Bioeconomic and game theoretic applications of optimal Baltic Sea fisheries management

Towards a holistic approach

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ACADEMIC DISSERTATION

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Abstract

This thesis examines the optimal economic management of the Baltic Sea fisheries from a more holistic approach than traditionally, and thus takes a step towards ecosystem-based management. Such management can be interpreted as integrated management of the ecosystem instead of concentrating on a single issue in isolation. First, the focus is on optimal multispecies fisheries management in the Baltic Sea under climate change, which is expanded to the international context in order to examine the prospects of cooperation among several countries. Furthermore, the optimal joint production of hydropower and migratory fish is investigated, thus taking into account the cross-sectoral approach in fisheries management. This thesis brings together important new information from different perspectives on the management of the Baltic Sea fisheries, and contributes to the existing literature with its novel bioeconomic and game theoretic applications enhancing holistic management.

Keywords: fisheries management, bioeconomic modelling, optimisation, multispecies model, Baltic Sea, international fisheries agreements, game theory, coalition formation game, partition function game, climate change, hydropower, migratory fish, policy instruments, holistic management, ecosystem-based management

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List of original publications

This thesis is based on the following studies:

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II. Nieminen, E., Kronbak, L.G. and Lindroos, M. 2016. International agreements in the multispecies Baltic Sea fisheries. *Environmental and Resource Economics* 65:109–134.

III. Nieminen, E., Hyytiäinen, K. and Lindroos, M. 2017. Economic and policy considerations regarding hydropower and migratory fish. *Fish and Fisheries* 18: 54–78.

IV. Nieminen, E. Optimal joint production of hydropower and migratory fish: A case study in the Northern Baltic Sea. *Manuscript*.

Contents

1 Introduction

Many fish stocks worldwide are overfished, i.e., the stocks are not harvested sustainably. Overfishing may be either biological or economic. Biological overfishing means that fish are harvested so extensively that the biomass has negative marginal growth. It is estimated that 31% of the world's commercial fish stocks are being biologically overfished (FAO 2016). Economic overfishing means that the profit, or the resource rent, is not maximised. The reasons for overfishing are failures of fisheries management (Beddington *et al.* 2007).

Fisheries management easily face difficulties, as fish stocks are often managed as a common pool or common property resource. This means that it is difficult to exclude anyone from using it, and that harvesting by one user reduces the stock availability for other users (Ostrom *et al*. 1999). Additionally, the harvest levels have often been set too high due to political pressure to chase short-term benefits, and holistic ecosystem-based management has largely been lacking, which has increased the uncertainty in predicting management effects (Botsford *et al.* 1997).

It is clear that the problems in fisheries management are complex and have many causes. Therefore, more holistic management has been called for in order to achieve biologically and economically sustainable fish stocks. Such an approach can be interpreted as integrated management of the ecosystem instead of concentrating on a single issue in isolation. The approach involves taking into account, for instance, the long-term perspective, including climate change effects, the integrated management of several sectors impacting on the ecosystem, the management of groups of countries in the form of fisheries agreements, as well as species interactions in a multispecies setting (UNEP 2011). Actually, the recent reform of the European Common Fisheries Policy has pursued multiannual ecosystem-based management, which relies on multispecies fisheries plans rather than single-species management (EC 2013). However, few fisheries are actually managed on a multispecies basis (Voss *et al.* 2014).

This thesis uses bioeconomic optimisation and game theory as the key methods in order to provide more holistic recommendations on how to manage fisheries in a biologically and economically sustainable manner. The management objective is maximum economic yield (MEY) instead of maximum sustainable yield (MSY), which is still widely applied in the real world, e.g., in the EU (EC 2013). MEY usually yields a more conservative management scheme in the long term than MSY, and thus enhances sustainable fisheries management. Indeed, MSY is not always seen as a sufficient level of management, and more conservative approaches have thus been suggested (Beddington *et al.* 2007). Additionally, MEY is a more holistic approach than MSY and takes into account, for instance, the costs of fishing in addition to the benefits (Botsford *et al.* 1997).

The thesis consists of four studies:

- Study I: Optimal bioeconomic multispecies fisheries management: A Baltic Sea case study;
- Study II: International agreements in the multispecies Baltic Sea fisheries;
- Study IIII: Economic and policy considerations regarding hydropower and migratory fish;
- Study IV: Optimal joint production of hydropower and migratory fish: A case study in the Northern Baltic Sea.

This thesis takes fisheries management towards a more holistic ecosystem-based approach, which can be interpreted as more integrated and holistic management of the ecosystem instead of concentrating on single issues in isolation (UNEP 2011). This is fulfilled in four separate dimensions: Firstly, the thesis studies included several species in optimal management instead of only one species (Studies I and II). Secondly, the focus of the studies was not only on management in a single country; instead, the thesis research had a wider scope and analysed the prospects of cooperation among several countries (Study II). Thirdly, the problems were modelled by taking into account the long-term perspective, i.e., by maximising the resource rent over a long time period (Studies I, II and IV), and by analysing the possible effects of climate change (Studies I and II). Fourthly, the studies in this thesis applied a cross-sectoral approach and examined several sectors affecting the ecosystem (fisheries and energy sectors) instead of only focusing on one (Studies III and IV).

Table 1 summarises the focus of the research in the thesis, the study region, methods applied, contributions to the literature, and dimensions of the holistic ecosystem-based management of each study. Studies I and II used a multispecies bioeconomic model that was applied in the Baltic Sea. Study I concentrated on the sole owner optimum management of multispecies fisheries using dynamic numerical bioeconomic optimisation modelling. Study I was among the first to apply multispecies bioeconomic modelling in this region. Study II analysed the same multispecies fisheries in an international context with several players, using a coalition formation game approach, and assessed the stability of fisheries agreements and the strategic behaviour of the fishing nations. Such applications using a coalition formation approach in a multispecies setting have been uncommon, which places this study in a central position in the literature. Study III adds to the literature by comprehensively reviewing the central literature related to the conflict between hydropower and migratory fish from the economic point of view. The review outlines the prerequisites for future policies based on environmental standards, rather than technology standards, which have rarely been applied to the topic. Study IV bridged this gap in the literature, and analysed the trade-off between hydropower production and migratory fish using a dynamic bioeconomic optimisation model. The study determined the optimal measures for the joint production of these two conflicting interests and highlighted that the optimal solution for each river may be case-specific, as was already argued in Study III.

Table 1. Summary of the key components of the studies.

Study	Research focus	Study region	Applied method(s)	Contribution to the literature	Dimension(s) of the ecosystem-based management
I	To study the sole-owner optimum for multispecies fisheries management under different environmental conditions	Cod, herring and sprat fisheries in the Baltic Sea	Bioeconomic optimisation Multispecies modelling	Applies dynamic multispecies bioeconomic optimisation in the Baltic Sea region	Multispecies fisheries Long-term optimisation Climate change effects
II	To analyse the stability of multispecies fisheries agreements under different climate conditions by taking into account the strategic interactions between fishing nations through a coalition formation game	Cod, herring and sprat fisheries of Denmark, Poland and Sweden in the Baltic Sea	Bioeconomic optimisation Multispecies modelling Coalition formation game	Combines coalitional games and dynamic multispecies bioeconomic optimisation	Multispecies fisheries Long-term optimisation Climate change effects Multi-country fisheries
III	To review the existing literature related to the effectiveness and costs of alternative measures promoting the joint production of hydropower and migratory fish species	Global	Literature review	Outlines the prerequisites for future policies based on environmental standards	Cross-sectoral approach
IV	To determine the economically optimal measures for the joint production of hydropower and migratory fish	The Iijoki River salmon stock in the Northern Baltic Sea in Finland	Bioeconomic optimisation	Determines the optimal measures for joint production of hydropower and migratory fish	Cross-sectoral approach Long-term optimisation

The next section introduces the study region and the challenges of managing the Baltic Sea fisheries. Section 3 presents the underlying methods used in the thesis research, while section 4 compiles the main results of each study. Finally, section 5 concludes the thesis.

2 Study region

The main focus in this thesis is on the Baltic Sea fisheries, which are managed through the Common Fisheries Policy (CFP) of the European Union (EU). The CFP allows equal access for its members to all EU fishing grounds, except for the 12 nm zone allocated to each nation (EEC 1970, modified in EC 2013), which creates a true common pool fishery. In 1983, total allowable catches (TACs) were introduced to the Baltic Sea fisheries, which set maximum fishing quotas for the most important species. TACs are set according to advice given by the Scientific, Technical and Economic Council of Fisheries (STECF) of the EU and the International Council for the Exploration of the Sea (ICES).

The allocation of the TAC between member countries is based on the relative stability principle, according to which each country receives a fixed share of the aggregate TAC, which is primarily based on its historical catch records (EC 2371/2002). The allocation mechanism for national TACs varies among member states. Different forms of individual quota systems are the most common approach (Blenckner *et al.* 2011), through which a quota is allocated to individual fishermen or vessels. Although the CFP and the relative stability principle set boundaries on member states, countries are allowed to make strategic choices in the form of temporary exchanges of fishing quotas between countries (Andersen *et al.* 2009). The results of Study II demonstrate a potential situation that could arise from a more flexible management system, in which countries can trade quotas without any restrictions for relative stability. In fact, the relative stability rule may be outdated, and according to van Hoof (2013), a fixed allocation principle based on fish catches from the 1973–1978 reference period is unable to accommodate new conditions, such as stock development, new fishing strategies, fleet evolution and demand.

The three most commercially exploited species in the area are Baltic cod (*Gadus morhua callaria*s), Baltic herring *(Clupea harengus membras*) and sprat (*Sprattus*

sprattus), which were the focus of Studies I and II. The cod is the most valuable of these species and the main predator in the Baltic Sea. It feeds on herring, which are used for human consumption or animal fodder, depending on their size, and on sprat, which are mainly used as fodder or for fish meal production.

In the 1970s, the Baltic fishery was cod dominated. However, the cod stock rapidly decreased, and the sprat – a prey species of cod – simultaneously started to dominate the fishery, leading to a regime shift in the Baltic Sea. One explanation for this shift is seen to be extensive harvesting of cod based on a biological MSY management. The declined cod stock could then no longer restrict the sprat stock. Another explanation is presumably the changed environmental conditions, which favoured sprat. The successful spawning of cod is highly dependent on favourable environmental conditions, especially salinity and oxygen levels, and thus cod are currently mainly found in the southern parts of the Baltic Sea (Köster *et al.* 2005). It is possible that continuing climate change will lead to a decrease in the salinity level in the Baltic Sea, and thus the currently unfavourable conditions for cod recruitment will likely continue into the future (Meier 2006; Neumann 2010). Additionally, cod have recently suffered from malnutrition because they have a relatively small geographical overlap with their prey species, and this has led to a lack of prey biomass (EC 2013; ICES 2014). These issues justify the importance of multispecies and climate change studies within this region, as addressed in Studies I and II. These studies demonstrated how the cod stock could be managed in a more sustainable way, both biologically and economically. Additionally, Study II showed how the international fisheries agreement among several countries harvesting cod and its prey species could be stabilised, and why it is important to include a multispecies approach in the management. Moreover, Study II provided an optimistic result suggesting that climate change may actually improve the likelihood of a binding fisheries agreement, because with a lower cod biomass, countries will gain more from cooperation.

Additionally, the Baltic salmon (*Salmo salar* L.) is a significant species in the Baltic Sea fisheries. Migratory fish, including Baltic salmon, formerly spawned in most of the Baltic rivers. However, the size of the natural populations has seriously declined due to the construction of hydropower dams. Currently, in some countries, among them Finland, hydropower companies compensate for their damage to fisheries through obligatory annual fish releases. These reared individuals do not, however, survive as successfully as their wild counterparts (e.g., Jokikokko *et al.* 2006; Michielsens *et al.* 2006), which has raised the question of whether such releases sufficiently compensate for the loss of the stock. Recently, natural salmon populations have started to increase in the Northern Baltic Sea, which has resulted in a growing interest in protecting the wild salmon spawning areas in regulated rivers (Erkinaro *et al.* 2011). A recent trend in many countries is a shift in focus from stocking to the accommodation of the natural life cycle of fishes and the protection of migratory routes and habitats (Romakkaniemi *et al.* 2014). To achieve this restoration, fishways or other types of bypass channels are often suggested. However, the use of fishways creates opportunity costs, as water is released through fish passes at the expense of electricity production. Although the main focus and the public debate on mitigating this problem have concerned fishways, other measures should be considered, as fishways may not be beneficial at all sites and under all conditions considering their costs. Studies III and IV focused on the trade-off and alternative optimal solutions for the conflict between salmon and hydropower production in dammed rivers.

3 Methods

This section presents the two key methods used in this thesis research: bioeconomic modelling and game theory. In particular, the sufficient level of biological complexity in bioeconomic models is discussed by focusing on a comparison of age-structured and biomass models, as well as the importance of taking into account the biological interactions between different species. Furthermore, the trade-off between hydropower production and migratory fish is introduced. Lastly, the central literature on game theoretic applications to fisheries management is reviewed.

3.1 Bioeconomic modelling

The main underlying method in Studies I, II and IV was numerical bioeconomic modelling combined with optimisation, in which the flow of resource rent over the considered time period was maximised using a relevant discount rate. Such models improve comprehension of the link between human activities, such as, harvesting, and natural resources, such as, fish stocks, as these two components are combined in the same model. Bioeconomic optimisation models can contribute to understanding the development of fishery behaviour, and they consequently enable an assessment of alternative policies. Additionally, a wide variety of external factors, such as climate change, multispecies interactions, harvesting costs, fish prices and management settings, affect both the ecological and the economic side (Prellezo *et al.* 2012). Therefore, it is essential to take both aspects into account when conducting comprehensive analysis.

The first bioeconomic applications to fisheries were performed by Gordon (1954) and Schaefer (1957), who introduced a solution to the static fisheries problem. A dynamic application in continuous time was introduced by Clark and Munro (1975), who used a biomass model to examine population dynamics. The number of bioeconomic studies related to fisheries is rapidly increasing, and the studies have tackled a variety of problems arising in fisheries, such as multispecies or ecosystem issues, uncertainty, fisheries agreements and climate change. Reviews on bioeconomic applications to fisheries include those by Bjørndal *et al.* (2004a) and Kronbak *et al.* (2014).

3.1.1 The level of biological complexity

A common debate in bioeconomic models regards the optimal or sufficient level of complexity in the biological representation. The practice was originally to use biomass models, where the population is simply lumped into a single parameter, i.e., the biomass is aggregated over all age classes. This approach, also known as a surplus growth model, is often sufficient to answer economic questions. In contrast, in fisheries science, fisheries ecology and stock assessment, practically all studies have adopted an age structure within the population dynamics, originating with Beverton and Holt (1957) (Tahvonen 2008). However, there is growing interest in also using age structures in bioeconomic studies, especially in empirical research (Tahvonen 2010), and economists have increasingly supported the use of such cohort models in order to avoid an oversimplistic representation of the real world (Steinshamn 2011). However, Clark (1990) argued that age-structured models are too complicated to determine analytical solutions, and such models are therefore still relatively rare. In contrast, Tahvonen (2009) stated that cohort models can be analytically tractable.

Studies I and II assessed the multispecies Baltic Sea fisheries using a deterministic bioeconomic age-structured model. The age structure provided more realistic population dynamics by taking into account, for instance, the higher predation by older cod on their prey species. Additionally, the age structure played an important role in one of the main results of the studies: decreased fishing pressure by cod leads to a stock with older individuals and therefore to a positive change in its age structure. However, the use of an age-structured model with a higher economic value for older individuals might also be problematic given the imperfect selectivity of fishing gear, leading to pulse fishing (Hannesson 1975). In addition to the multispecies models in Studies I and II, the population dynamics of salmon were presented as a detailed age-structured model in Study IV. Such a model enabled sufficient illustration of the complex life cycle of salmon, and allowed the segregation of wild and reared individuals, which have relatively disaggregated life stage parameters.

The interactions between different fish species affect the development of stocks in the Baltic Sea and have an important influence on both biological and economic performance. However, bioeconomic fishery models have often only been applied to one species, for example cod (Armstrong and Sumaila 2000; Kronbak and Lindroos 2007) or herring (Bjørndal *et al.* 2004b; Kulmala *et al.* 2007), and case studies including several species have mainly focused on regions other than the Baltic Sea (Danielsson *et al.* 1997; Ulrich *et al.* 2002; Brown *et al.* 2005). The interest in such multispecies studies in the economic literature started in the 1980s. Hannesson (1983) reported one of the first of such studies and concentrated on the role of the discount rate in the optimal fishery of ecologically interdependent species. More recently, studies have focused on a wide variety of topics, such as problems in bycatches (Reithe 2006), marine sanctuaries (Holland 2000) and technical interactions between fishing activities (Ulrich *et al.* 2002). However, there has been a lack of bioeconomic case studies on multispecies relationships in the Baltic Sea region (one recent example of such a study is that by Voss *et al.* 2014), although interest in ecosystem-based management, additionally taking into account the biological interactions between species, is increasing (Möllmann *et al.* 2014). Studies I and II bridged this gap in the literature.

3.1.2 Hydropower and migratory fish

The spawning migration route of salmon and several other migratory fish species has been blocked in many rivers in the Baltic Sea by the construction of hydropower plants in the 1950s and 1960s. In many cases, hydropower companies are obliged to annually compensate for the damage to fisheries by releasing reared individuals, and these individuals are commercially harvested by coastal and offshore fisheries (Erkinaro *et al.* 2011). However, there is evidence that these reared individuals have lower survival rates than wild fish (Michielsens *et al.* 2006). Additionally, demand for the recreational use of river fisheries has increased, and the EU Water Framework Directive calls for a good ecological potential in heavily modified waters. Thus, interest in salmon stock restoration by promoting the natural life cycle of individuals in regulated rivers has gained increasing attention (Erkinaro *et al.* 2011), and there is clearly a need to study the topic from the economic point of view in order to find the most cost-effective solution to the problem.

The optimal bioeconomic management of Baltic salmon has been investigated, for example, in the international context (Laukkanen 2003; Kulmala *et al.* 2008; Kulmala *et al.* 2013), as well as that of the conflict between grey seals and Baltic salmon (Holma *et al.* 2014). However, research related to Baltic salmon has often overlooked the connection with hydropower. The recreational benefits arising from salmon angling in freely flowing rivers have been estimated in the Baltic Sea area (e.g., Appelblad 2001; FGFRI 2009; Parkkila 2005), but studies considering the recreational value of regulated rivers have been scarce (Håkansson 2008; Kataria 2009; Parkkila *et al.* 2011).

Studies that address the trade-off between hydropower and migratory fish or aim at comparing alternative measures to improve salmon migration have used cost–benefit analysis (Laine 2006; Håkansson 2009; Johansson and Kriström 2012), multi-criteria assessment (Dufva and Marttunen 2010; Karjalainen *et al.* 2011) or optimisation modelling (Kuby *et al.* 2005; Jager and Martinez 2012; Halleraker *et al.* 2007; Fjeldstad *et al.* 2014). However, as Study III noted, economic literature aimed at defining optimal solutions for the conflict between hydropower production and salmon in a dynamic setting, and that can thus inform decision makers on alternative measures, is relatively scarce for the Baltic region. Study IV filled this gap in the literature.

3.2 Game theory

Game theory is a tool for analysing the strategic interactions of more than one rational decision maker, where the decisions made by one player also affect the outcome of the other players. This is what distinguishes a game theoretical problem from a traditional optimisation problem. In game theory, players choose their best action by taking into account the expected reactions of the other player (Miller *et al.* 2013). Due to the increased number and size of commercial fishing vessels, as well as improved technology, it is clear that fishing actions taken by one nation affect the size and composition of the catches of another nation, and thus the revenues of its fishing industry. Game theory can be used to assess how to manage internationally shared fish stocks to achieve biologically sustainable and economically efficient fishery management (Miller *et al.* 2013). Additionally, applications of game theoretic studies help to explain the conditions under which it is possible to achieve and maintain cooperation, and they are therefore useful when assessing policy options (Miller *et al.* 2013). Game theory can also be applied to study other problems such as competition between different uses of fish (commercial vs recreational fisheries) or principal-agent problems between boat owners and skippers or regulators and fishermen (Hannesson 2011).

The first game theoretic application to internationally shared fisheries was published by Munro (1979), who examined the problem of managing transboundary fish stocks, i.e., stocks migrating between several Exclusive Economic Zones. His main finding was that cooperation between nations can be easier to achieve if side payments are used instead of sharing the benefits based on catches. This seminal research was soon followed by the studies of Clark (1980) and Levhari and Mirman (1980), and since then the literature has grown, with game theory being applied to various issues related to fisheries. The literature and its development have been reviewed, for example, by Sumaila (1999), Bailey *et al.* (2010), Hannesson (2011), Miller *et al.* (2013) and Pintassilgo *et al.* (2015).

3.2.1 From cooperative to non-cooperative game theory

Game theory can roughly be divided into cooperative and non-cooperative actions, although most games include elements from both branches. The cooperative exploitation of shared fish stocks yields full rent maximisation, whereas non-cooperation is likely to lead to the tragedy of the commons and rent dissipation (Gordon 1954; Scott 1955, Munro 1979).

Cooperative game theoretic analysis has often relied on a characteristic function (C-function) approach, which examines how payoffs should be fairly shared among coalition members (see, e.g., Kaitala and Lindroos 1998; Li 1998; Arnason *et al.* 2000; Duarte *et al.* 2000). The prerequisite for successful cooperation is additional benefits, so that rationally behaving players will gain at least as much as from cooperation as they would from non-cooperation, and they consequently have an incentive to continue cooperating. Commonly used sharing rules (or sharing imputations) applied in C-function games based on different fairness concepts include the Shapley value (the average value of the marginal contribution to the coalition) (Shapley 1953), the nucleolus (maximising the minimum gain to any possible coalition) (Schmeidler 1969) and the Nash bargaining solution (yields equal weights of the gains) (Nash 1950). Ideally, the allocated benefits would be applied at the policy level and determined at the TAC level. However, as TACs are usually based on historical catches, the sharing rules are often not currently applicable and thus do not represent the optimal first-best outcome (Kronbak and Lindroos 2012).

Nevertheless, C-function games usually ignore positive externalities, which arise when decision makers affect the availability of the fish stock and hence the economic outcomes of others by their own actions. If externalities are neglected, the stability of the coalition may become threatened, as free-rider incentives may break the coalition (Kronbak and Lindroos 2007). When positive externalities are taken into account, i.e., the mergers' positive effects on the payoffs of non-mergers are considered, a non-cooperative game of coalition formation, also known as the partition function (P-function) approach, can be applied (Pintassilgo 2003), as in Study II. A partition function game takes into account the entire coalition structure and not just the coalition in question, and it aims to determine which coalitions will form and how other coalitions will affect the cooperation incentives (Pintassilgo *et al.* 2015). Additionally, coalition games are capable of assessing cheating, when coalition members do not follow the rules of the agreement, and free-riding, when non-members receive benefits from the cooperation (Miller *et al.* 2013).

Non-cooperative games aim at assessing which coalitions will form and how the existence of other coalitions will affect the incentives to cooperate. These incentives depend on the rules and the expected payoffs. Rules define, for instance, the information that each player has, the ability of players to communicate (bargaining) and whether actions are performed simultaneously or sequentially. In non-cooperative games, players maximise their own payoffs independently and take their actions accordingly (Miller *et al.* 2013). This process makes non-cooperative games particularly relevant for International Environmental Agreements (IEA), as no external authority exists that can force players to join an agreement (Barrett 2003). Thus, any agreement must be self-enforcing (Barrett 2003), according to which no player has the incentive to deviate from the strategy

(Gibbons 1992). This type of agreement can be facilitated by manipulating the rules in such a way that players find compliance to be the preferred strategy (Barrett 2003).

3.2.2 Climate change and fisheries agreements

The main challenge to fisheries management as related to climate change is that a lack of understanding and the unpredictability of biological impacts will have negative consequences for existing agreements, potentially even leading to breakdowns. Adaptation to climate change may be alleviated if more flexible allocation rules could be established (Miller and Munro 2004). Study II illustrated the effects of such a flexible management system, in which countries can trade quotas. As climate change may affect the migration routes and spatial distribution of fish stocks, among other effects, it may mean that the problem of new entrants becomes more common. Some suggested solutions to the problem include 1) sharing the quotas with the new entrant based on, for example, the Shapley value, 2) the expansion of quotas to create room for the new member, or 3) the introduction of property rights to the original members in the form of transferable quotas, allowing them to sell a portion to the new member. The second option has most commonly been implemented, leading to detrimental effects on fish stocks (Miller *et al.* 2013).

McKelvey *et al.* (2003) were the first to study this climate change effects on fisheries agreements. They argued that existing agreements may break down and that quota shares should therefore be more flexible. Liu *et al.* (2014) found that cost asymmetry improves the stability of a grand coalition when changes occur in the distribution of a fish stock. Liu and Heino (2013) demonstrated that players behave symmetrically when both players ignore future changes in the stock distribution. However, when the player losing stock takes climate change effects into account, it starts harvesting more aggressively than the other player. Ellefsen (2013a) concluded that a new entrant destabilises the agreement, but can be encouraged to join the agreement through monetary payment.

According to the "paradox of cooperation", introduced in the context of IEAs by Barrett (1994), cooperation is less likely when it is needed the most, i.e., when the most can be gained from it. This occurs, for instance, when the number of players is high and the relative gains from full cooperation would therefore be high, but the likelihood of reaching a large stable coalition remains low (Barrett 1994; Finus 2000). This paradox has been confirmed, for example, by Brandt and Kronbak (2010), who demonstrated that when climate change has a decreasing impact on the resource rent, stable fisheries agreements are less likely. However, the paradox is contradictory to the findings in Study II, according to which the need for cooperation increases under climate change, but so does the likelihood of establishing cooperation. This finding may be explained by the nature of the game involving multispecies fisheries, which affects the behaviour of the countries. Study II could be extended to take into account possible climate change effects on the spatial distribution of fish stocks, as currently only the effect on the size of fish stocks is examined.

3.2.3 Multispecies game applications

Multispecies or ecosystem game applications are still relatively scarce in the literature, although they might be useful for assessing international agreements in ecosystems that involve several species. Such studies include analyses of the optimal harvesting of species in a predator-prey system under cooperation (Sumaila 1997), the effects of the number of non-cooperative players on stock sizes in a two-species system (Kronbak and Lindroos 2011), comparison of cooperation and non-cooperation in a system of competing species and a predator-prey system (Wang and Ewald 2010), as well as in multispecies and single-species management (Ellefsen 2013b). Although game theoretic applications using the multispecies approach have gained increasing interest, the use of a coalition formation approach, or a P-function approach, in a multispecies setting has been more or less overlooked. Study II filled this gap in the literature.

4 Summaries of the studies

4.1 Study I: Optimal bioeconomic multispecies fisheries management: A Baltic Sea case study

This study compared the optimal and current multispecies Baltic Sea management under different environmental conditions. The study took into consideration species from two different levels of the food web: the cod as a predator and the herring and sprat as prey species. The biological interactions between the species were taken into account through simple predation functions. The fishery for each species was optimised and compared with the status quo fishing policy. Additionally, a comparison with the current as well as with past environmental conditions was conducted, and climate change was thus taken into account. In addition to the interactions between the species, the biological realism was increased by using an age structure in the population dynamics.

According to the results, the fishery of these species is not at the most profitable level, and with lower fishing mortalities, economic returns would be greater in the long term. A reduction in the fishing pressure on cod would result in the recovery of the stock, as individuals would have more time to grow and achieve a higher economic value, as well as a higher reproduction potential. Considering past environmental conditions, i.e., when conditions were better for cod recruitment, the cod stock had a better chance to recover even without a reduction in fishing mortality. Especially under the current environmental conditions, which are likely to prevail in the future due to the changing climate, optimal MEY management would yield significantly higher profits for the fishery than the current management.

This study contributed to the literature by being among the first to apply multispecies bioeconomic modelling to the Baltic Sea region. It did so by using a simple predation function to illustrate the biological species interactions, which is more applicable for economic optimisation. Such multispecies modelling provides more a realistic presentation of the population dynamics and moves bioeconomic fisheries management towards holistic ecosystem-based management.

4.2 Study II: International agreements in the multispecies Baltic Sea fisheries

This study continued Study I by analysing the age-structured multispecies fisheries in the Baltic Sea and taking into account the strategic interactions between fishing nations. The study focused on coalition formation through a partition function game between three asymmetric countries harvesting cod, herring and sprat. The players had complete information, i.e., the players' payoff functions were common knowledge among all players, and they adopted pure strategies. A multispecies approach is highly important for fisheries management, especially because the changing climate could cause regime shifts in marine systems and lead to the complete reorganization of marine communities (Miller *et al.* 2013).

The results demonstrated that full cooperation, or a grand coalition, can only be maintained and stabilised when the most efficient country compensates the other countries for harvesting less; otherwise, the less efficient countries will harvest more than has been agreed upon. However, when using a single-species model for the cod population, such a solution is not feasible. This confirms that the scope of cooperation increases when fishery management is based on multispecies advice. Interestingly, the study also determined that climate change may actually improve the likelihood of a binding agreement. This is in contrast to the predominant conception, and occurs because countries will gain more from cooperation when the cod biomass is low.

Although a wide range of game theoretic studies have been conducted in a single-species context, and multispecies aspects have gained increasing interest, applications using a coalition formation approach, or a partition function approach, in a multispecies setting have been more or less overlooked, which places this study in a central position in the literature. This study contributed to the existing literature by combining coalitional games and a dynamic multispecies model.

4.3 Study III: Economic and policy considerations regarding hydropower and migratory fish

This study comprised a comprehensive review of the existing literature related to the effectiveness and costs of alternative measures promoting the joint production of hydropower and migratory fish species. The purpose of the review was to outline the prerequisites for future policies based on environmental standards, rather than technology standards, which have rarely been applied to the topic.

The review details eight suggestions that must be taken into account when designing cost-effective measures to promote the sustainable production of hydropower while securing viable, genetically rich populations of migratory fish. According to the suggestions, the optimal measures are case-specific and highly dependent on their design, implementation and maintenance. In addition to tailored *ex ante* cost-effectiveness analyses, other preconditions for optimal solutions include effective and affordable monitoring and enforcement, and cooperation among power companies that share water-use rights within a river basin, as well as among other stakeholders, such as the local community, fishermen and recreational users.

4.4 Study IV: Optimal joint production of hydropower and migratory fish: A case study in the Northern Baltic Sea

This study determined the optimal measures maximising the benefits from the joint production of hydropower and salmon in a case river with five hydropower plants (the Iijoki River in the Northern Baltic Sea in Finland). The study used a numerical bioeconomic optimisation model and demonstrated that in such a heavily regulated river, it is optimal to trap and transport as many individuals as possible to restore the wild salmon stock. The construction of fishways would not be beneficial, as their investment and maintenance costs would exceed the benefits. Even a 20% decrease in the post-smolt or downstream mortality rate would not support the construction of fishways. However, if it is assumed that the river had only one hydropower plant blocking migration to the spawning area, a fishway would become the superior solution. Therefore, this study highlights that the optimal solution for each river may be case-specific, as was argued in Study III.

In general, the positive and negative externalities arising from hydropower production are well known, but literature related to the economic consequences of different measures ensuring the return of migratory fish to rivers, which could be used to effectively inform decision-makers, is scarce. This topical study contributed to the literature by using a dynamic bioeconomic optimisation model to dynamically determine the optimal measures.

5 Conclusions

This thesis brings together valuable knowledge on Baltic Sea fisheries management, and the studies forming the thesis have taken current research towards more holistic ecosystem-based management in four dimensions: 1) they applied a multispecies approach instead of relying on conventional single-species management; 2) they analysed the prospects of a fisheries agreement among several countries by applying a novel partition function approach, which took into account the positive externalities arising from the coalition formation; 3) they modelled the problems by taking into account the long-term perspective and analysed the possible future effects of climate change on the fishery; and 4) they applied the cross-sectoral approach by simultaneously focusing on the fisheries and hydropower sectors, which both affect the ecosystem.

Although this thesis introduces holistic recommendations for biologically and economically more sustainable Baltic Sea fisheries, there are still further steps to be taken in order to move to comprehensive ecosystem-based management. First of all, instead of treating fish stocks as static and uniformly distributed all over the Baltic Sea, the inclusion of spatial considerations of the stocks would be important for future research. Additionally, this thesis covers only two trophic levels, i.e., predator and prey fish species, but lower trophic levels, including plankton, could also be taken into account. In the case of hydropower and migratory fish, a model considering the whole Baltic Sea system with several salmon rivers would further contribute to the literature. Such a study would allow the targeting of management measures individually to each river in order to achieve the most effective solution. Furthermore, the multi-sectoral game could be developed to include other relevant sectors, such as agriculture, due to its effects on the marine ecosystem through eutrophication. Lastly, an analysis is needed in the setting of a dynamic membership game, in which the membership decision of fishing nations is periodically revised.

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