8000 wild salmon smolts have been respectively tagged and released in the river Tornionjoki and Simojoki. The use of data from related populations is based on the assumption that the migration patterns, life history characteristics and exploitation by the fisheries of these stocks are similar to those of the stock of interest.

The number of released hatchery-reared salmon smolts in each river, has been obtained from the ICES report of the Baltic salmon and trout working group (ICES, 2005). Probability distributions for the number of wild salmon smolts and the number of smolts originating from released salmon parr, have been obtained by smolt trapping (Simojoki) or by applying a linear regression analysis to convert parr density estimates into smolt abundance estimates (Kuivajoki, Kiiminkijoki and Pyhäjoki) (ICES, 2005). In case of potential salmon rivers some smolt trapping estimates exist for the rivers Kiiminkijoki and Pyhäjoki (Erkinaro et al. 2003) but because it is unclear what proportion of the smolt run is caught by the smolt trap, these figures can only be regarded as minimum smolt abundances originating from reared parr releases. In order to obtain estimates for the survival from reared parr to smolts, the number of parr released in the river Simojoki have been linked to the corresponding number of smolts. These estimates correspond to estimates obtained by Jutila and Pruuki (1988) and Jokikokko and Jutila (2004) but include the uncertainty in the estimates. A comparison of parr to smolt survival estimates for the river Kiiminkijoki (Kemppainen et al. 1995) with the estimates for the river Simojoki reveal that the parr to smolt survival is likely similar for this river. Because of the lack of recent data, the uncertainty in the parr to smolt survival estimates has been increased by increasing the CV by 20%. For the rivers Kuivajoki and Pyäjoki, no information exists indicating that the survival rate should be different than for the river Simojoki. Therefore the same survival rates has been used but the CV has been increased by 50%. The resulting median model inputs for wild smolts, hatchery-reared smolts and semi-wild smolts have been presented in Figure 4 in terms of the number of smolts in comparison to the smolt production capacity. With the exception of the river Simojoki, wild salmon smolts have been all but absent in these rivers.

The form and the parameter values for the stock-recruit relationship of the river Simojoki have been obtained from Michielsens and McAllister (2004) and the ICES report of the Baltic salmon and trout working group (2005). Because in potential salmon rivers, natural reproduction has been very low or non-existent, it has not been possible to estimate stock-recruit relationships for these rivers. In order to reflect any differences in river quality of potential salmon rivers in comparison to the river Simojoki, three different hypothesis about the steepness at the origin of the stock-recruit relationship have been explored. The steepness indicates how quickly the recruitment will respond to changes in the stock-size. It is assumed that the slope of potential salmon rivers is either the same, smaller or much smaller than for the river Simojoki. Through the use of expert opinion, a weighted average across the different hypotheses can be obtained for each of the potential salmon rivers. Similarly, the smolt production capacity for the potential salmon rivers have been obtained through expert opinion based on estimates of the production area and on available information about historical salmon production (ICES 2005). The natural mortality estimates, due to the occurrence of M74 at the alevin stage, which affect the stock-recruit relationship, has been estimated for the Simojoki salmon stock through an hierarchical model of M74 data obtained from the salmon hatcheries (ICES 2005). It is assumed that potential salmon rivers have been affected similarly as Simojoki.

Results

The different salmon stocks have been compared in terms of their ability to reach the SAP management objective i.e. to reach 50% of the smolt production capacity. Figure 5 shows the results for time periods corresponding to the release years. For example, it is assumed that the salmon smolts in 1993-1996 will mature and produce wild salmon that will reach the smolt stage in 1999-2002. For the river Simojoki, the amount of wild salmon smolts has increased significantly compared to the amount of wild salmon estimated before the start of the SAP and there will be almost 80% probability that the wild salmon smolts will reach 50% of the smolt production capacity by 2007-2010. When assuming that the response of potential salmon rivers to increased spawner numbers is as fast as for the river Simojoki, there should have been already some clear signs of a recovery in the different potential salmon rivers. Based on expert opinion however, the probability of having reached 50% of the smolt production capacity by 2003-2006 is lower because of the lower productivity of the potential salmon rivers, especially for the rivers Kuivajoki and Pyhäjoki. By 2007-2010 there should be a clear sign of recovery in all potential salmon rivers but the associated probability of successful recovery will be around 50-65%.

The stock-rebuilding program in Finland relies heavily on the release of hatchery-reared salmon. Based on the results in Figure 5 for the river Simojoki, it could be argued that the amount of wild salmon smolt in 1993-1996, in combination with the reduced fishing pressure thanks to the SAP program, made it unnecessary to supplement the population with hatchery-reared salmon. Figure 6 demonstrates that if such a strategy would have been followed for the river Simojoki, the probability of reaching 50% of the smolt production capacity by 2010 would be very low. Both the commercial offshore fishery as well as the coastal and river fishery would need to be closed entirely in order to obtain a sufficient increase in the probability to reach 50% of the smolt production capacity by 2010 and even then the probability reaches only about 60%.

Based on Figure 6 and the fact that potential salmon river are less productive than the Simojoki river stock, it becomes clear that the stocking of hatchery-reared salmon is an important management tool for the re-establishment of potential salmon rivers. Retrospectively we will analyse the amount and type of salmon smolts that should have been stocked in the river Kiiminkijoki in order to obtain successful recovery by 2007-2010 (Figure 7). If the amount of parr released in 1997-2000 would produce the maximum amount of semi-wild smolts that the river could support, the probability of having reached the SAP management objective by 2007-2010 would have been 63%. The same amount of smolts released during 1997-2000 would have resulted in 27% probability of reaching the SAP objective by 2007-2010. In case the amount of smolts stocked would be twice the smolt production capacity, the probability would not have increased much. A better strategy would have been to continue the annual stocking of an amount of smolts equivalent to the smolt production capacity until 2004. In order to increase the probability of successful recovery by 2010 above 60%, the amount of hatchery-reared salmon or salmon smolts would have to be very high. These results can be linked to the cost of stocking. Because the relatively low survival rate of reared parr in the wild, the annual releases of parr during the first 4 years of the recovery program is almost twice as expensive as smolts released during 8 years with amounts equivalent to the carrying capacity while the probability to reach 50% of the carrying capacity is almost the same.

Discussion

At the end of the 80’s several of the northern stocks had been close to extinction and stocks from the rivers Kiiminkijoki and Pyhäjoki had even disappeared (Romakkaniemi et al. 2003). Even though fishing effort has continuously reduced since that time, an increase in wild smolt production was initially hampered by high M74 mortality rates (ICES 2005). Once M74 mortality rates went down again, a significant increase in the number of wild smolts was seen near the turn of the century. For the river Simojoki, the decrease in fishing pressure and M74 mortality in combination with the additional hatchery-reared salmon stocked within the river during the stock recovery, means that there is a good chance that this stock will reach the SAP objective by 2010. This recovery would not have been possible without the stocking of hatchery-reared salmon unless all fishing activities affecting this stocks would have been halted, while the SAP objective clearly stated to keep the catch as high as possible.

The potential salmon river on the other hand started their recovery in 1997 at the beginning of the SAP. Because in some of them, the salmon population had completely disappeared, they rely heavily on the number of smolts stocked within the river. The average number of salmon smolts stocked between 1997-2000 had been relatively few for the rivers Kuivajoki and Kiiminkijoki. The delay in the contribution of released salmon parr to the number of smolts in the river, meant for the river Kuivajoki that only salmon smolts originating from smolt released had been present in 1997-2000. The lower survival probability of these salmon in combination with the low quality of the river environment meant that the resulting number of wild salmon smolt in 2003-2006 will be low. For the river Kiiminkijoki a much better survival probability of the released salmon parr and a better quality of the river environment resulted in a higher probability of successful recovery in 2003-2006 in comparison to the river Kuivajoki. Given the high number of smolt releases in the river Pyhäjoki, the number of wild smolts produced by the river should have been much higher than currently observed. The difference could be explained by the fact that the river Pyhäjoki has known some very dry years, hampering the salmon's access to the river. In addition it could be that the river quality is even worse than anticipated. By 2007-2010, there should however be a clear increase in the number of wild smolts produced in all potential salmon rivers provided that exploitation rates and M74 mortality rates remain the same. This is in contradiction to the general belief that the recovery of potential salmon rivers has been hampered by the present efficiency of the sea fishery. Even though the fishing pressure on the stocks have a clear impact on the probability of successful recovery, there should be a clear indication of stock recovery by 2010. In case no clear signs of recovery can be detected, other reasons should be examined e.g. river quality, quality of the stocking material, reproduction success of stocked salmon, etc.

The probability of success recovery of the potential salmon rivers have been evaluated in terms of their probability to reach 50% of the smolt production capacity. When taking the SAP objective literally this would mean that the probability to reach 50% of the smolt production capacity would need to be 100%. Using a probabilistic methodology, it should however be taken into account that 100% may be an impossible objective to reach, simply due to the uncertainty in the estimates, especially for potential salmon stocks for which not as much data and information is available as for the river Simojoki. Managers should evaluate what risk they are willing to take in order to decide what probability to reach 50% of the smolt production capacity is sufficient for a particular stock.

Because this analysis tries to give a realistic assessment about the uncertainty around the smolt production capacity and the smolt abundance, the probability of reaching 50% of the carrying capacity might be close to 50%, i.e. we are unable to say if the stock will recover sufficiently or not. This has important implications for the management advice since the probability of reaching 50% of the smolt production capacity can not only be improved by increasing the wild salmon population but also by increasing the data on which the assessment is based or improving the assessment of the population. Reducing the uncertainty about the smolt production and the carrying capacity will give a clearer indication of whether a stock will be able to reach the SAP objective or not.

The SAP uses the probabilistic estimate of the smolt production capacity as a reference point. As for most rivers in the Baltic, the reference points for the potential salmon rivers have been estimated at a time when there was little or no natural production in the river. As has been seen for other wild salmon rivers, these reference points are likely to be updated as the wild salmon population increases and more information about the possible stock-recruit relationship in the river becomes available. The amount of change in the estimates can be expected to be highest in the first year when data is brought in. Subsequent updates are expected to be smaller.

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Table 1: List of symbols used within the model

	Indices
y	Year group in which the salmon have been smolts i.e. 1993-1996, 1997-2000 and 2001-2004
r	Salmon river in which the smolts have been released or reared i.e. Simojoki, Kuivajoki, Kiiminkijoki and Pyhäjoki
t	Type of salmon smolts i.e. wild salmon smolts, reared salmon smolts released as parr and reared salmon smolts released as smolts
s	Stage within the salmon life cycle i.e. smolts (1), feeding salmon within the Main Basin (2), salmon migrating back to river (3), salmon near or in the rivermouth (4), adult salmon with the river (5), spawners (6)
l	Location or area of the salmon stocks i.e. the river (1, 5 and 6), the Baltic Main Basin (2), coastal areas of the Bothnian Sea (3) and coastal areas in the Bothnian Bay near or in the rivermouth (4)
	Model parameters
$M_{1,y,t}$	Average instantaneous natural post-smolt mortality rate for smolts of type t originating from smolt year group y ($year^{-1}$)
$M_{s\neq1}$	Average instantaneous natural adult mortality rate ($year^{-1}$)
$M_{0,y}$	Average natural mortality due to the occurrence of M74 at the alevin stage on salmon originating from smolt year group y ($year^{-1}$)
C_l	Commitment towards SAP program by fishermen active in area l
E_l	Economic fishing interests by fishermen active in area l
SR_r	Stock-recruit parameters for the salmon stock in the river r
	Model variables
$N_{s,y,r,t}$	Average abundance of salmon at stage s, which had occurred in river r as type t smolts originating from smolt year group y
$F_{l,y,r,t}$	Average instantaneous fishing mortality rate for the fishery in area l, on salmon of type t originating from river r and smolt year group y
	Management actions
$A_{f,l}$	Fisheries management action in fishing area l
$A_{c,l}$	Commitment action targeted towards fishermen fishing in area l
$A_{k,l}$	Knowledge action targeted towards fishermen fishing in area l

Figure 1. Migration route of Atlantic salmon stocks (*Salmo salar*) from Finnish rivers located at the north-east of the Baltic Sea. The rivers Tornionjoki and Simojoki are wild salmon rivers with natural wild smolt production. The rivers Kuivajoki, Kiiminkijoki and Pyhäjoki are potential salmon rivers where the original salmon stocks have disappeared but where wild salmon stocks have been re-established after improvements to the river habitat. The rivers Kemijoki, Iijoki and Oulujoki are rivers without natural reproduction. The presence of dams in these rivers, which prevents access to spawning grounds, are indicated by lines across the rivers.

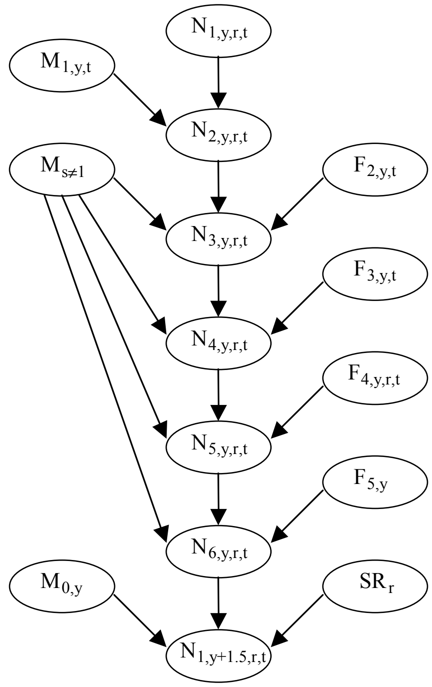

Figure 2: Historical causal Bayesian network of different factors affecting the survival of salmon smolts and their probability to produce wild salmon offspring. A description of the symbols used within the model can be found in Table 1.

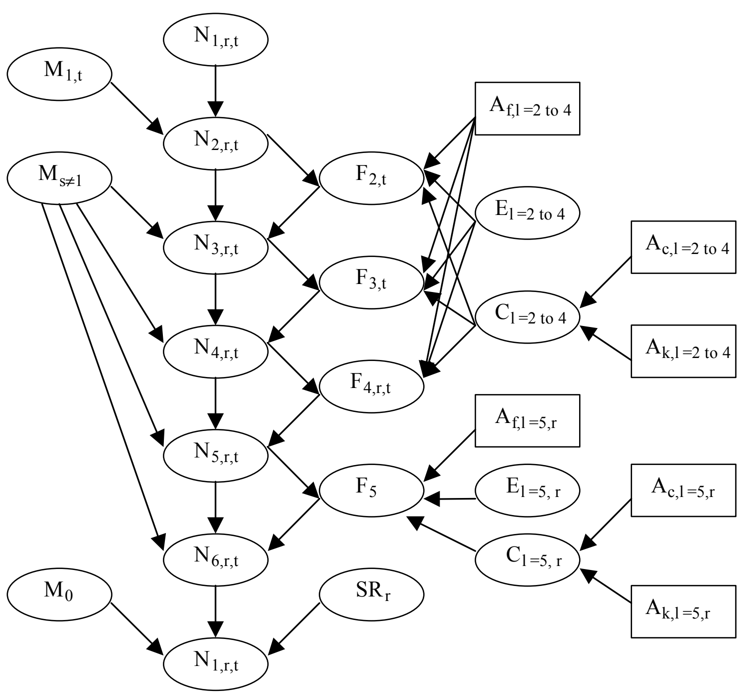

Figure 3: Causal Bayesian network of different factors affecting the survival of salmon smolts and their probability to produce wild salmon offspring, including different management actions which will affect the probability of successful recovery of wild and potential salmon stocks. A description of the symbols used within the model can be found in Table 1.

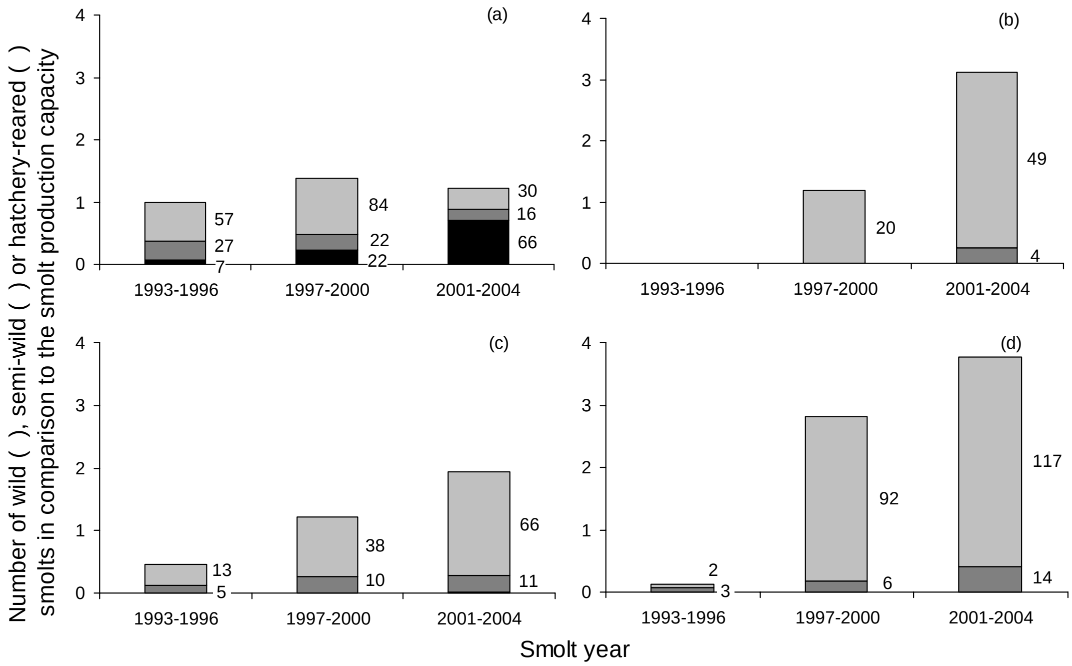

Figure 4: Median number of smolts stocked annually (thousands) in comparison to the smolt production capacity for the rivers Simojoki, Kuivajoki, Kiiminkijoki and Pyhäjoki. The smolts have either been produced in the wild ( ), hatchery-reared until the parr stage and released (semi-wild,) or hatchery-reared and released at the smolt stage ( ).

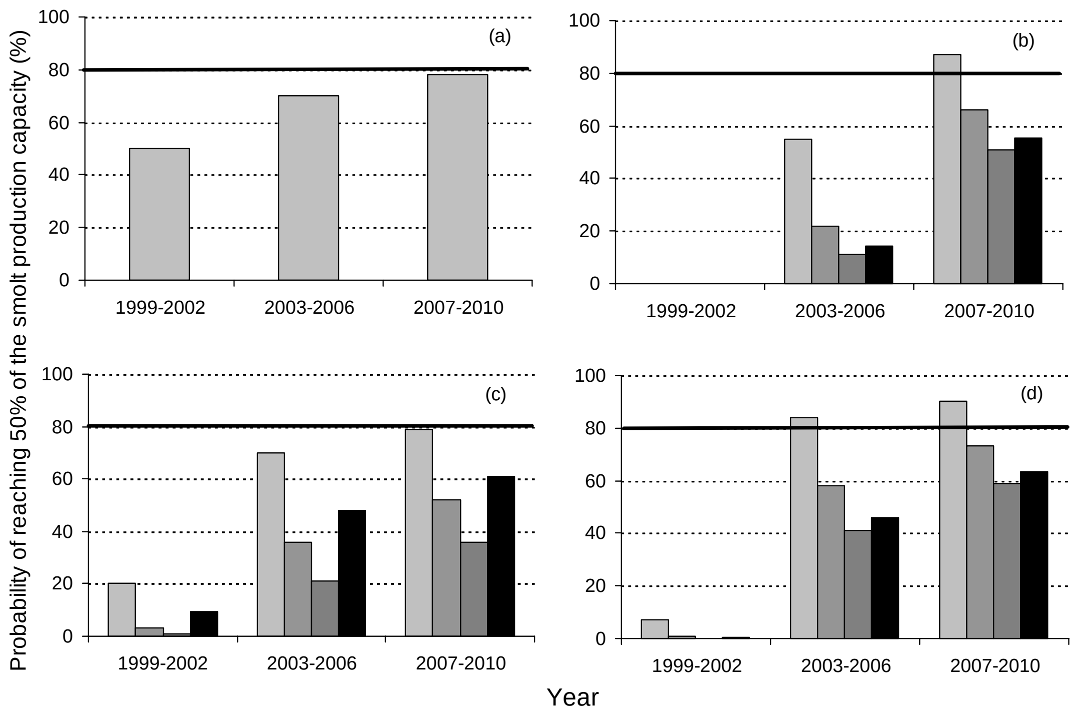

Figure 5: Probability that the amount of wild salmon smolts will reach 50% of the smolt production capacity in the rivers Simojoki (a), Kuivajoki (b), Kiiminkijoki (c) and Pyhäjoki (d) under different assumptions about the slope of the stock-recruit relationship indicating the quality of the river environment i.e. the same as for the river Simojoki ( ), lower than for the river Simojoki ( ), much lower than for the river Simojoki ( ), weighted according to expert opinion ( ).

Figure 6: Probability that the amount of wild salmon smolts will reach 50% of the smolt production capacity in the river Simojoki. The first scenario assumes no stocking of hatchery-reared salmon from 1993 onwards, the second scenario assumes no stocking or fishing and the third scenario assumes historic stocking and fishing levels.

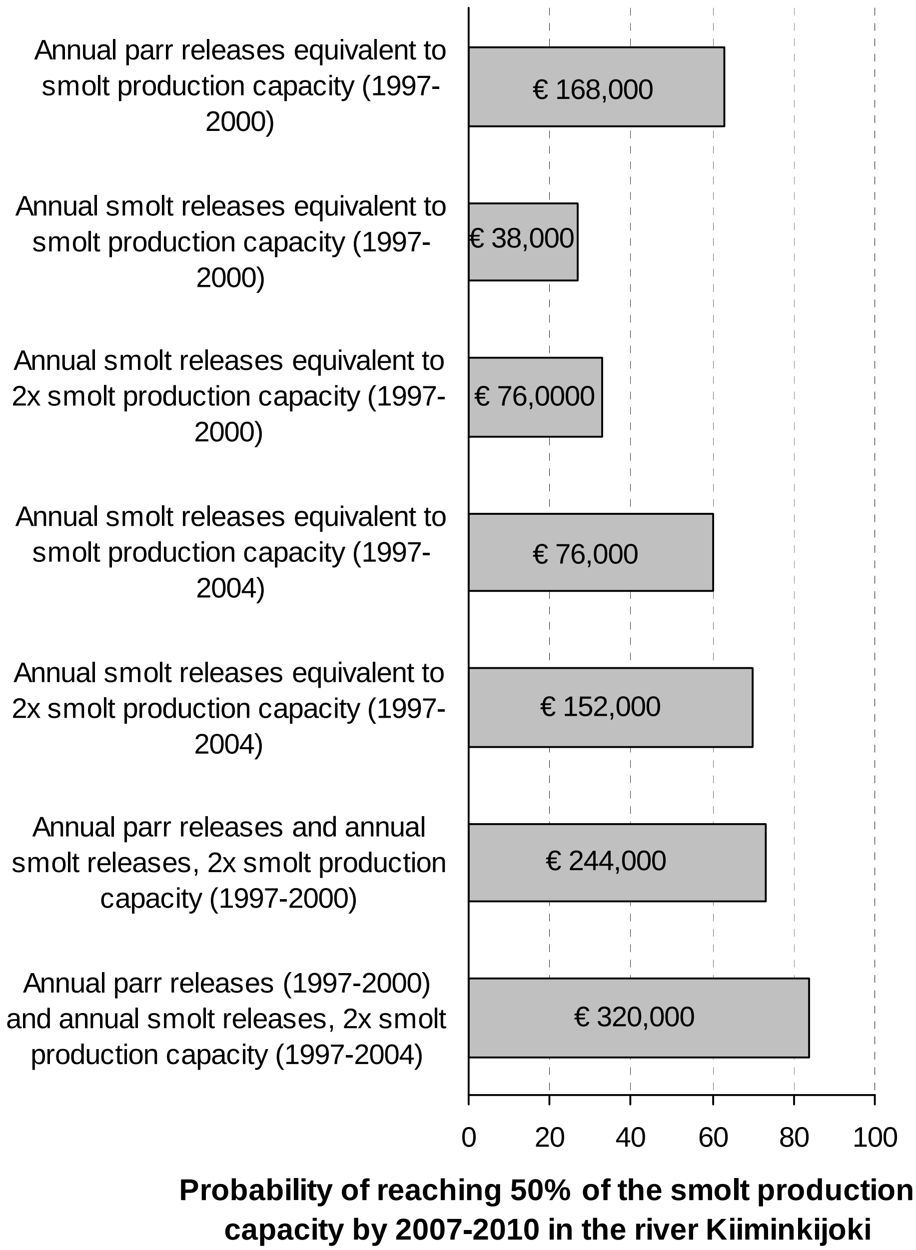

Figure 6: Probability that the amount of wild salmon smolts will reach 50% of the smolt production capacity by 2007-2010 in the river Kiiminkijoki under different assumptions about the type and amount of hatchery-reared salmon released. For each stocking strategy, the associated cost has been indicated.