Bio-economic and structural equation modelling for ecosystem-based management and ecosystem accounting: Fisheries management in the Baltic Sea

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DOCTORAL DISSERTATION

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Abstract

Ecosystem-based management is necessary for management of marine ecosystems because they are affected by multiple impacts, and some synergistic effects or conflicts may exist among these impacts and the possible solutions. This thesis applies three different approaches to contribute to ecosystem-based management. First, this research develops a multispecies bio-economic model that is able to consider food web interactions, different types of fisheries, and the various economic benefits provided by multiple ecosystem services. The developed model focuses on a food web consisting of migratory fish (salmon; *Salmo salar*), mammalian predators (grey seals; *Halichoerus grypus*), and schooling fish (herring; *Clupea harengus*) in the Baltic Sea. Additionally, the included ecosystem services include both provisioning and non-market cultural services, such as ecosystem services for fisheries, recreation and the existence of the species. By applying optimization approaches, the developed model is used to examine fisheries management. Second, structural equation modelling is applied to explore the causal relationship among climate and environmental factors, fisheries, prey availability and competitors to the salmon population. The last applied approach was ecosystem accounting, which is able to reveal the economic implications of ecosystem changes and the use of ecosystem services by different economic sectors. A framework integrating the ecosystem services and accounting system is proposed with a marine case study. Furthermore, the developed multispecies bio-economic model is applied with different valuation approaches to value the marine ecosystem for ecosystem accounting. By applying different approaches, this thesis provides insight and recommendations for ecosystem-based management from various perspectives.

Keywords: bio-economic modelling, multispecies, fisheries management, ecosystem-based management, structural equation modelling, migratory fish, climate, ecosystem services, ecosystem valuation, ecosystem accounting

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List of original publication

This thesis contains a summary of the research and the following four research articles.

I. Lai, T.-Y., Lindroos, M., Grønbæk, L., & Romakkaniemi, A. (2019). The role of food web interactions in multispecies fisheries management: bio-economic analysis of salmon, herring and grey seal in the Northern Baltic Sea. *Manuscript (submitted)*.

II. Lai, T.-Y., & Möllmann, C. Influence of compound anthropogenic impacts on salmon populations in the Baltic Sea. *Manuscript.*

III. Lai, T.-Y., Salminen, J., Jäppinen, J.-P., Koljonen, S., Mononen, L., Nieminen, E., Vihervaara, P., Oinonen, S. (2018). Bridging the gap between ecosystem service indicators and ecosystem accounting in Finland. *Ecological Modelling, 377*, 51-65.

IV. Lai, T.-Y., & Saikkonen, L. Valuing marine natural capital with multiple ecosystem services for ecosystem accounting by different valuation approaches. *Manuscript.*

Author's contributions

Study I — Lai participated in the development of the research idea and was responsible for the research planning, conducting the research (including model development, data collection on most of the data, producing all the research results, discussing and interpreting the results), and writing the manuscript. Other co-authors contributed to the development of the research idea, data provision, methodology guidance and manuscript revision.

Study II — Lai proposed the research idea, participated to methodology designed, and was responsible for research planning, conducting the research (including model development, data collection, producing all the research results, discussing and interpreting the results), and writing the manuscript. The co-author contributed to methodology guidance and manuscript revision.

Study III — Lai participated in the development of the research idea, research planning, and writing the manuscript. Lai was also responsible for parts of the research conducting, including framework comparison, designed the integration framework proposed in the paper, and produced the results for the second case study. Other co-authors contributed to the development of the research idea, research planning, conducting other parts of the research (e.g., framework revision, providing data and the model, producing the results of the first case study), and writing the manuscript.

Study IV — Lai was responsible for parts of the research conducting (including model revision and producing results) and writing the manuscript. Lai also participated in the development of research idea, research planning, and other parts of the research conducting (e.g., approaches comparison). The co-author contributed to the development of research idea, research planning, conducting parts of the research (e.g., estimation of the simulated exchange value and approaches comparison), and writing the manuscript.

Summary — Lai was solely responsible for writing the summary of this thesis.

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1. Introduction

Marine ecosystems are significant sources of food and nutrient for humans. The global wild catch from marine fisheries in 2016 was 79.3 million tonnes, and fish provide 17% of the animal protein per capita globally and other nutrients essential for human heath, such as fatty acids, vitamins and minerals (FAO, 2018). In addition, fisheries create income and employment opportunities for many countries and coastal areas (FAO, 2018). However, the results of failed and fragmented management of marine ecosystems (e.g., overfished, destruction of habitat and ecosystem function) have decreased marine productivity (Jackson et al., 2001; Srinivasan et al., 2010). The 2030 Agenda for Sustainable Development of the United Nations (UN) identified the conservation of oceans, seas and marine resources as one of the Sustainable Development Goals (SDGs) (UN, 2015). Under a growing global population, it is critical for food and economic security that marine ecosystems can maintain a certain health status and sustainably provide resources. This will eventually have effects on other SDGs, including those pertaining to poverty, hunger, and equality, worldwide.

The sustainability and productivity of marine ecosystems are threatened by many impacts, including those from overfishing, climate change, and pollution (Halpern et al., 2008). Different threats may have synergistic effects, e.g., overfishing and climate change (Ling et al., 2009), and some conflicts may exist among the solutions or between stakeholders (Fogarty, 2014). Conventional single-species and single-sector-based management are insufficient to address these synergistic effects and conflicts, which provokes the demand for more holistic and integrated approaches to marine management (Fogarty, 2014; Pikitch et al., 2004; UNEP, 2011). This thesis aims to contribute to the development of two integrated approaches: ecosystem-based management (EBM) and ecosystem accounting, both of which are still under development but are necessary for the proper management of marine resources.

The European Marine Strategy Framework Directive (MSFD) adopted EBM to achieve a "good environmental status" for European marine waters (European Union, 2008). The Common Fisheries Policy (CFP) of the European Union (EU) has also requested that EBM be implemented in fisheries management to minimize the negative impacts from fisheries on the marine environment (European Union, 2013). EBM is a holistic approach that takes an ecosystem, rather than an isolated issue, as the basis for considering the interactions of the elements within and between different systems during the establishment of management practices (Fogarty, 2014; UNEP, 2011). The considered interactions include species interactions and influences from climate and environmental factors that determine the system-wide productivities of marine ecosystems (Fogarty, 2014; Pikitch et al., 2004; Steinacher et al., 2010). In addition, humans inevitably influence and rely on marine ecosystems by fishing and using other marine resources. Therefore, the dynamics of social-ecological systems, activities from different economic sectors, and stakeholders are also key components that should be involved in EBM (Fogarty, 2014; Long et al., 2015; UNEP, 2011).

To tackle the elements and interactions mentioned above, this thesis applied the following approaches: (1) bio-economic modelling (Studies I and IV), (2) structural equation modelling (SEM) (Study II), and (3) ecosystem accounting (Studies III and IV). Bio-economic modelling can capture the interactions, dynamics, and trade-offs among the elements in biological and economic systems (Prellezo et al., 2012). SEM can analyse the relationship in complex systems by coupling multiple predictors and responses in a single causal network (Lefcheck, 2016). Both modelling approaches are suitable for providing recommendations for or implications of EBM in marine ecosystems.

Ecosystem accounting aims to integrate information on ecosystems and ecosystem services (ESs)[1] into the system of national accounts (SNA), which records and reports economic information in a standardized format in most countries (European Commission et al., 2009; United Nations et al., 2014b). The results of ecosystem accounting can measure the dependence of the economy on the ecosystem and be used in policy analysis and environmental assessments at the macroeconomic level (Kumar et al., 2013). For marine ecosystems, ecosystem accounting can contribute to EBM in several ways: (1) by conveying the status of the marine ecosystem and the ESs that are comparable and compatible with the economic indicators on a regular basis (Kumar et al., 2013); (2) by revealing how different sectors (stakeholders) use marine ESs in each accounting period; and (3) by using the accounting data to assess the potential impacts of specific policies on marine ecosystem conditions and ESs from different sectors. Either the ecosystem accounts with regularly recorded environmental statuses or the results of policy assessments based on the ecosystem accounts can serve as references for decision making in EBM.

1.1 Research purpose and the structure of the thesis

This thesis focuses on the topics and approaches that contribute to the development of EBM and ecosystem accounting. Figure 1 lists the topic of each study in this thesis and displays their relationship with EBM and ecosystem accounting. Studies I and II directly relate to EBM. Study I establishes a multispecies model to investigate the optimal economic and biological management with consideration of the food web interactions between grey seals (*Halichoerus grypus*), salmon (*Salmo salar*), and herring (*Clupea harengus*). Since multiple fisheries (salmon fisheries and herring fisheries) are included in the model, Study I also explores the trade-off between different

[1] Ecosystem services: all kinds of benefits that humans receive from the ecosystems (United Nations et al., 2014).

fisheries. The elements of EBM covered in Study I include food web interactions (multispecies), the dynamics between ecosystems and economic systems, and the conflicts among multiple stakeholders. In particular, from the perspective of species interactions, Study I contributes to the inclusion of migratory species (salmon) that migrate between river and marine ecosystems in the development of the bio-economic model. Study II also considers species interactions, multiple ecosystems and fisheries; however, the focal point of the study is the influences of climate and environmental factors. Study II applies SEM to analyse multiple environmental and anthropogenic factors that directly or indirectly affect the salmon population.

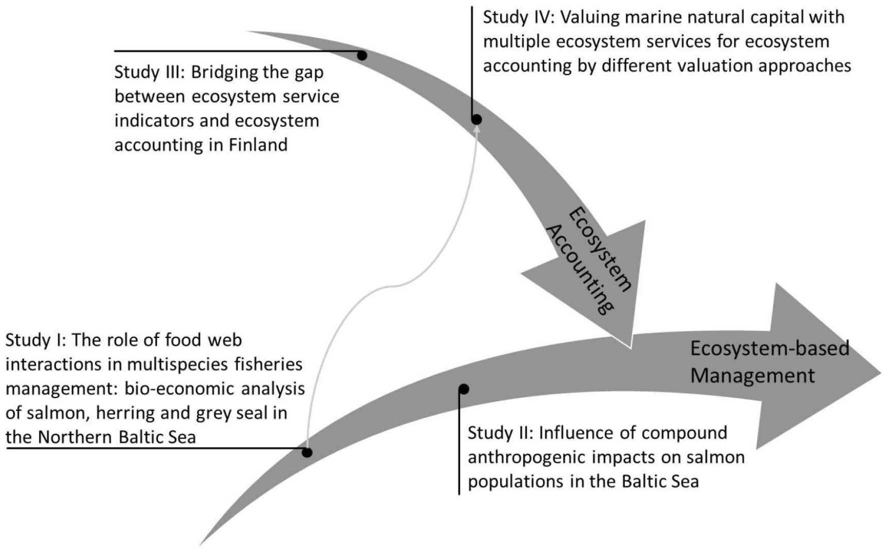

Figure 1 The topics of the studies in this thesis and their relationships to EBM

Studies III and IV contribute to the development of the framework and the clarification of the valuation approaches for ecosystem accounting (Figure 1), and the accounting results can be provided for EBM use. Study III establishes a framework to integrate the ecosystem and ES data from the Finnish ES database into the accounting system, which is a pilot study on ecosystem accounting that focuses on Finland. This study takes marine and freshwater ecosystems in Finland as case studies to demonstrate the framework by compiling sets of marine and water-related accounts. The accounting results from Study III show the bio-economic relations and provide the basis for cross-sectoral analysis in economics, such as input-output analysis or computable general equilibrium modelling (Banerjee et al., 2016; Obst and Eigenraam, 2016). Study IV aims to explore how recently developed valuation approaches, e.g., the simulated exchange value (SEV) approach for non-market cultural services and the value function approximation approach for ecosystem assets, are compatible with the ecosystem accounting standard described in the System of Environmental-Economic Accounting Experimental Ecosystem Accounting (SEEA EEA) (United Nations et al., 2014b). The EBM elements in Study IV are cross-sectoral analyses because both commercial and recreational fisheries are involved. Multiple ESs are another focal point of Study IV. Furthermore, the model applied in Study IV is an extension of the model developed in Study I (Figure 1); thus, it also covers the elements of food web interactions, bio-economic dynamics and stakeholder conflicts. Table 1 summarizes the study purposes, scopes, methods, literature contributions, and the included EBM elements of the four studies in this thesis.

Table 1 Summary of the four studies in the thesis

Study		I	II	III	IV
Study purpose		Investigate: (1) optimal economic and biological management considering food web interactions, and (2) the trade-off between different fisheries	Explore the impacts of multiple direct and indirect factors on the salmon population	Establish a framework to integrate ES indicators into the Finnish accounting system	Compare different valuation approaches for ecosystem assets and explore the SEV approach for non-market cultural services
Study scope	**Study area (ecosystem types)**	Northern Baltic Sea (marine ecosystem) River Torne (river ecosystem)	Northern Baltic Sea (marine ecosystem) River Torne (river ecosystem)	Finland (marine ecosystem and fresh aquatic ecosystem)	Northern Baltic Sea (marine ecosystem) River Torne (river ecosystem)
	ES	Provisioning ESs of fish for commercial fisheries	Focus on the species population rather than ESs	Marine case: -Provisioning ESs of fish for commercial fisheries -Cultural ESs from recreational fishing	Provisioning ESs of fish for commercial fisheries Cultural ESs from recreational fishing, seal watching, and the existence of seals
	Species	Grey seals, salmon, and herring	Salmon (research focus) Herring, sprat, and cod (explanatory variables)	Marine case study: Herring, sprat, and cod	Grey seal, salmon, and herring
Methods		Bio-economic modelling Optimization	Structural equation modelling	Ecosystem accounting	Ecosystem accounting SEV and value function approximation approaches
Contribution to the literature		Inclusive of migratory species in bio-economic modelling for the Baltic Sea	Explore the methods to consider temporal autocorrelation in the SEM Provide an overview of the causal relationship of the potential impacts on salmon population	A pilot study to compile Finnish ecosystem accounts Clarification of the mismatch between Finnish ES data and the accounting system	Explore how different valuation approaches are compatible with the ecosystem accounting
Covered EBM elements		Multispecies Bio-economic dynamics Stakeholder conflicts Multiple ecosystems	Influence of climate and environmental factors Multispecies Multiple ecosystems	Bio-economic relations The basis for cross-sector and multiple stakeholder analysis	Multiple ES Cross-sector analysis Stakeholder conflicts Bio-economic dynamics Multispecies Multiple ecosystems

*The table format refers to Nieminen (2017)

1.2 Study scope

All four studies in this thesis focus on the Baltic Sea, which is located between approximately 10°–30°E and 54°–66°N. The Baltic Sea is a body of brackish water surrounded by nine countries: Finland, Sweden, Denmark, Germany, Poland, Lithuania, Latvia, Estonia, and Russia. Due to the connection with the North Sea, the salinity of the Baltic Sea decrease from the southwest to the northeast. At least 6,065 species inhabit the Baltic Sea, including approximately 200 fish and 3 seal species (Ojaveer et al., 2010).

Fisheries management in the Baltic Sea needs to follow the CFP to implement EBM (European Union, 2013). One of the key components of EBM, the multispecies issue, is relatively well studied in the Baltic region. One example is the ecosystem including the most commercially harvested species in the Baltic Sea: cod (*Gadus morhua*), sprat (*Sprattus sprattus*), and herring (Figure 2). The multispecies models and data of the three species have been accumulated such that the International Council for the Exploration of the Sea (ICES) can provide information on the multispecies maximum sustainable yield (MSY) and the fishing effort for the multispecies MSY (F_{MSY}) for the Baltic fisheries (ICES, 2013). The commercial importance and the data availability in the multispecies context make the three species and their fisheries ideal for a pilot test of the Finnish marine ecosystem accounting in Study III. The three species and their fisheries are also included in Study II due to connection with salmon through the food web. In addition, herring, which accounts for the highest proportion of Finnish catch value (Figure 2), is also one of the study targets in Studies I and IV.

Salmon is another economically important species with high prices (Figure 3), even though its total harvest value accounts only for a small proportion of the total catch value from the Baltic Sea (Figure 2). The share of the salmon catch value in Finland is relatively important compared to the proportion of salmon catch in the total Baltic catch (Figure 2). However, salmon has seldom been studied in the multispecies or EBM context in the Baltic region. Therefore, three of the studies (I, II and IV) in this thesis take salmon and salmon fisheries as one of the research targets.

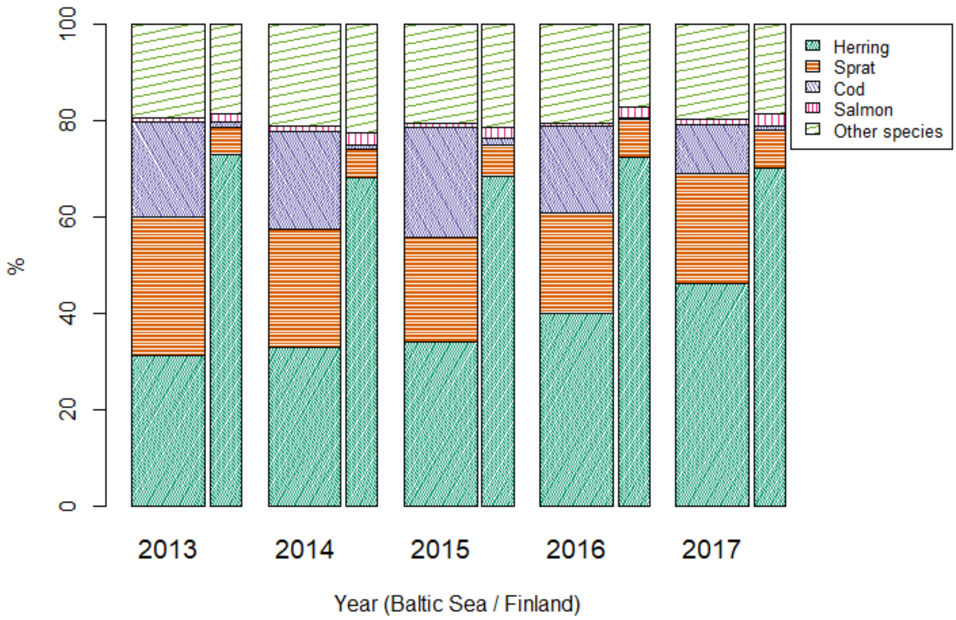

Figure 2 Catch percentage in the total catch value from the Baltic Sea (wide bar) and Finland (narrow bar) by species (source: European Commission (2018) and LUKE (2019)). The catch values of the cod, herring and sprat account for approximately 80% of the total Baltic catch. Herring and sprat make up the majority of the Finnish catch.

Figure 3 Average landing price of the species caught in the Baltic Sea (source: calculated by the data from European Commission (2018))

The concept of the EBM approach is essential for managing the Baltic salmon population as their life cycle alternates between river and marine ecosystems (Figure 4). Factors including climate change, the environmental conditions in rivers and marine areas, marine commercial fisheries, river recreational fishing, and the prey (herring and sprat) and predators (grey seals) of Baltic salmon all influence the survival and growth of salmon at different life stages (ICES, 2016, 2017; Mäntyniemi et al., 2012; Todd et al., 2011). Conversely, salmon plays an important role in the ecosystem balance by reducing the sediments and regulating the food web (as a predator), as well as supporting humans with provisioning and cultural services (Kulmala et al., 2013).

As salmon migrate between marine and river ecosystems, three of the studies address the interactions between river and marine ecosystems by considering different combinations of the components shown in Figure 4: including only the salmon life cycle and marine fisheries (Study I), considering the salmon life cycle, marine fisheries and recreational river fishing (Study IV), and involving the environmental factors in the river and marine ecosystems together with the salmon life cycle and fisheries (Study II). Study III also covers the river ecosystem in a case study that compiles water-related accounts. However, river and marine ecosystems are addressed in two independent cases in Study III, so the interrelationships between river and marine ecosystems are not included in this study.

Figure 4 shows the ecosystems and interrelationships covered in this thesis. In addition to cod, herring, sprat and salmon, grey seals are also included, not only because grey seals are the predators of the fish mentioned above but also due to the damage caused to the salmon caught by fisheries (Holma et al., 2014; Lundström et al., 2010). Therefore, grey seals are included in Studies I and IV, as well as the initial consideration in Study II[2].

The following section presents the methods used in this thesis, followed by a summary of each study (Section 3). Section 4 concludes this thesis with a discussion on the research limitations and future research directions.

[2] Grey seals were initially considered in Study II. However, they were excluded in the final version of Study II in this thesis as the models with grey seals were revealed to be insignificant during the testing of the model development.

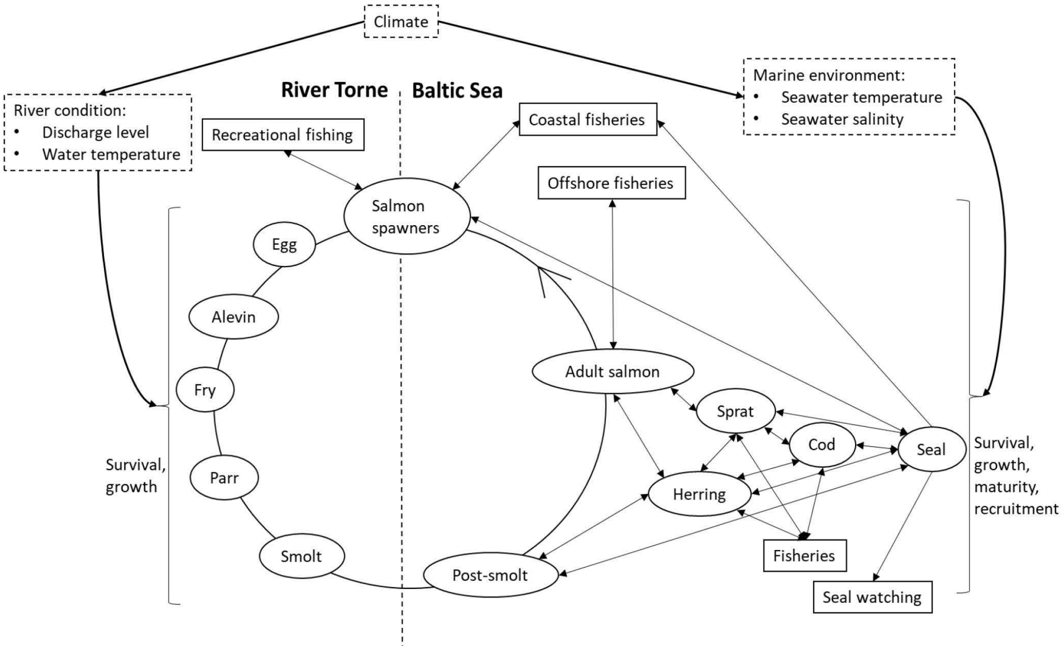

Figure 4 The research scope of the thesis: the climate conditions influence the river and marine environments locally and then influence the species. The salmon population from the Torne River migrates between the river and the Baltic Sea based on their life cycle and interacts through the food wed with sprat, herring, cod, and grey seals in the Baltic Sea. The species are influenced by and provide benefits to humans through commercial fisheries and recreational activities. The one-way arrows indicate the influence of one on another. The two-headed arrows imply interactions. For example, fisheries contribute to shaping the fish population, and the conditions of the fish population determine the amount of fish, income and enjoyment that can be provided to humans. The two-headed arrows between the species can be predator-prey relationships or competition. Different interactions are investigated or considered in the different studies: Study I covers the life cycle of salmon and the food web interaction among grey seals, salmon and herring, along with the herring and salmon commercial fisheries (costal and offshore). Study II includes the climate, river and marine environments, and food web relationships among salmon, herring, sprat, and coastal salmon fisheries. Study III focuses on the food web of herring, sprat, and cod and their fisheries. Study IV extends the scope from Study I by adding salmon recreational fishing and seal watching.

2. Methods

This section introduces the three methods used in this thesis: (1) bio-economic modelling, (2) structural equation modelling, and (3) ecosystem accounting. Each subsection focuses on one method by introducing the relevant theories and the ways that the theories and literature are linked to this thesis.

2.1 Bio-economic modelling

Bio-economic modelling was used in Studies I and IV and was also applied for the case study of marine ecosystem accounting in Study III. Section 2.3 will illustrate why and how bio-economic modelling can help in ecosystem accounting. This section focuses on bio-economic modelling as a method and reviews the literature related to the bio-economic model developed in Studies I and IV[3].

The model developed in Studies I and IV is an age-structured multispecies bio-economic model. The multispecies components of bio-economic models can be from biological (e.g., food web interactions) or/and economic (e.g., fisheries harvesting multiple fish species, which are also known as multispecies fisheries) perspectives (Kronbak et al., 2014). The multispecies focus of this model was on the biological part, which included the food web interactions of grey seals, salmon and herring in the Northern Baltic Sea. The two fisheries involved in both Studies I and IV were the commercial herring fisheries in the Northern Baltic Sea and the commercial salmon trap netting along the Finnish coast. The former mainly catches herring and a small proportion of sprat (ICES, 2016), and the latter almost exclusively catches salmon (Holma et al., 2014); thus, both were considered single species fisheries from the economic perspective of the model.

The foundation of bio-economic models in fisheries studies, which here specifically refer to the model type that consists of some kinds of population and economic sub-models linked by a production function and cost function with the species stock and fishing effort, can be traced back to the analytical model developed in the 1950s (Gordon, 1954; Schaefer, 1957; Scott, 1955). This type of modelling began as a static version of the single species model for both the economic and biological parts, and the biological part used lumped biomass as the only indicator to represent the population. The multispecies concepts evolved in both the biological and economic directions of the bio-economic models in the 1970s (see the reviews in Kronbak et al. (2014), Bjørndal et al. (2004a), and Seijo et al. (1998)). Recently, numerous numerical applications of multispecies bio-economic models or ecosystem models that covered wider ecosystem components than species interactions

[3] The bio-economic model applied in Study III was developed by Nieminen et al. (2012) and was not the contribution of this thesis. Thus, this review focuses on the model developed in Study I and IV.

have been developed and applied for different marine ecosystems worldwide (see the reviews in Nielsen et al. (2018) and Plagányi (2007)).

Due to their more comprehensive approach, age-structured models are believed to be more realistic than biomass for use in fisheries management, especially by ecologists (see reviews in Tahvonen (2009)). The use of the age-structured population in the bio-economic model in fisheries studies was first conducted by Hannesson (1975) and Clark et al. (1973) with a multicohort population model from Beverton and Holt (1957). Many recent empirical applications of age-structured bio-economic models can be found (e.g., Bjørndal et al. (2004b), Kulmala et al. (2007)), but Nieminen (2017) reviewed that the analytical analysis and the economic implications were mainly established by Clark (1976, 2010) and Tahvonen (2009, 2010). Clark (1976, 2010) provided the initial analytical analysis of age-structured bio-economic models in both the static and dynamic versions and pointed out the difficulties of analytical analysis in the dynamic versions. Tahvonen (2009, 2010) further explored several theoretical issues in the dynamic form, such as the situations for optimal pulse fishing occurrences and the conditions for cyclical equilibrium, and showed that age-structured bio-economic models can be analytically tractable (Nieminen, 2017).

Table 2 summarizes the numerical application of the multispecies bio-economic models that used age-structured form in their population model and focused on parts of or the entire Baltic Sea. The covered species ranged from three species to 30 functional groups, but none of these models included salmon. The bio-economic model focusing on salmon in the Baltic Sea was still in the single species form. Therefore, Study I bridged this gap by establishing a multispecies bio-economic model that included salmon. Recent single-species modelling studies (e.g., Holma et al. (2014)[4] and Kulmala et al. (2008)) and assessments (e.g., ICES (2016)) of Baltic salmon in Finland used age-structured population models originating from Michielsens et al. (2006). The model developed in Study I combined the seal and salmon models from Holma et al. (2014) and the herring model from Nieminen et al. (2012) and focused on the commercial fisheries of herring and salmon. Study IV further extended the model to include recreational salmon fishing based on Holma et al. (2018).

[4] Holma et al. (2014) included grey seals and salmon in their model. The model, however, did not include the seal-salmon food web relationship, and the salmon fisheries do not catch seals. Therefore, this thesis identifies Holma et al. (2014)'s model as a single species model for salmon.

Table 2 Multispecies bio-economic model focused on the Baltic Sea regions

Model	Multispecies from the biological or economic perspectives	Included species	Representative studies
Baltic Sea Atlantis (Atlantis model+ FishRent model)	both	30 functional groups, including seal, cod, herring, and sprat	Bossier et al. (2018)
Central Baltic Sea multispecies heterogeneous fleet model	both	cod, herring, and sprat	Hutniczak (2015)
Central Baltic Sea ecological-economic optimization model	biological	cod, herring, and sprat	Voss et al. (2014)
Stochastic multispecies model+ Fisheries Library in R (FLR) Baltic model	both	cod, herring, and sprat	Bastardie et al. (2012)
Baltic Sea climate multispecies model	both	cod, herring, and sprat	Nieminen et al. (2012)
Central Baltic Sea food-web NEST model (based on Ecopath with Ecosim)	both	28 functional groups, including seal, cod, herring, sprat	Blenckner et al. (2011)

Table 2 also shows that there were two multispecies bio-economic models that included seals, but seals only played a role in the biological part of those models. In this thesis, Study I considered the economic damage from grey seals to salmon fisheries based on Holma et al. (2014), and Study IV included the recreational and existence values of grey seals in the model (see Section 2.3).

In the application of the model developed in this thesis, Study I combined bio-economic modelling with dynamic optimization approaches. Dynamic and temporal aspects are inherent factors in managing the sustainable use and future use of resources. Thus, this thesis focused on dynamic rather than static application of the model. The theoretical basis of dynamic optimization can be found in Clark (1976, 2010).

In the optimization of Study I, the sustainability of both economic and biological terms was explored, i.e., optimizing the maximum economic yield (MEY) and optimizing the harvest in the assumed long-term horizon. In Study IV, the annual economic values were optimized to generate data and simulate future scenarios.

2.2 Structural equation modelling

The main underlying method in Study II was SEM. SEM can be defined as the use of two or more structural equations to model multiple predictors and response variables in a single cause-effect network and is thus suitable for analysing complex systems (Grace, 2006; Lefcheck, 2016). The approach has two primary characteristics: (1) using paths to present the hypothesized cause-effect relationships among the variables, and (2) a variable can be a predictor and a response simultaneously (Lefcheck, 2016). The root of this approach can be traced back to the path analysis of Wright (1920, 1921), and many disciplines, including biometrics and econometrics, have influenced the development of this approach (Grace, 2006). Grace (2006) and Grace et al. (2012) described the history of the development of SEM, and Pearl (2012) explained the assumption of using hypothesized causal relationships behind the SEM approach. Here, this thesis focuses on the piecewise SEM approach used in Study II.

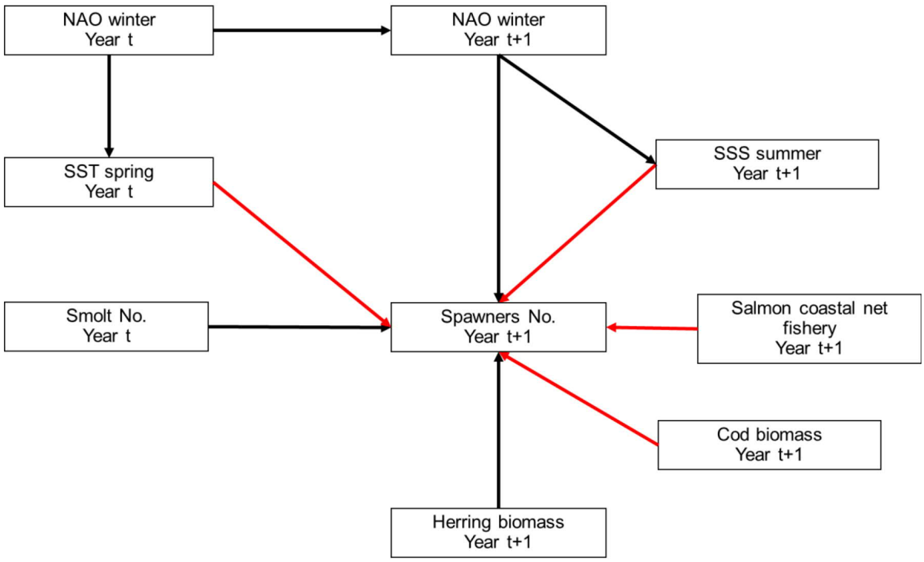

Figure 5 An example of a directed acyclic graph of a hypothesized candidate SEM. Black arrows imply positive relationships, and red arrows imply negative relationships. Abbreviations in the figure: North Atlantic Oscillation (NAO), sea surface salinity (SSS), and sea surface temperature (SST). (Note: the method used to establish this figure, the coefficient estimation method, the estimated results of the coefficient value, and the evaluation of the model results can be found in Study II).

Piecewise SEM establishes the hypothesized cause-effect relationships in directed acyclic graphs with the assumption of conditional independence between the variables (Lefcheck, 2016; Shipley, 2000). The modelling process of piecewise SEM converts the path graphs into a set of linear equations, and solves the equations individually (local estimation) based on the application of graph theory, to estimate the coefficient of each causal relationship (Lefcheck, 2016; Shipley, 2000). Figure 5 shows an example of a directed acyclic graph that displays the assumption of how environmental factors, fisheries and other species influence the populations of salmon spawners. One of the benefits of SEM is clearly shown in Figure 5; SEM is able to reveal the direct and indirect impacts. For example, the North Atlantic Oscillation (NAO) in winter may influence the number of salmon spawners in the next year by affecting the spring sea surface temperature (SST) in the current year (Figure 5). The limitations of piecewise SEM include (1) being unable to solve the cyclic and reciprocal feedback relationships among the variables and (2) being unable to directly measure latent variables (Lefcheck, 2016). However, piecewise SEM lifts several restrictions on the traditional variance-covariance SEM, including the restrictions of independence of the observations, multivariate normal distribution of the variables, and the minimum number of observations to allow degrees of freedom (Lefcheck, 2016), which makes SEM more applicable.

Within the past decade, many studies have applied SEM to analyse the impacts of environmental and climate change on marine ecosystems (Alsterberg et al., 2013; Arkema et al., 2009; Blake and Duffy, 2012; Byrnes et al., 2011; Duffy et al., 2016; Maureaud et al., 2019). However, the studies that investigated the impacts of climate and environmental conditions on salmon were mainly experimental or statistical studies that focused on single or multiple environmental effects on the development of specific biological traits of salmon (e.g., Hvidsten et al. (2015), Jokikokko et al. (2016), Jonsson et al. (2012), and Kallio-Nyberg et al. (2011)). These studies lack a comprehensive overview of how different environmental factors directly or indirectly connect to salmon populations. Considering the complexity of the salmon life cycle and the influences of the climate, river conditions, and the marine environment, SEM is a suitable approach for exploring the relationships.

2.3 Ecosystem accounting

Ecosystem accounting under the scope of environmental accounting is the core of Studies III and IV. Environmental accounting has been under development since the 1990s to complement the system of national accounting (SNA), as the SNA cannot sufficiently consider environmental externalities (e.g., environmental pollution or the depletion of natural resources). Such insufficiency made the SNA unable to reveal possible unsustainable economic growth and development when measuring the performance of the national economy (Bartelmus et al., 1991). Currently, the standard of environmental accounting is guided by the System of Environmental-Economic Accounting Central Framework (SEEA CF) (United Nations et al., 2014a).

Ecosystems are a type of natural capital (eftec, 2015; Hein et al., 2015). When natural capital is considered a single type of environmental asset, the approaches for compiling the relevant physical and monetary accounts of flows or stock are mainly addressed in the SEEA CF (La Notte and

Rhodes, 2020; United Nations et al., 2014a). For example, the SEEA CF includes fish stocks, which provide fish for human use, as a type of individual environmental asset in the accounting system (United Nations et al., 2014a). However, when using the approaches described in the SEEA CF to record the fish stock level in the accounting system, the effects of food web interactions among the species and the interlinkage between fish provisioning services and other marine ESs cannot be considered comprehensively. As such, the SEEA Experimental Ecosystem Accounting (SEEA EEA), which provides a principle for ecosystem accounting, was developed (United Nations et al., 2014b).

Ecosystem accounts include a set of accounts that compile information about the ecosystem extent, ecosystem conditions, ecosystem capacity, ES supply and use, and ecosystem assets (see detailed definition of each account in the SEEA EEA (United Nations et al., 2014b) and Study III). The accounts for the supply and use of ESs and ecosystem assets can be in physical or monetary units (United Nations et al., 2014b). Bio-economic modelling plays a critical role in compiling monetary ecosystem asset accounts, or say, in valuing ecosystem assets. Based on the SEEA EEA (United Nations et al., 2014b), the value of ecosystem assets should be the net present value (NPV) of future ES flows; thus, one of the steps is to predict possible future flows of ESs. Bio-economic models have the ability to simulate possible future flows of ESs in physical units or monetary units, depending on how the model is used, with some assumptions about future scenarios. In Studies III and IV, bio-economic modelling was applied during the procedures of valuing ecosystem assets.

The SEEA EEA (United Nations et al., 2014b) is not yet an internationally acceptable standard since several issues have not yet been resolved. The unclarified issues include disagreement over how to measure the ecosystem capacity in the accounting context (the conflict can be found between Hein et al. (2016) and La Notte et al. (2017)) and the gaps between the ES framework (e.g., the Common International Classification of Ecosystem Services (CICES)) and the accounting framework (La Notte and Rhodes, 2020). In addition, the current literature on ecosystem accounting lacks practical examples in which a comprehensive set of ecosystem accounts was compiled for marine ecosystems; in particular, examples of ecosystem capacity accounts were absent in the current case studies (see the reviews in Study III). Study III addressed these three issues and proposed the framework shown in Figure 6 to integrate the ES and accounting frameworks.

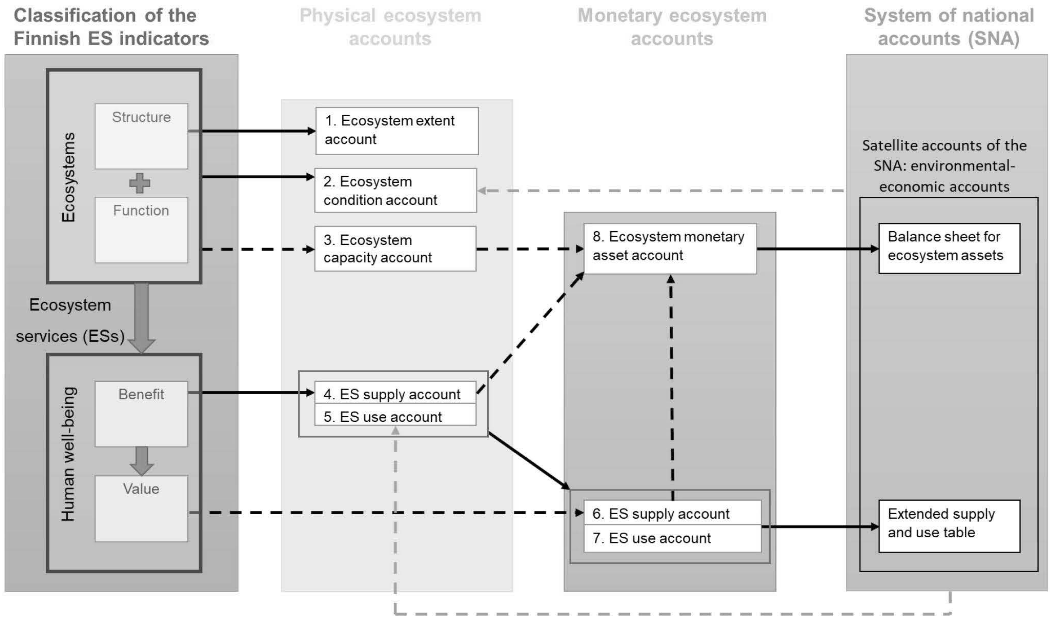

Figure 6 Framework for integrating Finnish ES indicators into the accounting system (published in Study III)

Study IV, by contrast, solely focused on the valuation methods that were not yet clarified for ecosystem accounting, which were related to the information that should be compiled into the monetary ES supply account (block 6 in Figure 6) and the monetary ecosystem asset account (block 8 in Figure 6). Many valuation approaches have been developed to estimate the value of ESs, but not all of them are consistent with the accounting standard. The accounting framework takes exchange value as the central basis. The exchange value of the provisioning services (e.g., the example of fish provisioning for commercial fisheries in Study III) is derived in a straightforward manner by deducting the production and the intermediate cost of the related good from the market price of that good, which is also known as the resource rent (United Nations et al., 2014b). However, some non-market valuation techniques (e.g., the stated preference method) for cultural ES are not consistent with the SNA since they not only consider the producer surplus (such as the exchange value) but also incorporate the consumer surplus and welfare effects in the valuation (Obst et al., 2016; United Nations et al., 2014b; United Nations Environment Programme et al., 2017). Using inconsistent approaches prevents comparison of the results for ecosystem accounts with the economic accounts compiled in the SNA; thus, they are not suitable for use in ecosystem accounting. However, the possibility of using non-market valuation techniques to estimate the demand curve to simulate the market and exchange value, which is called the simulated exchange value (SEV) approach, was pointed out by United Nations Environment Programme et al. (2017). Some case studies on forest ecosystems have applied the SEV approach for ecosystem accounting (Campos et al., 2019; Caparrós et al., 2017). Study IV applied the SEV approach for the marine ecosystem case with the ESs of salmon recreational fishing, seal watching, and seal existence value. The demand curves of these ESs were simulated and incorporated into the multispecies bio-economic model developed in Study I and combined with various valuation approaches to value marine ecosystem assets.

Comparing different valuation methods for ecosystem assets was another focus of Study IV due to the disagreement about which components (e.g., capital gains) should be included in ecosystem accounting and which natural capital valuation approaches should be used (Cairns, 2011; Fenichel and Obst, 2019; Polasky et al., 2015). The comparison in Study IV covered the NPV approach proposed in the SEEA CF and SEEA EEA (United Nations et al., 2014a; United Nations et al., 2014b) and the value function approximation approach (Fenichel et al., 2018) proposed by the latest expert consultation for the SEEA EEA revision (Fenichel and Obst, 2019).

3. Summary of the studies

This section summarizes the results of the four studies, which are presented individually in four sub-sections.

3.1 Study I: The role of food web interactions in multispecies fisheries management: bio-economic analysis of salmon, herring and grey seal in the Northern Baltic Sea

Study I had two research focuses. The first was to explore the optimal harvest of salmon fisheries with the consideration of the following food web interactions: grey seals are predators of salmon and herring, and herring is the food resource of salmon. Under the assumption of single species management, this research optimized the salmon harvest from both the biological (i.e., maximizing the harvest) and economic (i.e., maximizing the NPV of the fisheries profit) perspectives and compared the results in different scenarios. The designed future scenarios included that the herring harvest and the seal population would be maintained at the 2014 levels, that herring mortality from fishing would increase, that the seal population would increase, and that both would increase. The purposes of applying this multispecies model in a single species policy context were not only to explore the potential influences of food web interactions on salmon fisheries but also to compare the model with the existing single species model. The results showed the credibility of this multispecies model: when the herring and seal populations were set to maintain the same level as that of the single species model, the optimal results for the salmon population and harvest were similar between the two different models. The results also revealed that the recent high salmon population might benefit from the high herring population and low seal population. If the seal population continued to increase along with the low herring population, the salmon population might be threatened.

The second purpose of this paper was to explore the trade-offs between the herring and salmon fisheries when different optimal targets were combined. In the designed scenarios, salmon fisheries and herring fisheries pursued their optimal target simultaneously, but both fisheries chose either the maximum harvest or the maximum NPV of profits, which was a multispecies management context. The trade-offs between herring fisheries and salmon fisheries were revealed in the results, which showed that the herring harvest level and the harvesting approaches to managing herring fisheries could influence the performance of salmon fisheries.

The main contribution of this study was the demonstration of a new approach to a multispecies bio-economic model setup that included both migratory fish and mammalian predators. This study developed the first multispecies bio-economic model that included salmon in the Baltic Sea areas.

The developed model has the potential to be further incorporated into a multispecies bio-economic model for the entire Baltic Sea since the sub-model of the herring population and fisheries from this article was based on the Baltic Sea multispecies bio-economic model developed by Nieminen et al. (2012).

3.2 Study II: Influence of compound anthropogenic impacts on salmon populations in the Baltic Sea

This study used the SEM approach to explore the direct and indirect effects of different climate and environmental factors, fisheries, and food web relationships on the salmon population. The model showed the results that were supported by the literature: large-scale climate conditions (NAO in winter and Atlantic Multidecadal Oscillation) might indirectly influence the salmon population. The model also revealed that such influences might take paths through precipitation in autumn, air temperature in winter, river discharge in winter, and sea surface salinity in summer. The results indicate that the salmon population during the river stages might benefit from future climate change due to the potential for increased winter river discharge. However, the final impacts on the salmon population from climate change are uncertain since the climate impacts on salmon at the sea stage were ambiguous. In addition, prey, competitors and fisheries also had substantial effects on the salmon population at sea.

This study contributed to the literature from three perspectives. First, the study provided an overview of how the potential factors that might influence the salmon population were interlinked with each other and revealed the mechanism through which the factors finally affected the salmon population. The second contribution was exploring two different methods that could address the temporal autocorrelation issue when applying SEM. In particular, one of the approaches demonstrated the ability to handle the appearance of both time-lag effects and autocorrelation of a variable within the same model. The last contribution of the study was the application of SEM to a fish population. Including fish in SEM is not novel. However, the existing applications of SEM have involved fish as community biomass to present a functional trait of the ecosystems (Duffy et al., 2016; Lefcheck and Duffy, 2015; Maureaud et al., 2019) but have not analysed the causal relationship with the population of specific fish species.

3.3 Study III: Bridging the gap between ecosystem service indicators and ecosystem accounting in Finland

Study III clarified the mismatch between the Finnish ES indicators, which were developed based on CICES, and the ecosystem accounting within the scope of environmental-economic accounting in Finland. Based on this clarification, this paper proposed a framework to integrate the ES indicators into the ecosystem accounts and demonstrated the integration framework with two Finnish examples: (1) freshwater-related ESs and (2) the ESs of marine fish provisioning. In the freshwater case study, an account of the ecosystem extent and condition was compiled, and a list of freshwater-related ESs in various ecosystems was summarized. The ES supply and use accounts in this freshwater case were only compiled for specific ESs. However, the ES supply and use accounts were compiled with detailed information on the amount of use of the ESs from different sectors in physical and monetary terms. The marine case study, by contrast, only focused on one ES but contributed to providing an example of a full set of marine ecosystem accounts, including the ecosystem capacity and monetary ecosystem asset accounts that were not able to be compiled in the freshwater case study. Using the multispecies MSY as a suitable indicator for the marine capacity account was also first proposed by this case study, even though the linkage between the capacity accounts and ecosystem monetary asset account was not adequately established.

The demonstrated example suggests that the Finnish ES indicators could serve as a basis for ecosystem accounting, but further elaboration and adjustment were needed to make the indicators compatible with the accounting system. The study also pointed out ways in which the Finnish ES database could be improved, such as updating the data regularly, including ecosystem condition data that could aid the evaluation of the ecosystem capacity and ES supply, and developing indicators that could reveal the sustainability of the ES supply. Although the accounts of the case studies were not comprehensive and parts of the results were compromised due to data limitations, the case studies provided clear procedures for following the proposed framework to integrate ESs and accounting systems. Additionally, the study served as a pilot test of how the Finnish ES indicator database could be used for ecosystem accounting.

3.4 Study IV: Valuing marine natural capital with multiple ecosystem services for ecosystem accounting by different valuation approaches

The ESs provided by the same ecosystem may conflict or have synergistic effects with each other, which influences the estimated value of an ecosystem. This research used a case study of the marine ecosystem, which provides provisioning services to commercial herring and salmon fisheries as well as the non-market cultural services of salmon recreational fishing, seal watching and seal existence in the Northern Baltic Sea, to compare different valuation approaches. This study compared three types of value with two approaches that were used to value the ecosystem assets in the accounting context: (1) the approximation value and inclusive wealth (IW) estimated by the value function approximation approach and (2) the ecosystem value estimated by the NPV approach with the future flows of the ESs. In addition, each ecosystem valuation approach was combined with the SEV approach that was used to value the non-market cultural services in the case study.

According to the results, the effects of including the non-market cultural ESs into the ecosystem valuation varied in the different valuation approaches. The IW and NPV were relatively stable compared to the approximation value. The NPV estimated with the 25-year future ES flows was higher than the IW in all simulated scenarios, while the approximation value could be higher or lower than the NPV values and IW in different simulations. The absolute value of the target marine ecosystem was quite different in terms of the IW, approximation value and NPV, but the changes in value reflected that the physical changes in the ecosystem had the same directions and approximate amounts. This study pointed out the pros and cons of each approach. Changes in the IW could directly reflect the value of the stock change and did not necessarily predict the future flows of ESs, which could reduce the uncertainties regarding the assumptions from different future scenarios. The NPV approach, in contrast, was able to more flexibly apply the different components required by the SEEA EEA, while some of the methods for applying the NPV approach might not fully reflect the capital gains that should be included in the ecosystem valuation. Another major advantage of using the NPV approach was that the individual values of the ESs could be revealed, and therefore, trade-offs among different ESs could be observed. The contribution of this study included clarifying the differences among the natural capital valuation approaches that could potentially be used in future SEEA EEA revision and applying the SEV approach with cultural services in a marine case study.

4. Discussion and Conclusion

This thesis applied and combined various modelling, framework, and valuation approaches to address different components and elements of EBM. The covered aspects included multispecies systems with consideration of food web interactions, climate and environmental effects, various human activities with stakeholder conflict, and cross-systems (ecosystems vs economic systems) and cross-sectoral interactions.

While this thesis covered many aspects of EBM, each of the studies and approaches had some limitations and has room to improve to more comprehensively provide information and recommendations. For example, Study II investigated the influences of climate, the environment, fisheries and food web relationships on the salmon population but did not explore the further impacts on economic systems. Therefore, the next step could be to incorporate the results from Study II to extend the bio-economic model developed in Studies I and IV to enable it to include the effects of climate and the environment in simulations or optimization. The developed bio-economic model can also be extended in other directions, such as increasing the trophic levels by involving plankton in the model, broadening the food webs to link to the entire Baltic Sea, and including salmon from other rivers. Such extensions could not only provide more information for EBM but also more comprehensive data for ecosystem accounting. The research related to ecosystem accounting done by this thesis also only decreased the gap between ES and accounting frameworks. Many issues regarding ecosystem accounting remain unsolved. For example, the appropriate method for aligning the scopes of the results from the bio-economic modelling and those of the accounting is related to the research in this thesis and could influence the produced results, but this issue was only briefly touched upon but not deeply explored.

Even though some limitations exist, the different approaches applied in this thesis still provide many insights regarding EBM for the study area. The case studies in this thesis showed the trade-offs between the herring and salmon fisheries, the potential routes for large-scale climate conditions to influence salmon populations with other anthropogenic factors, and the effects of multiple ESs on ecosystem valuation. The results provided information from different angles on the same ecosystems in the Baltic Sea. The variety of the approaches used in this thesis reflected the fact that EBM needs to address many issues from different aspects, and no single approach can solve all issues.

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