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Biological Modeling of Migratory  
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# Reconciling Economic and Biological Modeling of Migratory Fish Stocks: Optimal Management of the Atlantic Salmon Fishery in the Baltic Sea

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## Abstract

The paper puts forward a model of the Atlantic salmon fishery in the Baltic Sea that integrates the salient biological and economic characteristics of migratory fish stocks. Designed to be compatible with the framework used for actual stock assessments, the model accounts for age-structured population dynamics, the seasonal harvest and competing harvesting by commercial and recreational fishermen. It is calibrated using data and parameter estimates for the Simojoki River stock. The socially optimal policy for maximizing discounted net benefits from the fishery within an uncertain environment is determined using a dynamic programming approach and numerical solution method. Our results indicate that substantial economic benefits could be realized under optimal management without compromising stock sustainability.

**Key words:** bioeconomic modeling, uncertainty, age-structured population dynamics, optimal resource management, integrated biological and economic modeling, Atlantic salmon

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## 1. Introduction

The management of salmon and other migratory species is complicated by the disparate interests of the fisheries that harvest the fish at their different life stages and by the complexity of stock dynamics. The management of the fishery for Atlantic salmon (Salmo salar) in the Baltic Sea has emphasized biological objectives, and past management efforts have drawn heated criticism from the fishing industry. Despite regulation based on stock conservation goals, wild salmon stocks have declined over time. An active policy debate has sprung up in the Nordic countries due to the low profitability of commercial salmon fisheries and the high status of salmon for anglers. Scientists, fishermen, environmentalists and administrators alike have called for the protection of wild salmon stocks. The Regional Council of Lapland has established a Salmon Fund, which aims at settling the ongoing dispute over harvest allocation between professional and recreational fishermen. The International Baltic Sea Fishery Commission has launched the “Salmon Action Plan 1997-2010”, a program designed to enhance wild salmon populations and increase salmon catches.

Restoring salmon stocks and improving the profitability of the salmon harvest requires that both the ecological and economic characteristics of the fishery be taken into consideration. To be scientifically sound, management prescriptions must explicitly account for the conflicting interests of the different user groups as well as the ecological complexity and uncertainty inherent in salmon stock dynamics. Although the European Commission has emphasized the socio-economic aspects of fisheries management (European Commission, 2001), management authorities in the Baltic Sea region have primarily relied on management advice from natural scientists. One reason why the economic point of view has remained underrepresented in management decisions may lie in the highly simplified population models generally used in economic analyses. If the underlying biological model is elementary, management guidelines proposed by economists are easily dismissed by natural scientists and management authorities.

The objective of this study is to develop tools for producing economically and biologically sound management guidelines by constructing an economic optimization model that accommodates the complexity of the biological modeling of resource stock dynamics. To this end, we construct a bioeconomic model of the fishery for Atlantic salmon in the Baltic Sea. The model takes into account the migration patterns of salmon, age-structured stock dynamics and reproduction

uncertainty<sup>1</sup>, as well as the different economic and biological characteristics of the several fisheries that target salmon. The bioeconomic model reconciles the economic modeling of salmon fisheries in the Baltic Sea with the stock assessment models currently used as the basis for management advice (see, e.g., ICES, 2005). We apply the model to develop optimal policy prescriptions for managing the salmon fisheries in the Baltic Sea. In order to contribute to the ongoing policy debate, the model is calibrated with data for the Simojoki salmon stock, whose native river is located in the northern Baltic Sea.

Earlier studies addressing harvest allocation between different user groups targeting a migratory species have collapsed the stock dynamics into simple biomass models (Charles and Reed, 1985; Cook and McGaw, 1996; Laukkanen, 2001). Economic analyses accounting for uncertainty have also generally resorted to such models (Reed 1974, 1978, 1979; Clark and Kirkwood, 1986, Sethi et al., 2005). Bjørndal et al. (2004) studied the Norwegian spring-spawning herring fishery using an age-structured model with recruitment uncertainty but relied on simulations to compare alternative management strategies. The present paper extends the sequential harvest models presented by Charles and Reed (1985) and Laukkanen (2001, 2003). It combines an explicit analysis of sequential harvesting by competing user groups, an age-structured population model and an account of the uncertainty in the relationship between the stock size and the corresponding recruitment. Dynamic programming and a numerical solution method are used to derive optimal management prescriptions.

The paper is structured as follows. The section to follow presents the biological, economic and institutional characteristics of the Baltic Salmon fishery. Section three describes the population dynamic model and defines the economic benefits of the salmon harvest. Section four formulates the decision problem that the fishery manager faces. In section five, we calibrate the model. Section six discusses the optimal harvest policy and section seven concludes the paper with a summary of the insights gained in the study.

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<sup>1</sup> Due to the M74-syndrome, a reproduction disorder of salmon that causes close to 100 % mortality in the juvenile phase, recruitment uncertainty is the principal source of salmon population fluctuations in the Baltic Sea (see, e.g., Karlsson and Karlström, 1994).

## **2. The Salmon Fishery in the Baltic Sea**

In the Baltic Sea region, juvenile salmon usually spend three years in rivers, after which they migrate into the Baltic Main Basin in the springtime. Adult salmon then spend 1 to 4 years feeding at sea before they start the migration back to their natal rivers in the early summer to spawn (see e.g. Karlsson and Karlsström, 1994). The focus of this study is the fishery exploiting salmon whose native rivers are in the Northern Baltic Sea area. The fishery operates in the Gulf of Bothnia and the Baltic Main Basin (Figure 1.) Characteristic of the fishery is the sequential harvesting of migrating fish. The sequential fisheries differ in terms of gear, catchability, fishing costs, and the price obtained for their catch. The commercial offshore fisheries use driftnets and longlines to harvest salmon feeding in the main basin. Historically, most of the commercial salmon catch has been harvested by the coastal fisheries in the Gulf of Bothnia, which take mature salmon migrating to their native rivers during the early summer (June and July) using driftnets and trapnets. In the rivers, the fish are harvested by recreational fishermen, with angling being the only form of fishing permitted. The current international salmon fishery regulations are based on total allowable catch and technical management measures such as minimum landing size, minimum driftnet mesh size, and minimum hook size. In addition, each Baltic Sea nation has its own regulatory measures. As of 2008, EU fishery regulations will ban the use of driftnets.

[Figure 1 about here]

## **3. Bioeconomic Model**

Our bioeconomic model encompasses the five fisheries harvesting the salmon stocks from the Northern Baltic Sea area: the coastal driftnet fishery (cdn), the coastal trapnet fishery (ctn), the river fishery (ri), the offshore driftnet fishery (odn) and the offshore longline fishery (oll). Figure 2 illustrates the structure of the fishery. In our model, a year begins in May, which is when smolts migrate from their natal river to the Baltic Main Basin and join the feeding adult population. For the sake of tractability, the model assumes that the different fisheries take place sequentially. The coastal harvest occurs in the early summer, when mature salmon start their spawning migration north towards their natal rivers. The coastal driftnet fishery harvests the migrating salmon in June, and the coastal trapnet fishery the surviving salmon once they arrive in the Gulf of Bothnia in July. The salmon surviving both coastal fisheries are harvested by the recreational river fishery in August, when they reach their home river. Salmon that survive the

river fishery reproduce. The immature salmon that remain in the Baltic Main Basin in the spring to feed are harvested by the offshore fishery in the fall. The offshore driftnet fishery takes place in October, the offshore longline fishery in December.

[Figure 2 about here]

### 3.1 Population Dynamics

We consider a discrete time and age-structured model of population dynamics that follows the life cycle of salmon. Our model takes into account the following age groups: eggs, fry, parr, smolts, one-sea-winter and two-sea-winter salmon. The one-sea-winter age group is further divided into two life stages - immature salmon which remain in the Baltic Main Basin to feed and grilse which mature and start their spawning migration. We assume here that all two-sea-winter salmon mature. The coastal driftnet, coastal trapnet and river fisheries harvest both grilse and two-sea-winter salmon while the offshore driftnet and longline fisheries target immature one-sea-winter salmon. The population dynamics model for the salmon stock is the same as the one proposed by Michielsens et al. (2006) and implemented within the International Council for the Exploration of the Sea (ICES) working group for the assessment of Atlantic salmon within the Baltic Sea (ICES 2005), with the exception that the model only accounts for the two most abundant types of mature salmon i.e. grilse and 2SW salmon.

The structure of the salmon population can be summarized in a state vector,  $S$ ,  $S_t \equiv \{s_{1,t}, s_{2,t}, \dots, s_{6,t}\}$ , which traces the size of each age group. The state of the salmon stock in period  $t$  depends on the state of the stock and the fishing effort in period  $t-1$ . The fishing efforts of the five fisheries are summarized in vector  $X$ ,  $X_t \equiv \{X_t^{cdn}, X_t^{ctn}, X_t^{ri}, X_t^{odn}, X_t^{oll}\}$ . Thus, the state changes from one fishing season to the next follow  $S_t = G(S_{t-1}, X_{t-1})$ , with the state transition functions defining  $s_{a,t} = g_a(S_{t-1}, X_{t-1})$ . Index  $a$  indicates the age group,  $a \in \{1, \dots, 6\}$ , and  $G \equiv \{g_1, g_2, \dots, g_6\}$  is the vector of state transition equations.

The elements of the state vector  $S$  and the state transition vector  $G\{\cdot\}$  are described in Table 1. Appendix A describes the population model in more detail. The notation is as follows:  $r_s$  is sex ratio and  $fe$  average fecundity,  $m$  is the instantaneous natural mortality rate, and  $q_t^f$  is the

catchability coefficient of life stage  $l$  by fishery  $f$ . The harvested life stages - grilse, immature one-sea-winter salmon and two-sea-winter salmon - are subscripted by  $gr$ ,  $1$  and  $2$ . Further,  $\theta_t$  are independent and identically distributed random shocks on recruitment,  $\alpha$  and  $\beta$  are the recruitment parameters,  $m_{p-sm}^w$  and  $m_{p-sm}^r$  are the post-smolt mortalities for wild and reared salmon,  $I$  is the number of stocked smolts, and  $L$  is the maturation rate of one-sea-winter salmon.

[Table 1 about here]

### 3.2 Economic Model

This section describes the catches and annual net economic benefits to each of the five fisheries. Catch price, fishing costs and catchability may vary between the fisheries, as they operate at different times of the year, catch salmon of differing size and use different equipment. The catch weight of salmon also varies according to life stage. Throughout the model,  $p_f$  is the price of salmon in fishery  $f$  and  $c_f$  the cost of fishing effort in the fishery. The harvest rate of life stage  $l$  by fishery  $f$  is given by  $\left(1 - e^{-q_l^f X_t^f}\right)$ , and the catch weight of life stage  $l$  is denoted by  $W_l$ .

The coastal driftnet fishery harvests grilse and two-sea-winter salmon. The numbers of grilse and two-sea-winter salmon available to the fishery are given by  $e^{-m/12} Ls_{5,t}$  and  $e^{-m/12} s_{6,t}$ . The profits of the coastal driftnet fishery,  $\pi_{cdn,t}$ , are

$$\pi_{cdn,t} = p_{cdn} e^{-m/12} \left\{ Ls_{5,t} \left(1 - e^{-q_{gr}^{cdn} X_t^{cdn}}\right) W_{gr} + s_{6,t} \left(1 - e^{-q_2^{cdn} X_t^{cdn}}\right) W_2 \right\} - c_{cdn} X_t^{cdn}. \quad (1)$$

The coastal trapnet fishery harvests spawners after the coastal driftnet fishery. The numbers of grilse and two-sea-winter salmon that reach coastal trapnets are  $e^{-m/6} Ls_{5,t} e^{-q_{gr}^{cdn} X_t^{cdn}}$  and  $e^{-m/6} s_{6,t} e^{-q_2^{cdn} X_t^{cdn}}$ . The profits  $\pi_{ctn,t}$  of the fishery can be calculated using the following equation:

$$\pi_{ctn,t} = p_{ctn} e^{-m/6} \left\{ Ls_{5,t} e^{-q_{gr}^{cdn} X_t^{cdn}} \left(1 - e^{-q_{gr}^{ctn} X_t^{ctn}}\right) W_{gr} + s_{6,t} e^{-q_2^{cdn} X_t^{cdn}} \left(1 - e^{-q_2^{ctn} X_t^{ctn}}\right) W_2 \right\} - c_{ctn} X_t^{ctn}. \quad (2)$$

The river harvest is taken by recreational anglers. The numbers of grilse and two-sea-winter salmon reaching the river fishery are given by  $e^{-m/4} L s_{5,t} e^{-q_{gr}^{cdn} X_t^{cdn}} e^{-q_{gr}^{ctn} X_t^{ctn}}$  and  $e^{-m/4} s_{6,t} e^{-q_2^{cdn} X_t^{cdn}} e^{-q_2^{ctn} X_t^{ctn}}$ .

For the sake of tractability, we assume that the net social benefits from the recreational river fishery are quadratic in the river harvest; i.e.,

$$NB_{ri,t} = k H_{ri,t} - v (H_{ri,t})^2, \quad (3)$$

where  $H_{ri,t} = e^{-m/4} \left[ L s_{5,t} e^{-q_{gr}^{cdn} X_t^{cdn}} e^{-q_{gr}^{ctn} X_t^{ctn}} \left( 1 - e^{-q_{gr}^{ri} X_t^{ri}} \right) W_{gr} + s_{6,t} e^{-q_2^{cdn} X_t^{cdn}} e^{-q_2^{ctn} X_t^{ctn}} \left( 1 - e^{-q_2^{ri} X_t^{ri}} \right) W_2 \right]$  is the period  $t$  harvest of the river fishery and  $k$  and  $v$  are parameters of the net benefit function.

The offshore fisheries harvest only the salmon feeding in the Baltic Main Basin. The number of one-sea-winter salmon available in the main basin in October is supplied by  $e^{-5/12m} (1-L) s_{5,t}$ . The profits of the offshore driftnet fishery are

$$\pi_{odn,t} = p_{odn} e^{-5/12m} \left( 1 - e^{-q_1^{odn} X_t^{odn}} \right) (1-L) s_{5,t} W_1 - c_{odn} X_t^{odn}. \quad (4)$$

Finally, with the number of salmon available for harvest given by  $e^{-7m/12} e^{-q_1^{odn} X_t^{odn}} (1-L) s_{5,t}$ , the profits of the offshore longline fishery, which harvests one-sea-winter salmon after the offshore driftnet fishery, are

$$\pi_{oll,t} = p_{oll} e^{-7m/12} e^{-q_1^{odn} X_t^{odn}} \left( 1 - e^{-q_1^{oll} X_t^{oll}} \right) (1-L) s_{5,t} W_1 - c_{oll} X_t^{oll}. \quad (5)$$

Therefore, the total annual net economic gain  $\pi_t$  for the Northern Baltic salmon fishery is

$$\pi_t = \pi_{cdn,t} + \pi_{ctn,t} + NB_{ri,t} + \pi_{odn,t} + \pi_{oll,t} \quad (6)$$



#### 4. The Optimization Problem

Equations (1) to (5) illustrate the interdependence of the sequential fisheries. The harvest of each fishery affects the profits of the next and reduces the future salmon stock. The optimal harvest strategy would balance the marginal profits of each fishery to equal the revenues foregone in the next fishery in the sequence in the current season and in the future. The objective of the fishery manager is to maximize the discounted net benefits from the salmon fishery through the optimal choice of fishing effort for the five sequential fisheries. In the beginning of every season, the manager observes the size of the salmon stock  $S_t$  and then chooses the optimal vector of fishing efforts  $X_t$ , where  $X_t \equiv \{X_t^{cdn}, X_t^{ctn}, X_t^{ri}, X_t^{odn}, X_t^{oll}\}$ . The net economic benefits for the fishery as a whole,  $\pi_t(S_t, X_t)$ , depend on state of the salmon stock  $S_t$  and the fishing efforts  $X_t$ .

The salmon stock evolves from one period to the next according to the state transition equations  $S_t = G(S_{t-1}, X_{t-1})$  presented in Table 1. This is a controlled Markov process. The net benefits of the five fisheries targeting salmon are given by equations (1) to (5). The fishery manager seeks a sequence of fishing policies,  $X^{\{\cdot\}}$ , which prescribes the efforts  $X_t = X_t^*(S_t)$  that in a given state and period will maximize the expected net present value of the current and future harvest over an infinite time horizon  $T$ .

Bellman's (1957) principle of optimality implies that the optimal policy must satisfy the functional equation

$$V(S) = \max_{X \in X(S)} \{ \pi(S, X) + \delta E_\theta [V(G(S, X, \theta))] \}, \quad (7)$$

where  $V$  is the value function,  $\delta$  is the discount factor, and  $E_\theta$  is the expectation operator over the recruitment shocks  $\theta_t$ . The reward function  $\pi(S, X)$  is bounded. Where the value of  $\delta$  is less than one, the mapping underlying the Bellman equation is a strong contraction on the space of bounded continuous functions and thus, by the Contraction Mapping Theorem, will possess a unique solution.

We solved the dynamic program numerically using the collocation method. This technique involves writing the value function approximant as a linear combination of  $n$  known basis functions  $\varphi_1, \varphi_2, \dots, \varphi_n$  whose coefficients  $c_1, c_2, \dots, c_n$  are determined by the equation

$$V(S) \approx \sum_{j=1}^n c_j \phi_j(S) \quad (8)$$

The coefficients  $c_1, c_2, \dots, c_n$  are defined by requiring the value function approximant to satisfy the Bellman equation in (20) at a finite set of collocation nodes. The solution was implemented using the CompEcon Toolbox for Matlab.<sup>2</sup> The Matlab code is available from the authors upon request. The solution produces policy functions for  $X_i^*(S)$  that provide a mapping from the current state to the optimal harvest policy.

The solution to the problem can be characterized by the first-order equilibrium conditions known as Euler conditions. The relevant Euler conditions in the present case can be derived by applying the Karush-Kuhn-Tucker and Envelope Theorems to the optimization problem in (7). The effort levels are bounded from below by zero. The Euler equations take the form

$$\pi_x(S, X) + \delta E_\theta [\lambda(G(S, X, \theta)) \cdot G_x] = \tau \quad (9)$$

and

$$\pi_s(S, X) + \delta E_\theta [\lambda(G(S, X, \theta)) \cdot G_s] = \lambda(S), \quad (10)$$

where  $\lambda(S) \equiv V'(S)$  is the shadow value of the resource. Here,  $\pi_x, \pi_s, G_x$  and  $G_s$  denote the partial derivatives. The efforts  $X$  and  $\tau$  must satisfy the complementary condition

$$X \geq 0 \text{ and } X_i > 0 \Rightarrow \tau_i = 0. \quad (11)$$

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<sup>2</sup> The CompEcon Toobox is a library of MATLAB functions for numerically solving a variety of problems in economics and finance that was developed to accompany Miranda and Fackler (2002). The library is downloadable at <http://www4.ncsu.edu/~pfackler/compecon/toolbox.html>.

Here,  $\tau$  is a  $1 \times d_x$  vector whose  $i$ th element,  $\tau_i$ , measures the current and expected future reward from a marginal increase in the  $i$ th action variable  $X_i$ . If  $X_i > 0$ ,  $\tau_i$  must be zero; otherwise rewards could be increased by decreasing  $X_i$ .

## 5. Calibration

We calibrate the model by using parameter estimates for the salmon stock in the Simojoki River. In keeping with the current salmon management advice and the underlying parameter estimates, we measure fishing effort in terms of geardays (see, e.g., ICES, 2005). Thus, our control variables are the optimal number of geardays for each fishery. A gearday is defined as units of gear times number of fishing days. As each fishery uses different gear, the definition of a gearday differs accordingly: for the offshore and coastal driftnet fisheries, a gearday is the number of nets times the number of fishing days; for the coastal trapnet fishery it is the number of trapnets times the number of fishing days; for the offshore longline fishery it is the number of hooks times the number of fishing days; and for the river fishery, a gearday is equal to an angling day.

Table 2 displays the biological parameters of the Simojoki salmon stock. The parameter estimates are based on the assessments currently used by the corresponding ICES working group (ICES, 2005). Following Michielsens and McAllister (2004), the recruitment shocks  $\theta_t$  are assumed to follow a lognormal distribution. The recruitment errors are thus defined as  $\theta_t = e^{z_t}$ , where the process errors  $z_t$  are normally distributed with mean  $\mu$  and standard deviation  $\sigma$ .

[Table 2 about here]

Table 3 presents the economic parameters. We obtained the fishing cost data by interviewing fishermen. The cost estimates account for the variable costs: gear price, gear maintenance, vessel maintenance, fuel and labor costs. The costs differ due to the differences in the equipment and techniques used in the five fisheries. The price parameters were obtained from official Finnish statistics (FGFRI, 2004) and the statistics produced by the Danish Fisheries Directorate (Anon., 2004). We assume here that the small-scale catches of salmon native to Simojoki do not affect the market price of salmon. According to Setälä et al. (2002), salmon prices in Finland are

determined mainly by the imports of Norwegian salmon. The price differences reflect seasonal variation in the volume and quality of the salmon harvest as a whole.

The net benefits of the recreational harvest in the Simojoki have been estimated based on results of a contingent valuation study (Parkkila (2005)) ascertaining the willingness to pay (WTP) for stock improvements that would double the expected catch per angling day in the river from its 2003 level of 0.35 kg to 0.70 kg. The estimated WTP among anglers for a stock improvement that would double the catch was 8.50 euros per angling day in addition to the current expense of 12 euros a day. We assumed a linear marginal WTP for recreational harvest, fit the associated curve to the estimated WTP values to obtain individual net benefits, and then aggregated across the approximate angler population of 2900 anglers to obtain a measure of the social net benefits of the recreational harvest.

[Table 3 about here]

## 6. Results

The dynamic behavior of the model was studied using a Monte Carlo simulation. The simulation generated 10,000 state and policy paths using as input the optimal effort levels  $X_t = X_t^*(S_t)$  defined as the solution to the dynamic program in (7). The current stock estimates were used as the initial state. Figure 3 presents the means and 90 % probability intervals for optimal fishing effort in the coastal trapnet and river fisheries. Under the optimal policy, only the coastal trapnet fishery and the river fishery would remain active; the result holds for all state configurations produced by the simulation. The fact that the coastal trapnet fishery would continue to harvest under the optimal harvest policy while the other commercial fisheries would not – despite higher prices and lower unit costs - is explained by the differences in the catchabilities. The catchabilities of the targeted life stages by trapnet fishery are markedly higher than those by the other commercial fisheries, which suffices to compensate for the higher unit costs and lower price. Figure 4 shows the means and 90 % probability intervals for the net benefits to the two active fisheries. The variation in the coastal trapnet fishery's effort and net benefits is considerable, whereas the river fishery's effort and net benefits remain stable. When low stock levels are observed, the coastal trapnet fishery reduces its harvest to the benefit of the river fishery, which is able to harvest from a relatively stable stock of salmon. The result follows from the different character of commercial and recreational fishing, which is manifested in the

curvature of the net benefit functions: the marginal net benefit of harvesting is constant in the trapnet fishery but decreases in the river fishery. Figure 5 presents the mean and 90 % probability interval for smolt-stage salmon under the optimal policy. The expected number of smolts converges to near 75,000, some 20,000 more than the expectation if the fishery maintained its current fleet configuration and effort levels.

[Figure 3 about here]

[Figure 4 about here]

[Figure 5 about here]

The results are in line with the forthcoming changes in the EU Common Fisheries Policy, which will prohibit driftnet harvesting. The finding that three of the four commercial fisheries studied - the coastal driftnet, the offshore driftnet and the offshore longline – should be excluded from harvesting is robust to changes in the key economic and biological parameters. We conducted a sensitivity analysis to study the effect of such changes on the optimal policy. The parameters determining the relative performance of the commercial fisheries are the catch price, unit cost of fishing effort, and catch per unit of effort. Where the economic parameters were concerned, our sensitivity analysis focused on the costs and net benefits of the river fishery, for which data are sparse compared to price and catch per unit of effort data. We limited the analysis to the steady state of the certainty-equivalent problem obtained by fixing the recruitment shock at its mean.

Table 4 displays the certainty-equivalent steady state and the results of the sensitivity analysis. The optimal effort levels in the certainty-equivalent steady state computed at the base case parameters are 50,408 gear-days for the coastal trapnet fishery and 4093 angling days for the river fishery. The corresponding harvest levels are approximately 43,000 kg and 3700 kg. The coastal trapnet harvest in the certainty-equivalent steady state is slightly smaller than the current catch of the coastal fisheries as a whole, which is 63,600 kg (personal communication, Marjaliisa Koljonen, Finnish Game and Fisheries Research Institute). In contrast, the estimated recreational harvest is close to seven times the present harvest of 560 kg (personal communication, Erkki Jokikokko, Finnish Game and Fisheries Research Institute). The cost savings from closing down the less efficient fisheries and the substantial increase in the recreational harvest would produce social net benefits substantially above those realized at present: in the certainty-equivalent steady

state, the annual net benefits of the Simojoki salmon stock are near 137,000 euros, as opposed to the current net benefits of approximately 80,000 euros.

Other things being equal, the unit cost of fishing effort in the coastal trapnet fishery would have to be 80 % higher than the current estimate for the coastal driftnet fishery to be included in the optimal policy (Table 4). Further increases in costs for the coastal trapnet fishery would only shift catches between the coastal fisheries and the river fishery: at the current estimates of offshore unit costs, the offshore fisheries remain excluded from the harvest regardless of the coastal fisheries' unit costs. If instead the unit cost of the offshore driftnet fishery were 89 % below the current estimate, both coastal fisheries would be excluded from the optimal policy and replaced by the offshore driftnet fishery. Similarly, a unit cost 95 % below the current estimate for the offshore longline fishery would make that fishery the only active commercial one. On balance, the results appear robust to changes in the cost parameters. As fuel is the most important operating cost in fishing, a decrease in fishing costs is unlikely. An increase in the costs of trapnet fishing is a more likely scenario, since the increasing seal population in the Baltic Sea may force salmon fishermen to switch to seal-safe nets.

[Table 4 about here]

Figure 6 illustrates the effect of the fisheries' relative costs on the optimal fishery configuration. The left-hand side shows the case where the costs of the offshore driftnet and longline fisheries and net benefits of the river fishery remain at their current level while the costs of the coastal driftnet and trapnet fisheries vary. The offshore driftnet and trapnet fisheries harvest together with the river fishery only for a narrow range of costs. The right-hand side depicts the case where the coastal fisheries' costs and the net benefits of the river fishery remain at their current level while the offshore driftnet and longline costs change. A significant decrease in fishing costs would be required in both offshore fisheries for them to be included in the optimal harvest policy. Again, the two offshore fisheries coexist only for a narrow cost range. The effect of costs on the optimal fishery configuration is tied to the catchabilities by the fisheries. The costs of offshore longline fishing would have to fall roughly one order of magnitude below those of offshore driftnet fishing to compensate for the difference in the catchabilities by the fisheries and allow both to continue harvesting. The effect is similar in the case of the coastal fisheries.

[Figure 6 about here]

Changes in the marginal WTP for a recreational harvest and in the biological parameters resulted only in a shift of harvest between the coastal trapnet fishery and the river fishery; the optimal fishery configuration remained unchanged (Table 4). Shifts in the marginal WTP of up to 20% downward or upward, as well as similar relative changes in the slope, maintained the optimal fishery configuration of coastal trapnets and river fishery only. As one would expect, an upward shift in the marginal WTP allocates more harvest to the recreational river fishery and decreases the profits of the coastal trapnet fishery.

The optimal fishery configuration also remains unaltered irrespective of changes in the maturation rate, the stockings and the post-smolt mortality (Table 4). Decreasing the maturation rate to 0.1 from the current estimate of 0.15 did not affect the number of active fisheries. The effort, catch and profits of the trapnet fishery all increased slightly while the outcome for the river fishery remained essentially unchanged. Without offshore fisheries, the smaller availability of grilse would be compensated for by an increased number of two-sea-winter salmon available to the trapnet and river fisheries. The trapnet fishery, which is the first to harvest homing fish, would reap the benefits of an increased number of the larger two-sea-winter salmon. As a decrease in the maturation rate increases the number of salmon that are available to the offshore fisheries (equations 4 and 5), the assumption that the offshore fisheries harvest only one-sea-winter salmon while the other three fisheries harvest both one- and two-sea-winter salmon cannot be considered crucial for the exclusion of the offshore fisheries in the optimal policy.

Kallio-Nyberg et al. (2004) propose higher post-smolt mortality rates for wild and reared salmon than those used in the ICES stock assessments. Although post-smolt mortality is the principal biological parameter affecting salmon stock sizes after reproduction, an increase in post-smolt mortality rates did not affect the optimal policy with regard to the number of active fisheries. It did, however, result in a significant decrease in the effort, catch and profits in the coastal trapnet fishery. The higher post-smolt mortalities result in a close to 60 % decrease in the optimal harvest to the trapnet and river fisheries as a whole. At low stock levels the marginal benefit of additional effort falls more rapidly in the coastal trapnet fishery than in the river fishery, where the catchability of two-sea-winter salmon is markedly higher than in the coastal trapnet fishery, and where the marginal benefit of additional harvest is relatively high at low harvest levels.

We also studied the sensitivity of the optimal policy to the number of stocked smolts (Table 4). In the period 1996-2002, the average number of stocked smolts in the Simojoki was approximately 80,000 (Erkinaro et al., 2003), which is significantly higher than the current number of 2000. Increasing the number of reared smolts did not affect the optimal policy in terms of active fisheries. The effect on efforts and catches is the opposite of that brought about by an increase in post-smolt mortalities: the optimal efforts, catches and profits of the coastal trapnet fishery now increase somewhat while those of the river fishery remain virtually constant. At issue here again are the different catchabilities and decreasing versus constant marginal benefits of harvesting in the river and coastal trapnet fisheries. Higher effort and catches are now required in the coastal trapnet fishery to balance the marginal net benefits to equal those in the river fishery.

## **7. Conclusion**

This paper provides a bioeconomic model of the fishery for Atlantic salmon in the Baltic Sea that is compatible with the stock assessment models currently used to produce management advice. It thus bridges the gap between economic and biological models. The study extends the bioeconomic literature on the optimal management of salmon by considering an age-structured model of population dynamics and sequential harvest by multiple fisheries with different economic characteristics and impacts on the stock. The paper outlines a framework for numerically determining the optimal harvest policy for each fishery. Using data calibrated for the Simojoki salmon stock, the model has been applied to solve for the optimal harvesting policy and the optimal allocation of harvest between the five fisheries harvesting salmon from the Northern Baltic Sea area.

Uncertainty was included in the model in the form of recruitment fluctuations, which are the principal source of salmon population uncertainty in the Baltic Sea. In the case of a risk-neutral fishery manager, the optimal policy depends exclusively on the mean of the recruitment shock. When the mean shock is one, the optimal policy for each state produced by the stochastic model coincides with the optimal policy produced by the deterministic model, in which the recruitment



shock is fixed at its mean.<sup>3</sup> While the optimal policy in each state is similar to that indicated by the deterministic model, accounting for recruitment uncertainty yields insight into the volatility that the process may exhibit and its effect on the optimal fishery configuration. The result that the coastal and offshore driftnet fisheries and the offshore longline fishery should be excluded from harvesting is robust to variation in the population size: the fisheries were excluded everywhere along the simulated state paths, even when very large shocks were realized and the harvestable population was abundant.

The results support future fishery policy changes which will ban driftnet fisheries in the Baltic Sea. However, the empirical analysis presented here is confined to the Simojoki salmon stock, and the results on the optimal fishery configuration and harvest allocation cannot be generalized as such to other Baltic salmon fisheries. To obtain economically optimal management advice for the Baltic as a whole, the framework provided here should be extended to consider multiple coexisting stocks, and the data needed for empirical analysis should be gathered for all Baltic salmon fisheries.

The current guidelines for managing Baltic salmon ignore the economic aspects of the fishery (ICES, 2005). The sensitivity analysis carried out here underlines the importance of economic information for fisheries management. In the sequential fishery model, relative changes in the fishing costs affect the optimal fishery configuration, whereas changes in the biological parameters only alter the allocation of the harvest between the active fisheries. Collecting representative fishing cost data for all the Baltic salmon fisheries is essential for producing management recommendations that account for economic considerations. Further research on the value of recreational fisheries in the Baltic salmon rivers is also needed. Finally, our focus here has been on optimal harvest policy under the assumption that the Baltic salmon fishery is managed by a single authority. A worthwhile extension would be transboundary cooperation to sustain the optimal policy, for there are a number of countries that harvest salmon in the Baltic Main Basin.

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<sup>3</sup> In models with both recruitment uncertainty and uncertainty driving from stock measurements or policy implementation, the harvest policy produced by the stochastic model is more conservative than that produced by the corresponding deterministic model. See, e.g., Clark and Kirkwood (1986) and Sethi et al. (2005).

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## Appendix A. Population Dynamics.

The appendix describes the population dynamics by age group. The eggs hatch in the spring. After hatching, it takes a salmon approximately three and a half years to sequentially develop into fry ( $s_2$ ), parr ( $s_3$ ) and finally reach the smolt stage ( $s_4$ ). The relationship between the number of eggs and the number of smolts can be summarized by a Beverton-Holt stock-recruitment function (see, e.g., Michielsens and McAllister, 2004). Fry ( $s_2$ ) and parr ( $s_3$ ) are used as accounting variables in the our model:  $s_{3,t} = s_{1,t-2}$ . The number of wild smolts in May of year  $t$  is therefore given by

$$s_{4,t} = \frac{s_{3,t-1}}{\alpha + \beta s_{3,t-1}} \theta_t. \quad (\text{A1})$$

The salmon stock is safeguarded through stocking of juveniles. We assume that the reproduction function and associated parameters are the same for wild and reared salmon. The number of one-sea-winter salmon in May of year  $t$  is given by

$$s_{5,t} = s_{4,t-1} e^{-m_{p-sm}^w} + I_{t-1} e^{-m_{p-sm}^r}. \quad (\text{A2})$$

The population dynamics of reared salmon are similar to those of wild salmon except that the reared salmon enter the system through stocking. The natural mortality during the first year that salmon spend at sea (post-smolt mortality) is also higher for reared salmon than for wild salmon (Brown and Laland, 2001).

The mature one-sea-winter salmon, grilse, start their spawning migration. The number of grilse available to the coastal driftnet fishery in June of year  $t$  is given by

$$N_{gr,t}^{cdn} = L s_{5,t} e^{-m/12}. \quad (\text{A3})$$

The number of grilse that are available to coastal trapnets in July of year  $t$  is defined by

$$N_{gr,t}^{ctn} = N_{gr,t}^{cdn} e^{-q_{gr}^{cdn} X_t^{cdn}} e^{-m/12}. \quad (\text{A4})$$

The number of grilse that reach the river fishery in August of year  $t$  is given by

$$N_{gr,t}^{ri} = N_{gr,t}^{ctn} e^{-q_{gr}^{ctn} X_t^{ctn}} e^{-m/12}. \quad (A5)$$

We assume that grilse, which are predominantly males (Jokikokko et al., 2004), die naturally if they are not caught in the river fishery. Thus, they do not reproduce in our model.

The number of immature one-sea-winter salmon available to the offshore driftnet fishery in October of year  $t$  is given by

$$N_{1sw,t}^{odn} = (1 - L) s_{5,t} e^{-5m/12}. \quad (A6)$$

The number of one-sea-winter salmon reaching the offshore longline fishery in December of year is given by the equation

$$N_{1sw,t}^{oll} = N_{1sw,t}^{odn} e^{-q_1^{odn} X_t^{odn}} e^{-m/6}. \quad (A7)$$

The number of two-sea-winter salmon in May equals the number of one-sea-winter salmon surviving the offshore longline fishery, minus natural mortality:

$$s_{6,t} = (1 - L) e^{-m} s_{5,t} e^{-q_1^{odn} X_t^{odn}} e^{-q_1^{oll} X_t^{oll}} \quad (A8)$$

The number of two-sea-winter salmon available to the coastal driftnet fishery in June of year  $t$  is given by equation

$$N_{2sw,t}^{cdn} = e^{-m/12} s_{6,t}. \quad (A9)$$

The number of two-sea-winter salmon available to the coastal trapnet fishery is given by

$$N_{2sw,t}^{ctn} = N_{2sw,t}^{cdn} e^{-q_2^{cdn} X_t^{cdn}} e^{-m/12} . \quad (A10)$$

The number of two-sea-winter salmon reaching the river fishery is

$$N_{2sw,t}^{ri} = N_{2sw,t}^{ctn} e^{-q_2^{ctn} X_t^{ctn}} e^{-m/12} . \quad (A11)$$

Finally, the number of spawning salmon (*SSN*) is given by

$$SSN_t = N_{2sw,t}^{ri} e^{-q_2^{ri} X_t^{ri}} e^{-m/6} . \quad (A12)$$

By assumption all salmon die spawning. The number of eggs produced is given by

$$N_{eg,t}^w = SSN_t \cdot r_s \cdot fe . \quad (A13)$$



Table 1. The elements of the state vector  $S_t$  and transition vector  $S_t = G(S_{t-1}, X_{t-1})$

Age group	State variable	State transition equation $g_a(S_{t-1}, X_{t-1})$ for age group $a$ as function of $S_{t-1}$ and $X_{t-1}$
Egg	$s_{1,t}$	$g_1(S_{t-1}, X_{t-1}) = r_s \cdot fe \cdot e^{-5m/12} \cdot s_{6,t-1} \cdot e^{-q_2^{cdn} X^{cdn}} e^{-q_2^{ctn} X^{ctn}} e^{-q_2^{ri} X^{ri}}$
Fry	$s_{2,t}$	$g_2(S_{t-1}, X_{t-1}) = s_{1,t-1}$
Parr	$s_{3,t}$	$g_3(S_{t-1}, X_{t-1}) = s_{2,t-1}$
Smolt	$s_{4,t}$	$g_4(S_{t-1}, X_{t-1}) = \theta_t s_{3,t-1} / (\alpha + \beta \cdot s_{3,t-1})$
One-sea-winter salmon	$s_{5,t}$	$g_5(S_{t-1}, X_{t-1}) = e^{-m_{p-sm}^w} s_{4,t-1} + e^{-m_{p-sm}^i} I_{t-1}$
Two-sea-winter salmon	$s_{6,t}$	$g_6(S_{t-1}, X_{t-1}) = (1-L) e^{-m} \cdot s_{5,t-1} \cdot e^{-q_1^{odn} X^{odn}} e^{-q_1^{oll} X^{oll}}$

Table 2. Biological parameters (from ICES 2005).

<b>Symbol</b>	<b>Definition</b>	<b>Value</b>	<b>Unit</b>
$r_s$	sex ratio	0.5	males and females
$fe$	fecundity	10,000	eggs/female
$m$	instantaneous adult natural mortality	0.18	year <sup>-1</sup>
$q_2^{cdn}$	catchability of two-sea-winter salmon by <i>cdn</i> fishery	$1.6 \text{ e}^{-7}$	geardays <sup>-1</sup>
$q_2^{ctn}$	catchability of two-sea-winter salmon by <i>ctn</i> fishery	$1.3 \text{ e}^{-5}$	geardays <sup>-1</sup>
$q_2^{ri}$	catchability of two-sea-winter salmon by <i>ri</i> fishery	$2.1 \text{ e}^{-5}$	geardays <sup>-1</sup>
$q_1^{odn}$	catchability of one-sea-winter salmon by <i>odn</i> fishery	$1.6 \text{ e}^{-7}$	geardays <sup>-1</sup>
$q_1^{oll}$	catchability of one-sea-winter salmon by <i>oll</i> fishery	$6.6 \text{ e}^{-8}$	geardays <sup>-1</sup>
$q_{gr}^{cdn}$	catchability of grilse by <i>cdn</i> fishery	$1.5 \text{ e}^{-9}$	geardays <sup>-1</sup>
$q_{gr}^{ctn}$	catchability of grilse by <i>ctn</i> fishery	$1.9 \text{ e}^{-5}$	geardays <sup>-1</sup>
$q_{gr}^{ri}$	catchability of grilse by <i>ri</i> fishery	$2.0 \text{ e}^{-5}$	geardays <sup>-1</sup>
$\alpha$	parameter of recruitment function	105	
$\beta$	parameter of recruitment function	$8.515 \text{ e}^{-6}$	
$I$	stockings	2000	number of smolts
$m_{p-sm}^w$	post-smolt mortality of wild salmon	1.67	year <sup>-1</sup>
$m_{p-sm}^r$	post-smolt mortality of reared salmon	2.2	year <sup>-1</sup>
$L$	maturation rate for one-sea-winter salmon	0.15	
$W_{gr}$	catch weight for grilse	0.97	Kg
$W_1$	catch weight for one-sea-winter salmon	3.95	Kg
$W_2$	catch weight for two-sea-winter salmon	8.65	Kg
$\mu$	mean of process error $z_t$	0	
$\sigma$	standard deviation of process error $z_t$	0.48	

Table 3. Economic parameters

<b>Abbreviation</b>	<b>Definition</b>	<b>Value</b>	<b>Unit</b>
$c_{cdn}$	unit cost of coastal driftnet fishery	0.03	€/gearday
$c_{ctn}$	unit cost of coastal trapnet fishery	0.97	€/gearday
$c_{odn}$	unit cost of offshore driftnet fishery	0.05	€/gearday
$c_{oll}$	unit cost of offshore longline fishery	0.03	€/gearday
$p_{cdn}$	price for coastal driftnet fishery <sup>1</sup>	3.4	€/kg
$p_{ctn}$	price for coastal trapnet fishery <sup>2</sup>	2.5	€/kg
$p_{odn}$	price for offshore driftnet fishery <sup>3</sup>	3.6	€/kg
$p_{oll}$	price for offshore longline fishery <sup>3</sup>	3.6	€/kg
$k$	parameter of river net benefit function	39.3	
$\nu$	parameter of river net benefit function	0.00493	

<sup>1</sup>Price of salmon in the Åland Islands in June 2003 (FGFRI, 2004).

<sup>2</sup>The average producer price of salmon in the Bothnian Sea and the Bothnian Bay in July 2003 (FGFRI, 2004).

<sup>3</sup>Average price of salmon landed in Denmark in the year 2003 (Anon., 2004). In winter in particular, the Finnish offshore harvest is landed primarily in Denmark.

Table 4. Optimal policy and sensitivity analysis

Fishery	Base case			80 % increase CTN costs			89 % decrease in ODN costs			95 % decrease in OLL costs		
	Effort (geardays)	Catch (kg)	Net benefits (EUR)	Effort (geardays)	Catch (kg)	Net benefits (EUR)	Effort (geardays)	Catch (kg)	Net benefits (EUR)	Effort (geardays)	Catch (kg)	Net benefits (EUR)
CDN	0	0	0	78517	1168	1616	0	0	0	0	0	0
CTN	50408	43073	58787	41179	3891	41355	0	0	0	0	0	0
RI	4093	3725	78040	3469	3755	78112	4737	3716	78017	5208	3698	77965
ODN	0	0	0	0	0	0	4748680	22599	55238	0	0	0
OLL	0	0	0	0	0	0	0	0	0	11640400	21991	60660

Fishery	80000 stocked smolts			Increased post-smolt mortalities: $m_{p-sm}^w = 2.2, m_{p-sm}^r = 2.8$			Lower maturation rate: $L=0.1$		
	Effort (geardays)	Catch (kg)	Net benefits (EUR)	Effort (geardays)	Catch (kg)	Net benefits (EUR)	Effort (geardays)	Catch (kg)	Net benefits (EUR)
CDN	0	0	0	0	0	0	0	0	0
CTN	82693	95101	157541	15751	7756	4111	53249	47421	66899
RI	3851	3717	78018	5757	3783	78173	3981	3723	78032
ODN	0	0	0	0	0	0	0	0	0
OLL	0	0	0	0	0	0	0	0	0

Fishery	20 % increase in the intercept of marginal WTP for recreational harvest			20 % decrease in the intercept of marginal WTP for recreational harvest			20 % increase in the slope of marginal WTP for recreational harvest			20 % decrease in the slope of marginal WTP for recreational harvest		
	Effort (geardays)	Catch (kg)	Net benefits (EUR)	Effort (geardays)	Catch (kg)	Net benefits (EUR)	Effort (geardays)	Catch (kg)	Net benefits (EUR)	Effort (geardays)	Catch (kg)	Net benefits (EUR)
CDN	0	0	0	0	0	0	0	0	0	0	0	0
CTN	49594	42419	57941	51214	43721	59624	49413	42273	57753	51065	43601	59469
RI	4939	4487	112428	3250	2964	49910	5126	4655	97546	3406	3105	65035
ODN	0	0	0	0	0	0	0	0	0	0	0	0
OLL	0	0	0	0	0	0	0	0	0	0	0	0

Figure 1. Migration routes of the salmon stocks from the Northern Baltic Sea. Salmon are harvested during feeding and spawning migrations in the Baltic Main Basin, the Gulf of Bothnia and rivers.

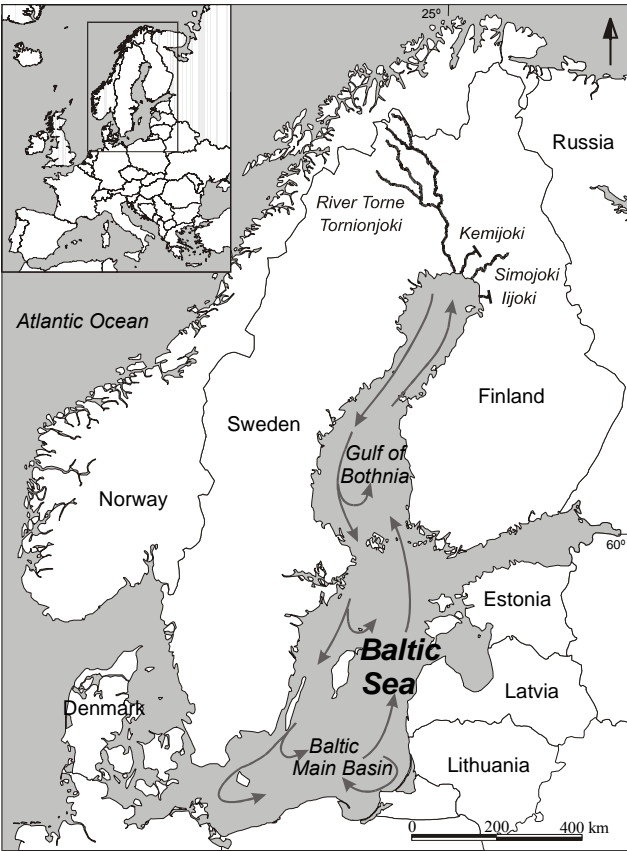


Figure 2. Structure of the salmon fishery in the Baltic Sea, following Michielsens et al. (2006). The coastal driftnet, coastal trapnet and river fisheries harvest spawning salmon. The offshore driftnet and longline fisheries harvest immature salmon that remain in the Baltic Main Basin to feed.

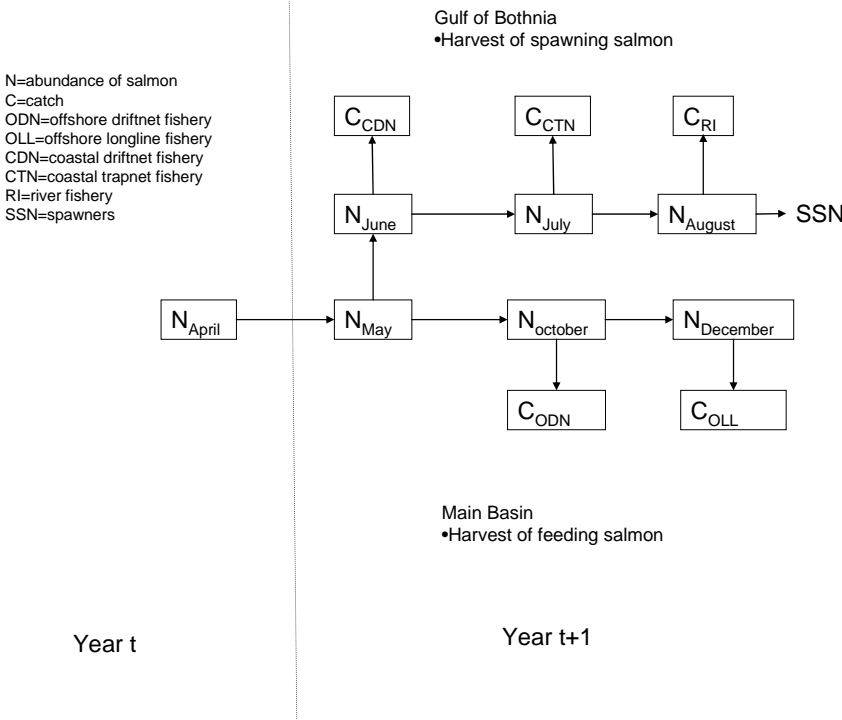
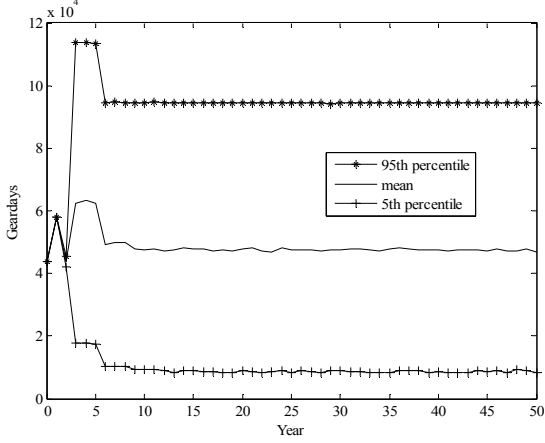
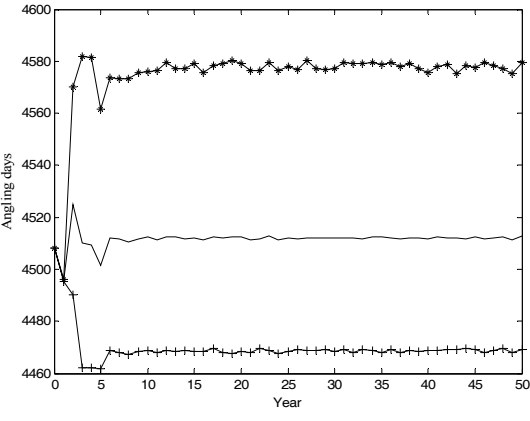


Figure 3. Means and 90 % probability intervals for fishing efforts in (a) the coastal trapnet and (b) river fisheries for a 50-year simulation period.

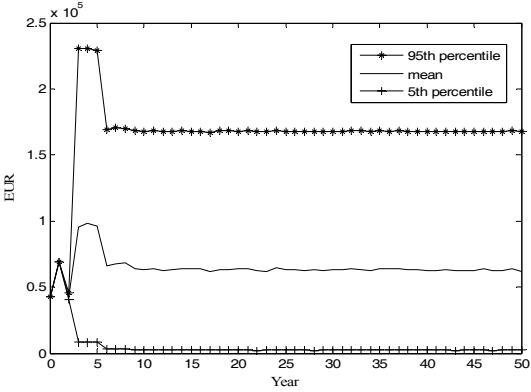


(a)

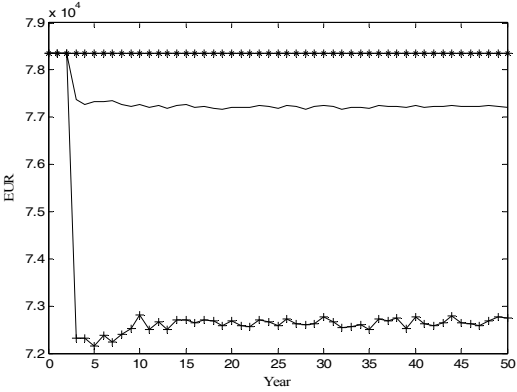


(b)

Figure 4. Means and 90 % probability intervals for (a) the net benefits to the coastal trapnet and (b) river fisheries for a 50-year simulation period.



(a)



(b)



Figure 5. Mean and 90 % probability interval for smolt-stage salmon for a 50-year simulation period. The initial state corresponds to the current stock estimates.

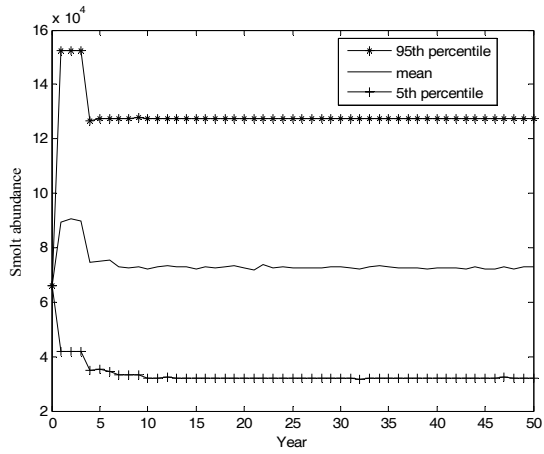


Figure 6. Optimal fishery configuration as a function of fisheries' unit costs.

