Department of Economics and Management
University of Helsinki

Essays on the Bioeconomics of the Northern Baltic Fisheries

Soile Kulmala

ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public examination in the Auditorium of the Arppeanum, Snellmaninkatu 3, Helsinki,
on 28 October 2009, at 12 noon.

Helsinki 2009

Opponent:	Professor Claire Armstrong Department of Economics and Management Norwegian College of Fisheries Science University of Tromsø Tromsø, Norway
Pre-examiners:	Professor Veijo Kaitala Department of Biological and Environmental Sciences University of Helsinki Helsinki, Finland
	Associate Professor Lone Grønbæk Kronbak Department of Environmental and Business Economics University of Southern Denmark Esbjerg, Denmark
Supervisor:	University Lecturer Marko Lindroos Department of Economics and Management University of Helsinki Helsinki, Finland
Instructors:	PhD Marita Laukkanen MTT Economic Research Helsinki, Finland
	Professor Pedro Pintassilgo Faculty of Economics University of Algarve Faro, Portugal
Cover design:	© Laura Korkalainen

ISBN 978-952-92-6068-3 (paperback)
ISBN 978-952-10-5708-3 (PDF)
http://ethesis.helsinki.fi

Printed in Copy-Set Oy
Helsinki 2009

Abstract

World marine fisheries suffer from economic and biological overfishing: too many vessels are harvesting too few fish stocks. Fisheries economics has explained the causes of overfishing and provided a theoretical background for management systems capable of solving the problem. Yet only a few examples of fisheries managed by the principles of the bioeconomic theory exist.

With the aim of bridging the gap between the actual fish stock assessment models used to provide management advice and economic optimisation models, the thesis explores economically sound harvesting from national and international perspectives. Using data calibrated for the Baltic salmon and herring stocks, optimal harvesting policies are outlined using numerical methods.

First, the thesis focuses on the socially optimal harvest of a single salmon stock by commercial and recreational fisheries. The results obtained using dynamic programming show that the optimal fishery configuration would be to close down three out of the five studied fisheries. The result is robust to stock size fluctuations. Compared to a base case situation, the optimal fleet structure would yield a slight decrease in the commercial catch, but a recreational catch that is nearly seven times higher. As a result, the expected economic net benefits from the fishery would increase nearly 60%, and the expected number of juvenile salmon (smolt) would increase by 30%.

Second, the thesis explores the management of multiple salmon stocks in an international framework. Non-cooperative and cooperative game theory are used to demonstrate different "what if" scenarios. The results of the four player game suggest that, despite the commonly agreed fishing quota, the behaviour of the countries has been closer to non-cooperation than cooperation. Cooperation would more than double the net benefits from the fishery compared to a past fisheries policy. Side payments, however, are a prerequisite for a cooperative solution.

Third, the thesis applies coalitional games in the partition function form to study whether the cooperative solution would be stable despite the potential presence of positive externalities. The results show that the cooperation of two out of four studied countries can be stable. Compared to a past fisheries policy, a stable coalition structure would provide substantial economic benefits. Nevertheless, the status of the salmon stocks would not improve significantly.

Fourth, the thesis studies the prerequisites for and potential consequences of the implementation of an individual transferable quota (ITQ) system in the Finnish herring fishery. Simulation results suggest that ITQs would result in a decrease in the number of fishing vessels, but enables positive profits to overlap with a higher stock size.

The empirical findings of the thesis affirm that the profitability of the studied fisheries could be improved. The evidence, however, indicates that incentives for free riding exist, and thus the most preferable outcome both in economic and biological terms is elusive.

Acknowledgements

First and foremost I am deeply indebted to my supervisor Marko Lindroos for his support, guidance, advice and confidence in my abilities. He equipped me to deal with academic life, and never spared his effort or time.

I have been extremely fortunate in receiving the guidance of Marita Laukkanen and Pedro Pintassilgo. They taught me new skills and ideas, and their invaluable advice has clearly improved the quality of my thesis. My warmest appreciation goes to my other co-authors Sakari Kuikka, Catherine Michielsens, Polina Levontin, Hanna Peltomäki, Tapani Pakarinen and Pirkko Söderkultalahti for their rewarding cooperation.

Sincere compliments to Markku Ollikainen for re-establishing and developing the teaching of environmental economics in the University of Helsinki, and for his support during my studies. Heartfelt thanks to Chiara Lombardini-Riipinen for an excellent introduction to the Gordon-Schaefer model, to Olli Tahvonen for inspiring lectures on bioeconomics, to the pre-examiners of my thesis, Veijo Kaitala and Lone Grønbæk Kronbak, for their encouraging statements and to Claire Armstrong for agreeing to be my opponent.

I am indebted to my fellow students, especially Katja Parkkila, Anna-Kaisa Kosenius, Piia Aatola, Jenni Miettinen, Antti Iho, Kimmo Ollikka and Anna Sahari for all those educational experiences during the process; you have been a great reserve of help, comments and support. Special thanks to Mika Rahikainen for sharing his knowledge of herring. The Centre for Fisheries & Aquaculture Management & Economics (FAME) has organized high quality workshops and PhD courses on fisheries economics and provided funding for participation. Thanks for this opportunity for networking! My colleagues, especially Sakari Kuikka, Samu Mäntyniemi, Laura Uusitalo and Päivi Haapasaari from the Fisheries and Environmental Management Research Group (FEM), have planted the idea of Bayesian modeling in my mind. I am looking forward to applying the approach.

During the process of completing this thesis I had an opportunity to work at the Finnish Game and Fisheries Research Institute. I am grateful to Petri Suuronen, Jaakko Erkinaro, Tapani Pakarinen, Atso Romakkaniemi, Jarno Virtanen, Jukka Pönni, Matti Salminen, Outi Heikinheimo, Eija Nylander, Pirkko Söderkultalahti, Marja-Liisa Koljonen and Björn Ehrnsten for their kind help and cooperation. Atso and Tapani have been an invaluable source of information on salmon ecology and the features of the fishery, and Jarno, Eija and Pirkko on economic data. Special thanks to Atso for inviting me to be a member of the ICES Baltic Salmon and Trout Stock Assessment Working Group (WGBAST). I feel privileged to have had that experience. Thanks to the working group members, especially the WGBAST modelers' team: Catherine Michielsens, Polina Levontin, Samu Mäntyniemi and Henni Pulkkinen. A toast to scenarios!

This study has been carried out with financial support from three projects: BIREME (Finnish Academy), EFIMAS (EU Commission contract no. SSP8-CT-2003-502516) and COMMIT (EU Commission contract no. SSP8-CT-2003-502289), and with grants from the Emil Aaltonen foundation and from the University of Helsinki. During most of the time spent completing this thesis I was employed by the Department of Economics and Management of the University of Helsinki. Warmest thanks to the Head of the Department

Markku Koskela and to the secretaries Outi Pajunen, Nina Niemeläinen and Kirsi-Marja Mustonen for their support and assistance.

I am indebted to my old friends and to those with whom I became friends during this process. You have been an inexhaustible reserve of support and laughter. Special thanks to Nina Hyytiä for helping me to complete the summary of the thesis. Warmest thanks to Laura Korkalainen for designing the front cover, and to the horses, teachers and fellow students at the Poni-Haka riding school for providing the perfect counterbalance to this work.

Finally, I owe my sincere gratitude to my brother and parents for their support and to Tero for his patience, love and encouragement.

Contents

List of original publications

This thesis is based on the following publications:

I Kulmala Soile, Laukkanen, M. & Michielsens, C. (2008). Reconciling economic and biological modeling of migratory fish stocks: Optimal management of the Atlantic salmon fishery in the Baltic Sea. Ecological Economics 64: 4, p. 716-728.

II Kulmala Soile, Levontin, P., Lindroos, M., Michielsens, C., Pakarinen, T. & Kuikka, S. (2009). International Management of the Atlantic Salmon Fishery in the Baltic Sea. Submitted.

III Kulmala Soile, Levontin, P., Lindroos, M. & Pintassilgo P. (2009) Atlantic Salmon Fishery in the Baltic Sea - A Case of Trivial Cooperation. Submitted.

IV Kulmala Soile, Peltomäki, H., Lindroos, M., Söderkultalahti, P. & Kuikka, S. (2007). Individual Transferable Quotas in the Baltic Sea Herring Fishery: a Socio-bioeconomic Analysis. Fisheries Research 84: 3, p. 368-377

The publications are referred to in the text by their roman numerals.

1 Introduction to Essays on the Bioeconomics of the Northern Baltic Fisheries

According to the Food and Agriculture Organization of the United Nations, in 2007, 27% of the world's fish stocks were either over-exploited or already depleted (FAO 2009). Also, in the European Union, the fishing fleets suffer from overcapacity, and as high a share as 80% of the fish stocks is harvested above the maximum sustainable yield (Commission of the European Communities 2008, European Communities 2008). This marine fisheries crisis suggests that the advanced theory of fisheries economics is not applied in practical fisheries management widely enough to create resource rents and healthy fish stocks. One reason that the economic point of view has been dismissed by natural scientists and management authorities may be the predominance of biomass dynamic models in fisheries economics literature addressing optimal harvesting (e.g. Deacon et al. 1998). Biomass dynamic models have been accused of being oversimplified, and thus incapable of providing management and policy guidelines. Instead, they have been considered as a useful pedagogical tool in teaching the basics of bioeconomics (Hilborn and Walters 1992, Townsend 1986, Wilen 1985). Thus, the objective of this thesis is to bridge the gap between the actual stock assessment models used to provide management advice and economic optimisation models.

Economically sound harvesting policies are derived from national and international perspectives. All the Baltic Sea riparian countries excluding Russia are members of the EU. For instance, TAC (total allowable catch) decisions are made on the EU level. Therefore, the Common Fisheries Policy (CFP) sets the international frames for this thesis. However, the member states have the power to decide on the use of other management measures, such as time and gear restrictions or the application of ITQs (individual transferable quotas). Further, the TAC considers commercial fishery only, whereas the management power over the recreational use of species under the TAC is in the hands of national authorities. The focus of the thesis is on the biologically and economically sound harvesting of two species: Baltic salmon (*Salmo Salar* L.) and Baltic herring (*Clupea harengus membras* L.). Both of the species are managed by TACs, and the stock assessment preceding TAC advice is carried out by ICES (the International Council for the Exploration of the Seas). However, economic studies related to Baltic salmon and herring harvesting are almost non-existent.

The ecology of these two species also provides perspectives on determining interesting research questions from the economic point of view. Salmon is an anadromous species, implying that during its feeding migration it is harvested by several countries, but during its spawning migration some stocks are mainly harvested by a single country with sequential fisheries. In contrast, herring is a pelagic species and one of the most important herring stocks in the Baltic Sea - the Bothnian Sea herring stock - is, compared to salmon, a local stock.

To these ends, the thesis combines the existing state-of-the-art population models of salmon and herring with the salient economic characteristics of the fleets targeting these species. Thus, the bioeconomic models underlying the thesis are complex relative to the mainstream models of fisheries economics. Optimal harvesting policies are therefore outlined using numerical methods. Internationally interesting problems are studied by applying both non-cooperative and cooperative game theory and coalition games in partition function form.

The aim of this introduction is to provide the context for the essays of the thesis. Thus, the following section reviews the existing bioeconomic literature on the topics necessary to demonstrate the thesis's niche. Further, fishery-specific knowledge prerequisite to understanding the developed models is provided. This chapter will be closed with a review of the thesis's essays, which are shortly introduced here. The thesis contains four essays: I) 'Reconciling economic and biological modeling of migratory fish stocks: Optimal management of the Atlantic salmon fishery in the Baltic Sea'. This essay is a baseline of the thesis in a sense that it introduces an age-structured salmon fishery model and provides socially optimal policy implications attained by using dynamic programming. The application is made for one country and one salmon stock. Essay II) 'International Management of the Atlantic Salmon Fishery in the Baltic Sea' turns the perspective to internationally optimal harvesting. The underlying biological model accounts for the age structure of 15 salmon stocks, and the economic model considers four countries. Outcomes of non-cooperative and cooperative games are compared to the performance of the fishery under the present management. Essay III) 'Atlantic Salmon Fishery in the Baltic Sea - A Case of Trivial Cooperation' expands on Essay II by applying a coalition game in the partition function form to the model developed in Essay II. Essay IV) 'Individual Transferable Quotas in the Baltic Sea Herring Fishery: a Socio-bioeconomic Analysis' introduces the first bioeconomic model for the Finnish herring fishery. The model is applied in order to give insights into the potential benefits from ITQs over the present management system.

2 Bioeconomics

2.1 Age-structured models and economic optimisation

The common denominators among the essays of the thesis are that 1) the population dynamic model underlying the analyses accounts for the age structure of the examined fish stock and that 2) the solutions for the economic optimisation problems are produced through numerical methods. However, the seminal bioeconomic models in fisheries economics literature by Gordon (1954) and Schaefer (1957) in a static framework and later Clark and Munro (1975) in a dynamic framework, applied biomass dynamic population models and provided analytical solutions. Different regulatory schemes for fisheries were analysed in similar settings by Clark (1980a). Game theoretical applications started also by adopting biomass dynamic models, but dynamic analysis by Munro (1979) and Clark (1980b) preceded the static formulation by Mesterton-Gibbons (1993).

The age structure of a fish stock includes important information regarding the fish stock dynamics and future harvesting possibilities. For instance, fisheries ecologists have concluded that the protection of older fish, especially old females, can be a key towards sustainable fisheries (Anderson et al. 2008, Conover and Munch 2002, Palumbi 2004). Surprisingly, the use of age-structured models in analytical fisheries economics is not very common, despite the fact that according to Tahvonen (2008), about 99% of the present biological fisheries models take into account the age structure of a population. Analytical fisheries economics models addressing the optimal harvesting of an age-structured population have mainly built upon the Beverton and Holt (1957) approach. However, this has lead to the conclusion, for instance by Clark (1990), that age-structured models are too complex for analytical solutions. Recently, Tahvonen (2009) applied a somewhat different approach and showed that age-structured fishery models are analytically tractable. He further argued that accounting for biological realism in the form of age structure in economic research may increase economists' contribution to practical management and increase dialogue between scientists in the field (Tahvonen 2008).

In the field of empirical fisheries economics and its game theoretical applications, age-structured models are common. In general, empirical applications restrict their optimal policy implications to comparisons of economic outcomes of management options or to the results attained via open-loop optimisation (e.g. Sumaila 1995, Pintassilgo and Duarte 2002, Bjørndal, Ussif & Sumaila 2004). In open-loop optimisation, the objective function is maximised by finding a constant in time level for the decision variable, given the population dynamics. In contrast, for optimal feedback solutions, the optimal solution is a function of time and fish stock. Further, in the case of an age-structured model, the optimal solution is derived for each age group. For instance, Bertignac et al. (2001) and Moxnes (2005) have taken steps towards optimal harvesting solutions. However, their approach was restricted to static linear programming and the requirement that the optimal harvest is a function of biomass, respectively.

In order to produce an optimal feedback solution for a model with six state and five decision variables, Essay I applies dynamic programming (Bellman 1957). The solution is found numerically by applying a collocation method where the Bellman functional equation is replaced with a system of *n* nonlinear equations in *n* unknowns. The resulting system of nonlinear equations, which is called a collocation equation, can then be solved using any nonlinear equation solution method. (Mercenier and Michel 1994, Biegler and Grossmann 2004) Here the solution is executed by using MATLAB together with the CompEcon toolbox (Miranda and Fackler 2002). Two essays of the thesis (II & III) that apply game theory employ open-loop optimisation. Thus, the games are semi-dynamic in the sense that even if the population dynamics evolves in time, the players make their decisions at the beginning of the game and keep their strategies constant during the game. The true novelty of the developed models using this stylised optimisation is in the modelling approach. The models are executed using object-oriented programming, and they are compatible with the models developed with FLR (Fisheries Library for R) by Kell et al. (2007). Such an approach allows tracing the life cycle and age structure of 15 salmon stocks (http://flr-project.org/). In addition, this framework is accompanied by an algorithm that is able to solve the Nash equilibrium (Nash 1951, 1953) of the games.

2.2 Individual transferable quota (ITQ): a practical tool towards the optimum

Under an ITQ scheme the TAC is divided into smaller quotas or shares, which in turn are allocated to individual fishermen or companies. These individual quotas can then be traded or leased. Hence, the most efficient fishers should be able to buy more quotas, and consequently, the TAC should be harvested with minimum costs. Originally, ITQs were proposed as a tool to provide economic incentives to stop the "race for fish" (Christy 1973, Moloney and Pearse 1979). When the discussion of ITQs started, the majority of the literature on it was in obscure publications, and economic analyses regarding property rights in the literature on pollution remained unexplored in fisheries literature (Scott 1979, Brown 2000).

One of the earliest analytical contributors in ITQ literature was Clark (1980a), who showed that if the TAC corresponds to the optimal sustainable catch, then the ITQ and the catch tax are equivalent in terms of economic efficiency. Copes (1986) criticised ITQs, but did not provide analytical results. Boyce (1992) in turn corresponded to the critiques of Copes and showed that ITQs are able to eliminate the costly race for fish, but only if no production externalities are present. However, despite the potential presence of externalities, compared to open access, ITQs will result in an improvement.

Since the introduction of ITQs in practical fisheries management in the 1980s, the number of published studies has exploded. A review by Squires et al. (1998) referred to 122 studies. Existing ITQ schemes provided a fruitful ground for empirical studies. In particular, the early experiences of New Zealand, Iceland and Australia were examined. For instance, Arnason (1990) proposed that ITQ prices can be used to inform annual harvest limits, and Batsone and Sharp (2003) confirmed his proposition using data from New Zealand's snapper fisheries. They used time series analysis and concluded that when advising management authorities, substantial cost savings could follow from the use of econometric modelling as a partial substitute for stock assessment methods. Moreover, Newell et al. (2005) studied New Zealand's ITQ schemes using econometric methods. Their data set covered 33 species and over 150 quota markets. Among other things, they found that especially in cases where fish stocks had recovered from overfishing after the implementation of ITQs, quota prices reflected the status of the stocks. Kompas and Nhu Che (2005) studied South-East Australian trawl fishery and estimated significant gains from ITQs both in terms of efficiency and cost savings. In addition, according to Arnason (2005, 2008), Iceland's ITQ system has been successful and has created wealth not only in the fisheries sector but also in other sectors of society.

In contrast to the studies addressing the performance of an existing ITQ system, the thesis provides an ex-ante insight into the potential effects of the implementation of ITQs on the commercially most important Finnish fishery. Even if ex-ante analyses have recently been scarce (e.g. Lanfersieck and Squires 1992, Armstrong and Sumaila 2001), the ex-ante design principles of ITQ schemes have drawn researchers' attention (e.g. Townsend, McColl & Young 2006, Grafton and McIlgorm 2009). In addition, the suitability of ITQs for solving the resource use allocation between different user groups, such as commercial and recreational fishermen and conservationists, has been further studied (Sutinen and Johnston 2003, Arnason 2009).

2.3 Game theoretical applications

Game theory is a tool for analysing strategic interactions between multiple agents. The United Nations Law of the Sea Convention in 1982 gave rise to the use of game theory in fisheries economics literature. The problems studied included issues of sharing the benefits from the exploitation of a stock moving within the EEZs (Exclusive Economic Zones) of several coastal states (Munro 1986) and of a stock migrating between the high seas and EEZs (Kaitala and Munro 1993, Munro 1996). The update of the convention in 1995 created a basis for the development of coalitional games. Before the introduction of coalitional games by Kaitala and Lindroos (1998), the literature addressed non-cooperative and cooperative behaviour in a two-player framework. Under an assumption of asymmetric fishing costs, the equilibrium of a non-cooperative game in a static setting was found to consist of two players both harvesting and earning positive profits (Mesterton-Gibbons 1993), whereas under the dynamic setting only the most efficient country would be harvesting (Clark 1980b). Munro (1979) established a framework for a fisheries cooperative game and the use of side payments as a tool to promote cooperation.

This thesis (Essay II) applies both non-cooperative and cooperative game theory. The outcomes of these games are then contrasted and compared with a past fisheries policy. The outcomes of non-cooperative and cooperative games can be interpreted as 'no management' and 'optimal management', respectively. The Relative Stability Principle (EEC Reg. no. 172/83), a corner-stone of the CFP according to which TACs are allocated to member states, has been accused of causing inflation pressure on the overall TAC (Boude, Boncoeur & Bailly 2001, Daw and Gray 2005). Thus, by using game theory, we gain insight into the problem called 'decision-overfishing' introduced by Eagle (2003). In the situation of decision-overfishing, the TAC is set above scientific recommendations. That is to say, game theory is used to shed light on the situation illustrated in Table 1, where the member states, in cooperation, set the TAC nearly 50% above the realised catches. The results suggest that regardless of the CFP, the past performance of the fishery has been closer to non-cooperation than cooperation. Moreover, the economic and biological benefits from cooperation outweigh the results from non-cooperation. However, in order to establish a cooperative agreement, side payments are needed.

Table 1 *The salmon TAC (excluding the Gulf of Finland) and catch per country in 2007 by number of salmon (ICES 2007 p.94, ICES 2008a p.5).*

Contracting party	Allocation key %	Quota	Catch	Utilised %
Denmark	20.3	88836	16145	18.2
Estonia	2.1	9028	325	3.6
Finland	25.3	110773	63441	57.3
Germany	2.3	9884	3086	31.2
Latvia	12.9	56504	5318	9.4
Lithuania	1.5	6642	537	8.1
Poland	6.2	26950	18988	70.5
Sweden	27.5	120080	95241	79.3
Total EU	**98.1**	428697	203081	47.4
Russia	1.9	8740	888	10.2
TOTAL	**100.0**	437437	203969	46.6

The theory of coalition games affirms, however, that in order to verify that the cooperative benefits suggested by Essay II can be reached, the stability of the cooperative solution must be examined. Accordingly, a coalition is internally stable if none of the members finds it optimal to leave the coalition, and it is externally stable if no player finds it optimal to join the coalition. Usually, coalition games are a combination of non-cooperative and cooperative games. Thus, singletons are assumed to play non-cooperatively and grand coalition cooperatively. Further, under partial cooperation the players inside a coalition cooperate and play non-cooperatively against the players outside a coalition. Coalition games in characteristic function form that addresses the sharing of cooperative surplus have been widely applied in empirical fisheries economics literature. For instance, Lindroos and Kaitala (2000), Duarte et al. (2000) and Lindroos (2004) employed an age-structured population model, whereas Arnason et al. (2000) used a biomass dynamic model.

Characteristic function games, however, do not account for the possible externalities of coalition formation. In fisheries games externalities are generally positive in the sense that members of a coalition while cooperating tend to reduce their fishing effort and thus increase the harvesting possibilities for non-members. Therefore, a grand coalition is rarely equilibrium of a game (Yi 1997). Partition function games are able to analyse the potential externalities of coalition formation. Pintassilgo (2003) was the first to apply a partition function in the fisheries context. By using Northern Atlantic blue fin tuna as a case study, he showed that in the presence of externalities, sharing of cooperative surplus among coalition members is not sufficient for stable cooperation, but a legal regime is needed to exclude singletons from using the resource. For later applications, see e.g. Pham Do and Folmer (2006) and Pintassilgo and Lindroos (2008).

In the presence of externalities, in order to stabilise a coalition, a sharing rule of cooperative benefits that accounts for the free-rider benefits should be applied (Pintassilgo 2003, Kronbak and Lindroos 2007). Thus, the second application of the game theory in the thesis applies the partition function and a sharing rule called the Almost Ideal Sharing Scheme by Eyckmans and Finus (2004). The applied sharing rule is optimal in the sense that it is able to stabilise a coalition with the highest aggregate payoff.

3 Fish and Fisheries

The thesis studies two species, Baltic salmon (*Salmo salar* L.) and Baltic herring (*Clupea harengus membras* L.), which are two out of the four species in the Baltic Sea (Figure 1) managed by using the TACs set by the EU. The other two species are cod (*Gadus morhua*) and sprat (*Sprattus sprattus*). Kronbak (2004) and Kronbak and Lindroos (2007) studied the internationally optimal harvesting of cod. On the other hand, economic analyses addressing sprat fishery are to the best of our knowledge non-existent.

Salmon fisheries have drawn more attention among economists. A few studies considering the value of recreational angling, however, exist: Appelblad (2001), Paulrud (2004), Parkkila (2005), Håkansson (2008) and Håkanson et al. (2004) applied cost-benefit analysis to the salmon passage-hydropower production conflict. Setälä et al. (2002) studied the effect of imported salmon on the price of wild salmon. Yet, in the niche of this thesis only two earlier studies exist. Laukkanen (2001) and (2003) developed a bioeconomic biomass dynamic model for Baltic salmon and applied dynamic optimisation and game theory.

In contrast, the economic aspects of herring fishery are primarily addressed in research reports. For instance, Setälä (1996) reviewed the economic impacts of the Finnish fodder herring fishery, and later Setälä (1998) studied the effect of chilling food herring on the Finnish food herring fishery. In their reviews Stephenson et al. (2001) linked the herring stock to its fishing, and consumption and Vetemaa et al. (2002) described the quota system of the Estonian herring fishery. In addition, EU fisheries statistics encompass fleets that target Baltic herring among other species (Anon. 2004). Thus, to the best of our knowledge, this thesis is the first to develop a bioeconomic model for the Baltic herring fishery.

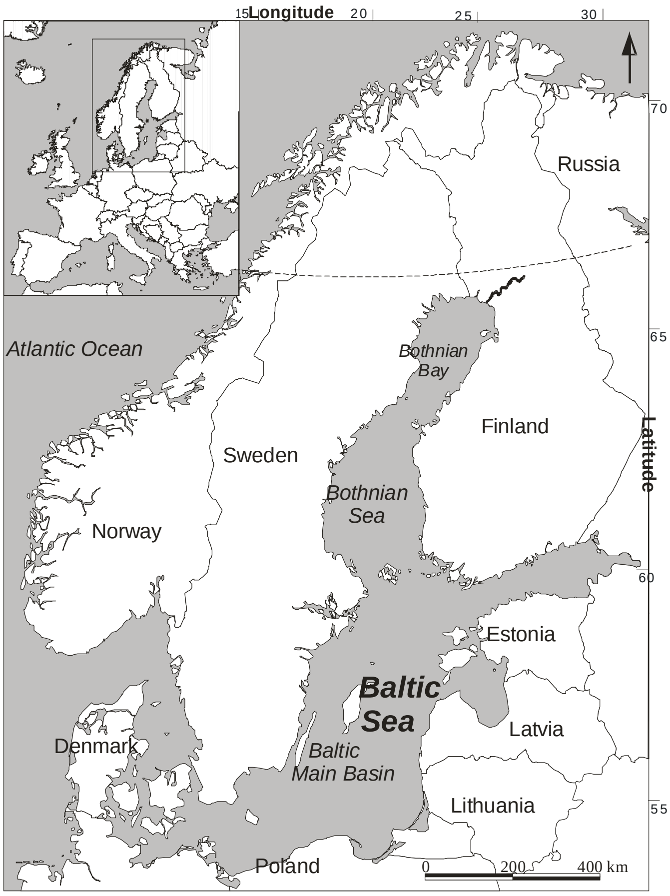

Figure 1 *The thesis studies the economically sound harvesting of salmon during their feeding and spawning migrations in the Baltic Main Basin, the Bothnian Sea and the Bothnian Bay. Also, the Finnish herring fishery in the Bothnian Sea is studied.*

3.1 Baltic Salmon

Baltic salmon (*Salmo salar* L.) is geographically and genetically isolated from Atlantic salmon stocks (Karlsson and Karlström 1994, Davidson, Birt & Green 1989). Salmon spawn in rivers in the autumn, and the eggs hatch in the following spring. Juvenile salmon usually spend three years in rivers, after which they migrate to the Baltic Sea in the springtime. Adult salmon then spend 1-4 years feeding at sea until starting the spawning migration back to their home rivers in the early summer (e.g. Karlsson and Karlström 1994). Nowadays, salmon reproduce naturally in nearly 30 rivers, but the number of wild stocks has been known to be around one hundred. Damming, habitat destruction, pollution and intensive fishing have been identified as the main causes of the decline. (IBSFC & HELCOM 1999) Presently, the majority of the wild salmon production originates from rivers located in Finland and Sweden (ICES 2008a).

In order to enhance and safeguard the wild salmon population and maintain salmon catches, the now defunct International Baltic Sea Fishery Commission launched the Salmon Action Plan (SAP) 1997-2010. The management objective set by the program was to increase the natural wild salmon production to at least half of the production capacity of each river by 2010 while keeping salmon catches as high as possible (e.g. Erkinaro et al. 2003). The tools for achieving these partially conflicting aims of SAP included the stocking of juvenile salmon. Around 5 million juvenile salmon are stocked annually, which accounted for over 90% of the total number of smolts during 1990s and lead to the dominance of reared salmon in the catches (Romakkaniemi et al. 2003). However, in recent years, the survival of reared salmon has decreased while the natural salmon production has increased, and therefore the contribution of the stockings to the catches has been less than 50% in the years 2003-2006 (ICES 2007, Kallio-Nyberg et al. 2004, Koljonen 2006).

The salmon catches have been declining from 5600 tonnes in 1990 to 1100 tonnes in 2007, which was the lowest registered catch since 1970 (ICES 2007). The catch is taken by different types of gear in different parts of the Baltic Sea in accordance with the salmon feeding and spawning migrations. Also, a dramatic decline in the fishing effort has been observed. The number of vessels has decreased by 60% during the period 2003-2007. In addition to the TAC, fishery is regulated by technical management measures such as the minimum landing size of salmon or the maximum amount of hooks in the longlines. As of 2008 EU fishery regulations completely banned the use of driftnets (Council regulation no. 88/98). In addition to these regulatory measures, the observed decline in both salmon catches and the fishing effort has been explained by the influx of farmed Atlantic salmon into the European fish markets, a drop in salmon prices in Europe from 10 €/kg in the early 1980s to 3 €/kg in 2000, and recently a partial closure of the fishery due to the dioxin contents of salmon (ICES 2007, Guillotreau 2004).

The value of commercial salmon landings in 2007 in the three most important salmon fishing countries, Finland, Sweden and Denmark, was altogether about 2.2 million euros (FGFRI 2009). However, the investments in stockings and river restoration indicate that the social value of salmon in the region considerably exceeds the value of the commercial catch. The Finnish state budget allocated nearly 1.4 million euros for annual stockings during the years 2000-2004, and over 9 million were spent for habitat restoration during 1997-2005 (Erkinaro et al. 2003, Salminen et al. 2004). In addition, salmon and sea trout are the most highly valued target species for recreational fishers in the Nordic countries (Toivonen et al. 2000).

3.2 Baltic Herring

Baltic herring (*Clupea harengus membras* L.) is a subspecies of Atlantic herring adapted to brackish waters. It is a pelagic species that feeds in pelagic areas but spawns in coastal areas. (e.g. Parmanne, Rechlin & Sjöstrand 1994). In 2007 the total catch was about 230 000 tonnes, from which Finland and Sweden together harvested over 60%. Other important countries targeting herring are Estonia, Poland and Latvia. The present catches are near half of the catches at the beginning of 1980s. The catches and stock size have declined in the central Baltic but increased in the Bothnian Sea. Finland catches over 90% of the Bothnian Sea herring catch. (ICES 2008b) Herring is the most important species in the Finnish fishery metered by landings and the value of landings (13.6 million euros in

2007), and the Bothnian Sea has been the most important fishing area since the 1990s (FGFRI 2008).

The Finnish herring fishery comprises approximately 90 vessels, including both bottom and pelagic trawlers. Smaller vessels supply herring primarily for fodder, and bigger vessels supply herring for food. In general, fodder vessels are unsuitable for fishing herring for food due to quality demands related to hygienic requirements. Thus the fishery, especially the food herring fishery, is very concentrated; usually, only ten percent of herring vessels harvest herring for food. In addition to the TAC, the fishery is regulated, for instance, by fishing time restrictions that are used to guarantee the adequacy of the TAC for the whole fishing season.

4 Essays of the thesis

4.1 Essay I: Reconciling economic and biological modeling of migratory fish stocks: Optimal management of the Atlantic salmon fishery in the Baltic Sea

Essay I extends the bioeconomic literature on the optimal management of salmon (Laukkanen 2001, Laukkanen 2003, Charles and Reed 1985) by combining an age-structured population dynamics model and dynamic programming. Further, the salmon fishery studied included the benefits from recreational salmon fishery and provided a commercial-recreational harvest allocation decision. The results show that the socially optimal solution would be to close down three out of four commercial salmon fisheries, resulting in a slight decrease in the commercial coastal catch but a nearly seven times higher recreational catch compared to the present situation. The optimal fishery configuration would increase the expected number of smolts to nearly 30%, and the expected net benefits would increase to nearly 60%.

The paper also addressed the uncertainty related to salmon reproduction. The earlier studies accounting for the uncertainty in this context applied aggregated biomass models (Reed 1974, Reed 1978, Reed 1979, Clark and Kirkwood 1986, Sethi et al. 2005). Even though the optimal policy under a stochastic model in this setting coincides with a deterministic one, accounting for the recruitment uncertainty gives insight into the robustness of the optimal policy. Here, the optimal policy that only two fisheries out of five were active remains unchanged despite large positive shocks on recruitment.

4.2 Essay II: International Management of the Atlantic Salmon Fishery in the Baltic Sea

Essay II turns the thesis's perspective from the national to the international and continues bridging the gap between economic and biological models. Game theoretic analysis is built upon a highly disaggregate population model that accounts for the age structure and migration pattern of 15 wild and 6 hatchery-reared salmon stocks. The model is used in the actual stock assessment of Baltic salmon (ICES 2008a, Michielsens et al. 2006, Michielsens et al. 2008). The paper accounts for four countries whose fishing fleets differ from each other in terms of the size of the fleet, fishing costs, salmon price and the stock size available. Non-cooperative and cooperative game theory is used to build scenarios for a retrospective analysis of the international salmon fishery. The performance of the fishery under a past fisheries policy is compared to the non-cooperative case, whose solution is given by a Nash equilibrium. Further, two versions of cooperation are analysed in order to give insight into the effects of the Relative Stability Principle on cooperation.

Essay II thus contributes to the existing empirical game theory literature (Lindroos 2004, Arnason, Magnusson & Agnarsson 2000, Bjørndal and Lindroos 2004, Bjørndal et al. 2004) by combining a state-of-the-art biological model and four heterogeneous players and by calibrating the model with economic data from four countries. The results show that even though the countries harvesting salmon agree on the TAC annually, the total net benefits from the fishery have been only slightly above the non-cooperative outcome. However, the outcomes of the analysed cooperative games suggest a near 50-100% increase in the total net benefits compared to the past performance of the fishery. Further, the weakest salmon stock, the Emån, would almost double its smolt production.

4.3 Essay III: Atlantic Salmon Fishery in the Baltic Sea - A Case of Trivial Cooperation

Essay III builds on Essay II by applying a coalition game in the partition function form to the model developed in Essay II. The chosen method is able to reveal if the substantial benefits of cooperation suggested by Essay II are possible to achieve. In general, fisheries games exhibit positive externalities, i.e. countries signing a contract to exploit a stock sustainably will yield a higher stock size to those outside the contract. Therefore the grand coalition is rarely an equilibrium of a game (Yi 1997). The partition function approach has recently been applied to the fisheries game (Pintassilgo 2003, Pham Do and Folmer 2006), and Essay IV provides an empirical application to the more theoretical work by Eykmans and Finus (2004) and Pintassilgo and Lindroos (2008). The results show that positive externalities are present, and thus cooperation is hard. Only two-player coalitions can be stabilised, which however increases the economic net benefits from the fishery above those given by cooperation under the Relative Stability Principle. However, the biological benefits suggested by Essay II cannot be reached.

4.4 Essay IV: Individual Transferable Quotas in the Baltic Sea Herring Fishery: a Socio-bioeconomic Analysis

Essay IV studies the Finnish herring fishery in the Bothnian Sea, and the question addressed is "what if" Finland implemented an ITQ system. The main contribution of the essay is the development and calibration of a bioeconomic model for the Baltic herring fishery. The model observes two type of vessels: 1) vessels supplying herring for human consumption and 2) vessels supplying herring for fodder. The underlying biological model is compatible with the model used in ICES to provide management advice. The analysis of the ITQ system relies on stylised optimisation and scenarios regarding the potential outcomes of transferable and non-transferable quotas compared to the existing management system. However, ex-ante analyses regarding ITQ systems are scarce (e.g. Lanfersieck and Squires 1992, Armstrong and Sumaila 2001). The results show that a prerequisite for realising the benefits from ITQs is a decrease in the fishing effort (in terms of vessels and of fishing mortality). The outcome would, however, yield substantial profits and a higher stock size. Further, the analysis regarding the present management system revealed that the herring stock was both biologically and economically overexploited.

The thesis also includes an erratum to Essay IV. The mistakes found in three equations in the text do not appear in the algorithm, and thus the results remain unchanged.

References

Anderson, C.N.K., Hsieh, C., Sandin, S.A., Hewitt, R., Hollowed, A., Beddington, J., May, R.M. & Sugihara, G. 2008, Why fishing magnifies fluctuations in fish abundance, *Nature*, vol. 452, no. 7189, pp. 835-839.

Anon. 2004, Economic Performance of Selected European Fishing Fleets. Annual Report 2004.

Appelblad, H. 2001, The spawning salmon as a resource by recreational use. The case of wild Baltic salmon and conditions for angling in North Swedish rivers, Department of Social and Economic Geography, Umeå University.

Armstrong, C.W. & Sumaila, U.R. 2001, Optimal Allocation of TAC and the Implications of Implementing an ITQ Management System for the North-East Arctic Cod, *Land Economics*, vol. 77, no. 3, pp. 350-359.

Arnason, R. 2005, Property rights in fisheries: Iceland's experience with ITQs, *Reviews in Fish Biology and Fisheries*, vol. 15, no. 3, pp. 243-264.

Arnason, R. 2008, Iceland's ITQ system creates new wealth, *The Electronic Journal of Sustainable Development*, vol. 1, no. 2, pp. 35-41.

Arnason, R. 2009, Conflicting uses of marine resources: can ITQs promote an efficient solution?, *Australian Journal of Agricultural and Resource Economics*, vol. 53, no. 1, pp. 145-174.

Arnason, R. 1990, Minimum Information Management in Fisheries, *The Canadian Journal of Economics*, vol. 23, no. 3, pp. 630-653.

Arnason, R., Magnusson, G. & Agnarsson, S. 2000, The Norwegian Spring-Spawning Herring Fishery: A Stylized Game Model, *Marine Resource Economics*, vol. 15, no. 2000, pp. 293-319.

Batstone, C.J. & Sharp, B.M.H. 2003, Minimum information management systems and ITQ fisheries management, *Journal of Environmental Economics and Management*, vol. 45, no. 2, Supplement 1, pp. 492-504.

Bellman, R.E. 1957, Dynamic Programming, Princeton University Press, Princeton, NJ.

Bertignac, M., Campbell, H.F., Hampton, J. & Hand, A.J. 2001, Maximizing Resource Rent from the Western and Central Pacific Tuna Fisheries, *Marine Resource Economics*, vol. 15, no. 3, pp. 151-177.

Beverton, R.J.H., Holt, S.J. 1957. On the Dynamics of Exploited Fish Populations. Reprint of First Edition. The Blackburn Press.

Biegler, L.T. & Grossmann, I.E. 2004, Retrospective on optimization, *Computers and Chemical Engineering*, vol. 28, no. 8, pp. 1169-1192.

Bjørndal, T., Ussif, A. & Sumaila, U.R. 2004, A bioeconomic analysis of the Norwegian spring spawning herring (NSSH) stock, *Marine Resource Economics*, vol. 19, pp. 353-365.

Bjørndal, T., Gordon, D.V., Kaitala, V. & Lindroos, M. 2004, International Management Strategies for a Straddling Fish Stock: A Bio-Economic Simulation Model of the Norwegian Spring-Spawning Herring Fishery, *Environmental and Resource Economics*, vol. 29, no. 4, pp. 435-457.

Bjørndal, T. & Lindroos, M. 2004, International Management of North-Sea Herring, *Environmental and Resource Economics,* vol. 29, no. 1, pp. 83-96.

Boude, J., Boncoeur, J. & Bailly, D. 2001, Regulating the access to fisheries: learning from European experiences, *Marine Policy,* vol. 25, no. 4, pp. 313-322.

Boyce, J.R. 1992, Individual Transferable Quotas and Production Externalities in a Fishery, *Natural Resource Modeling,* vol. 6, no. 4, pp. 385-408.

Brown, G.M. 2000, Renewable Natural Resource Management and Use without Markets, *Journal of Economic Literature*, vol. 38, no. 4, pp. 875-914.

Charles, A.T. & Reed, W.J. 1985, A Bioeconomic Analysis of Sequential Fisheries - Competition, Coexistence, and Optimal Harvest Allocation between Inshore and Offshore Fleets, *Canadian Journal of Fisheries and Aquatic Sciences,* vol. 42, no. 5, pp. 952-962.

Christy, F., T. Jr. 1973, Fisherman quotas: a tentative suggestion for domestic management, Occassional Paper, no. 19. Law of the Sea Institute, University of Rhode Island

Clark, C.W. 1990, Mathematical Bioeconomics: The Optimal Managment of Renewable Resources. Second edn, John Wiley & Sons, New York.

Clark, C.W. 1980a, Towards a predictive model for the economic regulation of commercial fisheries, *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 37, no. 7, pp. 1111-1129.

Clark, C.W. 1980b, Restricted access to common-property fishery resources: a game-theoretic analysis in Dynamic optimization and mathematical economics, ed. P. Liu, Plenum Pub Corp, New York, pp. 117-132.

Clark, C.W. & Munro, G.R. 1975, The economics of fishing and modern capital theory: a simplified approach, *Journal of Environmental Economics and Management,* vol. 2, no. 2, pp. 92-106.

Clark, C.W. & Kirkwood, G.P. 1986, On uncertain renewable resource stocks: Optimal harvest policies and the value of stock surveys, *Journal of Environmental Economics and Management*, vol. 13, no. 3, pp. 235-244.

Commission of the European Communities 2008, Annual Report from the Commission to the European Parliament and the Council on Member States' efforts during 2007 to achieve a sustainable balance between fishing capacity and fishing opportunities, Brussels.

Conover, D.,O. & Munch, S.,B. 2002, Sustaining Fisheries Yields Over Evolutionary Time Scales, *Science*, vol. 297, no. 5578, pp. 94-96.

Copes, P. 1986, The Individual Quota in Fisheries Management, *Land Economics,* vol. 62, no. 3, pp. 278-291.

Davidson, W.S., Birt, T.P. & Green, J.M. 1989, A review of genetic variation in Atlantic salmon, Salmo salar L., and its importance for stock identification, enhancement programmes and aquaculture, *Journal of fish biology,* vol. 34, no. 4, pp. 547-560.

Daw, T. & Gray, T. 2005, Fisheries science and sustainability in international policy: a study of failure in the European Union's Common Fisheries Policy, *Marine Policy,* vol. 29, no. 3, pp. 189-197.

Deacon, R., Kolstad, C., Kneese, A., Brookshire, D., Scrogin, D., Fisher, A., Ward, M., Smith, K. & Wilen, J. 1998, Research Trends and Opportunities in Environmental and

Natural Resource Economics, *Environmental and Resource Economics,* vol. 11, no. 3, pp. 383-397.

Duarte, C.C., Brasao, A. & Pintassilgo, P. 2000, Management of the Northern Atlantic Bluefin Tuna: An Application of C-Games, *Marine Resource Economics,* vol. 15, no. 2000, pp. 21-36.

Eagle, J. & Thompson, B.H. 2003, Answering Lord Perry's question: dissecting regulatory overfishing, *Ocean & Coastal Management,* vol. 46, no. 6-7, pp. 649-679.

Erkinaro, J., Mäki-Petäys, A., Juntunen, K., Romakkaniemi, A., Jokikokko, E., Ikonen, E. & Huhmarniemi, A. 2003, The Baltic Salmon Action Plan in Finland, 1997-2002. Finnish Game and Fisheries Research Institute. Kalatutkimuksia, 186. (in Finnish)

European Communities 2008, Facts and Figures on the CFP. Basic Data on the Common Fisheries Policy. Edition 2008.

Eyckmans, J. & Finus, M. 2004, An Almost Ideal Sharing Scheme for Coalition Games with Externalities, Fondazione Eni Enrico Mattei, Working Paper, no. 155.04.

FGFRI (Finnish Game and Fisheries Research Institute) 2008, Commercial Marine Fishery 2007, Finnish Game and Fisheries Reseach Institute, Official Statistics of Finland 3/2008. (in Finnish)

FGFRI (Finnish Game and Fisheries Research Institute) 2009, Data Analysis to Support the Development of a Baltic Sea Salmon Managment Plan, SI2.491891, FISH/2007/03 – Lot 6.

FAO (Food and Agriculture Organization of the United Nations) 2009, The state of world fisheries and aquaculture 2008, FAO Fisheries and Aquaculture Department, Rome.

Gordon, H.S. 1954, The Economic Theory of a Common-Property Resource: The Fishery, *Journal of Political Economy,* vol. 62, no. 2, pp. 124.

Grafton, R.Q. & McIlgorm, A. 2009, Ex ante evaluation of the costs and benefits of individual transferable quotas: A case-study of seven Australian commonwealth fisheries, *Marine Policy,* vol. 33, no.4, pp. 714-719.

Guillotreau, P. 2004, How does the European seafood industry stand after the revolution of salmon farming: An economic analysis of fish prices, *Marine Policy,* vol. 28, no. 3, pp. 227-233.

Håkansson, C., Kriström, B., Leonardsson, K. & Lundqvist, H. 2004, Salmon and Hydropower; Dynamic Cost-Benefit Analysis, Fifth International Symposium on Ecohydraulics, Congress Proceedings, Editors: Diego Garcia de Jakón Lastra and Pilar Vizcaino Martinez.

Håkansson, C. 2008, A new valuation question: analysis of and insights from interval open-ended data in contingent valuation, *Environmental and Resource Economics,* vol. 39, no. 2, pp. 175-188.

Hilborn, R. & Walters, C.J. 1992, Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty, Chapman & Hall, New York.

IBSFC & HELCOM 1999, Baltic Salmon Rivers - Status in the Late 1990s as Reported by the Countries in the Baltic Sea Region. The Swedish Board of Fisheries.

ICES 2008a, Report of the Baltic Salmon and Trout Working Group (WGBAST), 1-10 April 2008, Gdynia, Poland.

ICES 2008b, Report of the ICES Advisory Committee, 2008. ICES Advice, 2008. Book 8, 133 pp.

ICES 2007, Report of the Baltic Salmon and Trout Working Group (WGBAST), 11-20 April 2007, Vilnius, Lithuania.

Kaitala, V. & Lindroos, M. 1998, Sharing the Benefits of Cooperation in High Seas Fisheries: A Characteristic Function Game Approach, *Natural Resource Modeling,* vol. 11, no. 4, pp. 87-108.

Kaitala, V. & Munro, G.R. 1993, The management of high seas fisheries, *Marine Resource Economics,* vol. 8, no. 4, pp. 313-329.

Kallio-Nyberg, I., Jutila, E., Saloniemi, I. & Jokikokko, E. 2004, Association between environmental factors, smolt size and the survival of wild and reared Atlantic salmon from the Simojoki River in the Baltic Sea, *Journal of fish biology,* vol. 65, no. 1, pp. 122-134.

Karlsson, L. & Karlström, Ö. 1994, The Baltic salmon (Salmo salar L.): its history, present situation and future, *Dana,* vol. 10, pp. 61-85.

Kell, L.T., Mosqueira, I., Grosjean, P., Fromentin, J., Garcia, D., Hillary, R., Jardim, E., Mardle, S., Pastoors, M.A., Poos, J.J., Scott, F. & Scott, R.D. 2007, FLR: an open-source framework for the evaluation and development of management strategies, *ICES Journal of Marine Science* vol. 64, no. 4, pp. 640-646.

Koljonen, M.L. 2006, Annual changes in the proportions of wild and hatchery Atlantic salmon (Salmo salar) caught in the Baltic Sea, *ICES Journal of Marine Science,* vol. 63, no. 7, pp. 1274-1285.

Kompas, T. & Che, T.N. 2005, Efficiency Gains and Cost Reductions from Individual Transferable Quotas: A Stochastic Cost Frontier for the Australian South East Fishery, *Journal of Productivity Analysis,* vol. 23, no. 3, pp. 285-307.

Kronbak, L.G. 2004. The Dynamics of an Open-access Fishery: Baltic Sea Cod, *Marine Resource Economics*, vol. 19, no.4, pp.459-479.

Kronbak, L.G. & Lindroos, M. 2007, Sharing Rules and Stability in Coalition Games with Externalities, *Marine Resource Economics,* vol. 22, no. 2, pp. 137-154.

Lanfersieck, J. & Squires, D.E. 1992, Planning models for individual transferable quota programs, *Canadian Journal of Fisheries and Aquatic Sciences,* vol. 49, pp. 2313-2313.

Laukkanen, M. 2003, Cooperative and non-cooperative harvesting in a stochastic sequential fishery, *Journal of Environmental Economics and Management,* vol. 45, no. 2, Supplement 1, pp. 454-473.

Laukkanen, M. 2001, A Bioeconomic Analysis of the Northern Baltic Salmon Fishery: Coexistence versus Exclusion of Competing Sequential Fisheries, *Environmental and Resource Economics,* vol. 18, no. 3, pp. 293-315.

Lindroos, M. & Kaitala, V. 2000, Nash equilibria in a coalition game of the Norwegian spring-spawning herring fishery, *Marine Resource Economics,* vol. 15, no. 4, pp. 321-340.

Lindroos, M. 2004, Sharing the Benefits of Cooperation in the Norwegian Spring-Spawning Herring Fishery, *International Game Theory Review,* vol. 6, no. 1, pp. 35–53.

Mercenier, J. & Michel, P. 1994, Discrete-Time Finite Horizon Approximation of Infinite Horizon Optimization Problems with Steady-State Invariance, *Econometrica,* vol. 62, no. 3, pp. 635-656.

Mesterton-Gibbons, M. 1993, Game-theoretic resource modeling, *Natural resource modeling*, vol. 7, no. 2, pp. 93-147.

Michielsens, C.G.J., McAllister, M.K., Kuikka, S., Pakarinen, T., Karlsson, L., Romakkaniemi, A., Pera, I. & Mantyniemi, S. 2006, A Bayesian statespace mark-recapture model to estimate exploitation rates in mixed-stock fisheries, *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 63, pp. 321-334.

Michielsens, C.G.J., Murdoch, K.M., Sakari, K., Samu, M., Atso, R., Tapani, P., Lars, K. & Laura, U. 2008, Combining multiple Bayesian data analyses in a sequential framework for quantitative fisheries stock assessment, *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 65, pp. 962-974.

Miranda, M.J. & Fackler, P.L. 2002, Applied Computational Economics and finance, The MIT Press, London.

Moloney, D.G. & Pearse, P.H. 1979, Quantitative Rights as an Instrument for Regulating Commercial Fisheries, *Journal of the Fisheries Research Board of Canada*, vol. 36, no. 7, pp. 859-866.

Moxnes, E. 2005, Policy sensitivity analysis: simple versus complex fishery models, *System Dynamics Review*, vol. 21, no. 2, pp. 123-145.

Munro, G.R. 1996, Approaches to the Economics of the Management of High Seas Fishery Resources: A Summary, *The Canadian Journal of Economics*, vol. 29, Special Issue: Part 1, pp. S157-S164.

Munro, G.R. 1986, The Management of Shared Fishery Resources under Extended Jurisdiction, *Marine Resource Economics*, vol. 3, no. 4, pp. 271-296.

Munro, G.R. 1979, The Optimal Management of Transboundary Renewable Resources, *The Canadian Journal of Economics* vol. 12, no. 3, pp. 355-376.

Nash, J. 1953, Two-Person Cooperative Games, *Econometrica*, vol. 21, no. 1, pp. 128-140.

Nash, J. 1951, Non-Cooperative Games, *The Annals of Mathematics*, vol. 54, no. 2, pp. 286-295.

Newell, R.G., Sanchirico, J.N. & Kerr, S. 2005, Fishing quota markets, *Journal of Environmental Economics and Management*, vol. 49, no. 3, pp. 437-462.

Palumbi, S.,R. 2004, Fisheries science: Why mothers matter, *Nature*, vol. 430, no. 7000, pp. 621-622.

Parkkila, K. 2005, Estimating the willingness to pay for catch improvements in the river Simojoki (In Finnish). Master's thesis, Department Economics and Management, University of Helsinki.

Parmanne, R., Rechlin, O. & Sjöstrand, B. 1994, Status and Future of Herring and Sprat Stock in the Baltic Sea, *Dana*, vol. 10, pp. 29-59.

Paulrud, A. 2004, Economic valuation of sport-fishing in Sweden, Doctoral diss. Dept. of Forest Economics, SLU. Acta Universitatis Agriculturae Suecia. Silvestria.

Pham Do, K. & Folmer, H. 2006, International fisheries agreements: the feasibility and impacts of partial cooperation in The theory and practice of environmental and resource economics : essays in honour of Karl-Gustaf Löfgren, eds. T. Aronsson, R. Axelsson & R. Brännlund, Edward Elgar, Cheltenham, UK Northampton, MA, pp. 146-172.

Pintassilgo, P. & Duarte, C.C. 2002, Optimal Management of the Northern Atlantic Bluefin Tuna, *Marine Resource Economics,* vol. 17, no. 2002, pp. 47-67.

Pintassilgo, P. 2003, A Coalition Approach to the Management of High Seas Fisheries in the Presence of Externalities, *Natural Resource Modeling,* vol. 16, no. 2, pp. 175-197.

Pintassilgo, P. & Lindroos, M. 2008, Coalition Formation in Straddling Stock Fisheries: A Partition Function Approach, *International Game Theory Review,* vol. 10, no. 3, pp. 303-317.

Reed, W.J. 1979, Optimal escapement levels in stochastic and deterministic harvesting models, *Journal of Environmental Economics and Management,* vol. 6, no. 4, pp. 350–363.

Reed, W.J. 1978, The steady state of a stochastic harvesting model, *Mathematical Biosciences,* vol. 41, no. 3-4, pp. 273-307.

Reed, W.J. 1974, A stochastic model for the economic management of a renewable animal resource, *Mathematical Biosciences,* vol. 22, pp. 313-337.

Romakkaniemi, A., Pera, I., Karlsson, L., Jutila, E., Carlsson, U. & Pakarinen, T. 2003, Development of wild Atlantic salmon stocks in the rivers of the northern Baltic Sea in response to management measures, *ICES Journal of Marine Science,* vol. 60, no. 2, pp. 329-342.

Salminen, M., Kummu, P., Pasanen, P., Ikonen, E. & Aaron, H. 2004, Rearing of valuable fish 2004-2010 Finnish Game and Fisheries Research Institute, Helsinki, Finland. (in Finnish)

Schaefer, M.B. 1957, Some Considerations of Population Dynamics and Economics in Relation to the Management of the Commercial Marine Fisheries, *Journal of the Fisheries Research Board of Canada*, vol. 14, no. 5, pp. 669-681.

Scott, A. 1979, Development of economic theory on fisheries regulation, *Journal of the Fisheries Research Board of Canada,* vol. 36, no. 7, pp. 725-741.

Setälä, J. 1998, Does effective chilling increase the profitability of trawl fisheries?, Kalatutkimuksia 136. (in Finnish)

Setälä, J. 1996, The economic significance of fodder fishing, Kalatutkimuksia 115. (in Finnish)

Setälä, J., Mickwitz, P., Virtanen, J., Honkanen, A. & Saarni, K. 2002, The effect of trade liberation on the salmon market in Finland, Fisheries in the Global Economy–Proceedings of the Eleventh Biennial Conference of the International Institute of Fisheries Economics and Trade.

Sethi, G., Costello, C., Fisher, A., Hanemann, M. & Karp, L. 2005, Fishery management under multiple uncertainty, *Journal of Environmental Economics and Management,* vol. 50, no. 2, pp. 300-318.

Squires, D., Campbell, H., Cunningham, S., Dewees, C., Grafton, R.Q., Herrick, S.F., Kirkley, J., Pascoe, S., Salvanes, K., Shallard, B., Turris, B. & Vestergaard, N. 1998, Individual transferable quotas in multispecies fisheries, *Marine Policy,* vol. 22, no. 2, pp. 135-159.

Stephenson, R., Peltonen, H., Kuikka, S., Pönni, J., Rahikainen, M., Aro, E. & Setälä, J. 2001, Linking biological and industrial aspects of the Finnish commercial herring fishery in the northern Baltic Sea in Herring: Expectations for a New Millenium, eds.

F. Funk, J. Blackburn, D. Hay, et al, Alaska Sea Grant College Program, AK-SG-01-04, pp. 741-760.

Sumaila, U.R. 1995, Irreversible Capital Investment in a Two-Stage Bimatrix Fishery Game Model, *Marine Resource Economics,* vol. 10, no. 3, pp. 263-283.

Sutinen, J.G. & Johnston, R.J. 2003, Angling management organizations: integrating the recreational sector into fishery management, *Marine Policy,* vol. 27, no. 6, pp. 471-487.

Tahvonen, O. 2009, Economics of Harvesting of Age-Structured Fish Population, *Journal of Environmental Economics and Management*, in Press.

Tahvonen, O. 2008, Harvesting and Age-structured Population as Biomass: Does It Work?, *Natural Resource Modeling,* vol. 21, no. 4, pp. 525-550.

Thunberg, E.M., Helser, T.E. & Mayo, R.K. 1998, Bioeconomic Analysis of Alternative Selection Patterns in the United States Atlantic Silver Hake Fishery, *Marine Resource Economics,* vol. 13, no. 1, pp. 51-74.

Toivonen, A., Appelblad, H., Begtsson, B., Geertz-Hansen, P., Guobergsson, G., Kristofersson, D., Kyrkkjebo, H., Navrud, S., Roth, E., Tuunainen, P. & Weissglas, G. 2000, Economic value of recreational fisheries in the Nordic countries. TEMA NORD 2000

Townsend, R.E. 1986, A critique of models of the American lobster fishery, *Journal of Environmental Economics and Management,* vol. 13, no. 3, pp. 277-291.

Townsend, R.E., McColl, J. & Young, M.D. 2006, Design principles for individual transferable quotas, *Marine Policy,* vol. 30, no. 2, pp. 131-141.

Vetemaa, M., Eero, M. & Hannesson, R. 2002, The Estonian fisheries: from the Soviet system to ITQs and quota auctions, *Marine Policy,* vol. 26, no. 2, pp. 95-102.

Wilen, J.E. 1985, Bioeconomics of Renewable Resource Use in Handbook of Natural Resource and Energy Economics, eds. A.V. Kneese & J.L. Sweeney, Elsevier, Amsterdam, pp. 61-124.

Yi, S. 1997, Stable Coalition Structures with Externalities, *Games and Economic Behavior,* vol. 20, no. 2, pp. 201-237.