SEA CHANGE - Social-ecological co-evolution in Baltic Sea fisheries

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Full fathom five thy father lies,
Of his bones are coral made,
Those are pearls that were his eyes,
Nothing of him that doth fade,
But doth suffer a sea-change,
into something rich and strange,
Sea-nymphs hourly ring his knell,
Ding-dong.
Hark! now I hear them, ding-dong, bell.

W. Shakespeare 1611

§. 1.

Ibland alla land och riken i werlden lårer förmodeligen wårt kära fäderneslands Swerige ega de mästa och härligaste fiske-watn både uti salt- och frisk-sjö; ty merendels alle provincier och landskaper äro så belägne, at de på något ställe til en mer eller mindre del sträcka sig ned antingen til Wäster-hafwet, eller Öster-sjön. Derjemte har hwarje landskap högeligen at fägna sig af många, wakra och fisk-rika älfwar och strömmar, som flyta uti hafwen, och derutur wid sina utlop, såsom ock långt ofwanföre, gifwa oß allahanda slags fisk i myckenhet.

S.T. Schultze 1778

Abstract

Sustainable management of natural resources requires an in-depth understanding of the interplay between social and ecological change. Linked social-ecological systems (SES) have been described as complex adaptive systems (CAS), which mean that they are irreducible, exhibit nonlinear dynamics, have interactions across scales and are uncertain and unpredictable. These propositions have however rarely been tested empirically, in part due to a lack of methodological approaches and suitable datasets. In this thesis, I address this methodological and empirical gap in a study of long-term change of Baltic Sea fisheries. In **Paper I**, we develop the concept of *fishing style* through integrating multivariate statistical analysis and in-depth interviews. We thereby identify an intermediate level of detail for analyzing social-ecological dynamics, embracing the case specific and context dependent approaches of the social sciences with the generalizable and quantifiable approaches from the natural sciences. In **Paper II** we ask: How has the Baltic Sea fishery been regulated over time, and can we identify a way to quantify regulations in order to be able to analyze their effects? We analyze all regulatory changes in Sweden since 1995 with a new methodology and conclude that there is a clear trend towards increased micro-management. In **Paper III**, we use the fishing styles developed in **Paper I** and examine how they have changed over time. We relate these changes to the dynamics of regulation (**Paper II**), as well as to the dynamics of fish stocks and prices. We conclude that regulation has been the main driving force for observed changes, but also that regulation has prompted significant specialization and decline in flexibility for fishers over time. These changes are unintended consequences and may represent a looming risk for the long-term sustainability of this social-ecological system. **Paper IV** zooms in on a particular fishery, the pelagic trawl fishery for sprat *Sprattus sprattus* and Atlantic herring *Clupea harengus*, mainly targeted for the production of fishmeal and fish oil. Suspicions of non-compliance in this fishery motivated us to apply a statistical approach where we used socioeconomic data to re-estimate the historical catches in this fishery (a novel approach to catch-reconstruction estimates). We found that catches had been significantly underreported over several years, with consequences for the quality of stock assessments and management. The study underlines the importance of understanding linked social, economic and ecological dynamics for sustainable outcomes. Finally, **Paper V** takes a longer historical look at the Baltic Sea fishery, using regionally disaggregated data from 1914-2009 (96 years), which were analyzed with a novel type of nonlinear statistical time-series methods (Empirical Dynamical Modeling). Our analysis explicitly recognized the potential nonlinear dynamics of SES and showed high predictability across regions of catches and prices of cod *Gadus morhua* and herring. The signal was generally nonlinear and predictability decreased strongly with time, suggesting that the dynamics of this SES are ever-changing. To our knowledge, this is the first long-term analysis of a SES using empirical data and methods developed from the CAS field of research. The main contributions of this thesis are the integrated analysis of social and ecological data, the development of novel methods for understanding SES dynamics, insights on the ever-changing nature of CAS and the quantitative analysis of management outcomes. Future work should focus on assessing the generality of these findings across a broad range of SES and evaluate alternative governance approaches given the complexity and uncertainty of SES suggested by this thesis.

Key-words: resilience, social-ecological systems, complex adaptive systems, fisheries, Baltic Sea

Sammanfattning

För att långsiktigt uppnå en hållbar resursförvaltning krävs en ökad insikt om de kopplingar som finns mellan sociala och ekologiska processer. Sammankopplade social-ekologiska system har beskrivits som komplexa adaptiva system, vilket innebär att enskilda processer inte kan studeras i isolering, att samband kan vara ickelinjära, att processer på olika skalor växelverkar och att dessa system därigenom är svåra att prediktera. Dessa antaganden har dock sällan undersökts med empiriska data, delvis för att lämpliga metoder och data saknats. I denna avhandling tar jag mig an dessa frågor i en omfattande och detaljerad empirisk studie av förändringar över tid i fisket i Östersjön. I den första artikeln utvecklar vi det analytiska begreppet *fiskestil* genom att integrera en multivariat statistisk analys med intervjuer. I detta begrepp ryms både generaliserbarhet som karaktäriserar kvantitativa analyser, och viktiga kontextberoende faktorer som studier inom kvalitativ samhällsvetenskap brukar belägga, och vi tror att fiskestilar kan vara ett användbart begrepp i studier av dynamiken i social-ekologiska system. I den andra artikeln ställer vi frågan: Hur har Östersjöns fiske reglerats över tid, och finns det sätt att kvantifiera regleringar för att kunna studera deras effekt? Vi analyserar i denna artikel alla regelförändringar sedan Sveriges EU-inträde 1995 och drar slutsatsen att det finns en tydlig trend mot ökad detaljstyrning ("micro-management"). I den tredje artikeln använder vi de fiskestilar vi tidigare utvecklat, och studerar inom dessa hur antal fiskare förändrats över tid. Dessa förändringar försöker vi sedan relatera till förändringar i fiskbestånden, förändringar i försäljningspriser för fisk samt de ovan beskrivna regelförändringarna. Vi konstaterar att regelförändringar har varit den dominerande faktorn. Fiskarena har därutöver blivit alltmer specialiserade på enskilda fiskarter, och de byter alltmer sällan fiskeaktivitet. Med grunden i resiliensteori menar vi att denna specialisering och minskning i flexibilitet utgör ett potentiellt hot mot detta fiskes långsiktiga hållbarhet. Den fjärde artikeln gör ett nedslag i ett specifikt fiske: trålfisket efter skarpsill och strömming. Inom detta fiske, där den största delen av fångsten används som råvara till fiskmjöl och fiskolja, har det från flera håll länge funnits misstankar om regelöverträdelser. Vi valde därför att göra en statistisk analys, där vi använde socio-ekonomiska data för att uppskatta de historiska fångsterna. Våra resultat visar på en omfattande och systematisk felrapportering av både mängden fisk och fördelningen skarpsill/strömming. Detta har stora konsekvenser för den beståndsanalys som ligger till grunden för fiskeripolitiska beslut, eftersom den delvis bygger på de rapporterade fångsterna. I den femte artikeln analyserar vi fisket i Östersjön utifrån ett långtidsperspektiv. Vi använder fångst- och prisstatistik från svenska län från år 1914 till 2009, och analyserar dessa med en ny typ av ickeparametriska tidsseriemetoder, *Empirical Dynamical Modeling*. Med denna analysmetod visar vi på en deterministisk, ickelinjär dynamik i tidsserier av fångster och priser hos sill och torsk. Analyserna fungerande bättre på korta än långa tidsintervaller, vilket tyder på att dynamiken i detta social-ekologiska system långsamt förändras över tid. Utifrån vad vi känner till är detta första gången långtidsförändringar i ett social-ekologiskt system analyseras empiriskt med metoder sprungna ut teorin om komplexa adaptiva system. Det viktigaste denna avhandling bidrar med är den integrerade analysen av sociala och ekologiska data, utvecklandet av nya metoder för att förstå social-ekologiska system, insikter i hur komplexa adaptiva system förändras över tid, samt den kvantitativa analysen av förvaltningens effekter. Framtida forskning bör undersöka hur allmängiltiga dessa resultat är för andra social-ekologiska system och därtill utifrån de stora osäkerheter och den komplexitet som verkar utmärka social-ekologiska system utforska tänkbara alternativ till dagens resursförvaltning.

Nyckelord: resiliens, social-ekologiska system, komplexa adaptiva system, fiske, Östersjön

Contents

Glossary and abbreviations

	Abbr.	Meaning
Complex Adaptive System	CAS	A conceptualization of systems recognizing interactions at multiple scales, where local self-organization create emergent behavior at larger scales, feeding back into continuous adaption and dynamics
Common Fisheries Policy	CFP	The European Union fisheries policy
Empirical Dynamical Modeling	EDM	Method for nonlinear analysis of time series
Exclusive Economic Zone	EEZ	Part of the ocean within 200 nautical miles from the coast where the individual nations have the sovereign right to use the living resources
Governance		Policy-making broadly defined, including the division of power between different institutions and the actors in the system, the legislative framework and the actual regulations in place (cf. Management)
Individual Transferable Quota	ITQ	A fisheries management tool where the fishing quota is distributed to individual fishers; synonymous with catch shares
Management		The type of regulations and other measures applying to actors in a system, as decided by the relevant governing bodies (cf. Governance)
Maximum Sustainable Yield	MSY	A concept originating from population ecology specifying an optimal abundance or mortality level of fish in order to maximize long-term harvest
Natural Resource Management	NRM	A scientific discipline exploring how to achieve sustainable long-term use of natural resources
Resilience		The capacity of a system to maintain a similar function, identity and feedbacks under changing conditions and disturbance
Sustainability		An outcome where current practices are likely to assure future benefits, i.e. to not risking collapse or decline
Social-Ecological System	SES	A way of analyzing sustainability which considers humans and nature as tightly linked and interacting in both directions
Total Allowable Catch	TAC	The total fishing quota for a given year

Species names

English	**Scientific**	**Swedish**
(Atlantic) cod	*Gadus morhua*, L. 1758	torsk
(Atlantic) herring	*Clupea harengus*, L. 1758	sill/strömming
(European) eel	*Anguilla anguilla,* L. 1758	ål
(European) sprat	*Sprattus sprattus*, L. 1758	skarpsill
Great cormorant	*Phalacrocorax carbo sinensis*, L. 1758	storskarv
Grey seal	*Halichoerus grypus,* Fabricius 1791	gråsäl

Papers included in this thesis

Paper I
Boonstra WJ, **Hentati-Sundberg J**. 2015. Classifying fishers' behaviour. An invitation to fishing styles. *Fish & Fisheries* (published online). DOI: 10.1111/faf.12092

Paper II
Hentati-Sundberg J, Hjelm J. 2014. Can fisheries management be quantified? *Marine Policy* 48: 18–20. doi: 10.1016/j.marpol.2014.02.021

Paper III
Hentati-Sundberg J, Hjelm J, Boonstra WJ, Österblom H. 2015. Management Forcing Increased Specialization in a Fishery System. *Ecosystems* 18: 45–61. doi: 10.1007/s10021-014-9811-3

Paper IV
Hentati-Sundberg J, Hjelm J, Österblom H. 2014. Does fisheries management incentivize non-compliance? Estimated misreporting in the Swedish Baltic Sea pelagic fishery based on commercial fishing effort. *ICES J Mar Sci* 71 (7): 1846-1853. doi: 10.1093/icesjms/fsu036

Paper V
Hentati-Sundberg J, Deyle E, Ye H, Österblom H, Hjelm J & Sugihara G. Strong nonlinearities in an ever-changing social-ecological system: A data-driven empirical study of the historical development of the Baltic Sea. Manuscript.

In **Paper I**, my co-author conceived the original idea. We developed the idea together, I made the quantitative (multivariate) analysis and we wrote the paper together. In **Paper II**, both authors developed the idea together, and I did the whole analysis and wrote most of the paper. In **Paper III** I came up with most of the ideas, did the complete statistical analysis and wrote much of the paper. **Paper IV** is loosely based on work I did for my MSc thesis, and the ideas were developed together with my co-authors. I did the whole analysis and wrote most of the paper. In **Paper V**, I conceived the original ideas, but my co-authors helped me develop the analytical approach. I did the whole analysis, based on data in national archives I digitized, and wrote most of the paper.

Paper IV is loosely based on my MSc thesis, "Policy-driven non-compliance in the Baltic Sea" from Stockholm University 2011. Earlier versions of **Paper III-IV**, and the analysis in **Paper II**, were part of my Licentiate thesis "Social-ecological dynamics in a highly regulated fisheries system - Sources of resilience and limits to command-and-control management" from Stockholm University 2013.

Other contributions

This section lists other work that is not directly part of this thesis but addresses related issues.

1. Factors driving non-compliance in fisheries, and solutions to achieve compliance:

Österblom H, Sumaila U, Bodin O, **Hentati-Sundberg J**, Press AJ. 2010. Adapting to regional enforcement: fishing down the governance index. *PLoS One* 5: e12832.

2. Seabirds as indicators of change in the Baltic Sea, and cascading ecological effects:

Hentati-Sundberg J, Österblom H, Kadin M, Jansson Å, Olsson O. 2012. The Karlsö Murre Lab Methodology can Stimulate Innovative Seabird Research. *Marine Ornithology* 16: 11–6.

Kadin M, Österblom H, **Hentati-Sundberg J**, Olsson O. 2012. Contrasting effects of food quality and quantity on a marine top predator. *Mar Ecol Prog Ser* 444: 239–49.

Cross ADP, **Hentati-Sundberg J**, Österblom H, McGill R A R, Furness RW. 2014. Isotopic analysis of island House Martins Delichon urbica indicates marine provenance of nutrients. *Ibis* 156: 676–81.

3. Cross-scale interactions in fisheries systems:

Crona B, Daw TM, Swartz W, Norström A V, Nyström M, Thyresson M, Folke C, **Hentati-Sundberg J**, Österblom H, Deutsch L, Troell M. 2015. Masked, diluted and drowned out: how global seafood trade weakens signals from marine ecosystems. *Fish & Fisheries* (published online), doi: 10.1111/faf.12109

Lade SJ, Niiranen S, **Hentati-Sundberg J**, Blenckner T, Boonstra WJ, Orach K, Quaas M, Österblom H, Schlüter M. 2015. An empirical model of the Baltic Sea reveals the importance of social dynamics for ecological regime shifts. *PNAS* 112: 11120–5.

Introduction

About forty years ago, the Baltic Sea cod fishery experienced its best period for decades. There were fish everywhere, catches were plentiful and investments were made in new vessels, improved technology and infrastructure for fish processing. These new opportunities represented a welcome switch in focus from the troubled Baltic herring fishery, which had struggled with low profitability due to low prices and too many vessels chasing too few fish. Particularly, the situation for the Swedish offshore fleet had deteriorated since Sweden lost much of its North Sea fishery after the establishment of the Exclusive Economic Zones (EEZs) and the closing of the North Sea herring fishery in the early 1970s. For the offshore fleet, but also for the struggling small-scale Baltic Sea fishers, Baltic cod became a true salvation. People living around the Baltic Sea remember this period as a very special time, when one could just put some potatoes to boil, then go out and catch some cod for dinner.

But what glory days last forever? After a peak in 1981, cod catches started to decline rapidly. Fishers that had made the investment of their lives in modern vessels were suddenly on the brink of bankruptcy. Management authorities also started catching up and introduced the first internationally negotiated fishing quotas for cod, based on scientific advice from a new generation of Baltic Sea fisheries scientists. Opportunities seemed to cease and the future appeared bleak.

However, the Baltic Sea may have other, untapped opportunities. A group of fishers whose fishing grounds were previously outside the Baltic Sea started catching a new fish that suddenly appeared in great numbers: sprat. Sprat was sought after to produce fishmeal to a booming international market. This market was in turn fuelled by an emerging aquaculture industry including Norwegian salmon. In the aftermath of the events of the late 1980s and early 1990s, science suggests an ecological regime shift occured, where sprat replaced cod on the throne of the Baltic Sea ecosystem. Scientists have argued that high sprat abundance can even prevent recovery of cod because sprat eat cod eggs and compete with young cod for food. Despite this, most fishers continued have their (often inherited) cod fishing practices, hoping that the cod stock will eventually recover.

The low water mark for the Baltic cod population was reached in 2005, with biomass only a tenth compared to the peak years. At the same time, policy development - notably the EU membership of all Baltic Sea countries except Russia - created a stronger new framework for the management of shared natural resources. For the Baltic cod, the 18th September 2007 marked a unique day in history, when EU leaders signed the first international, science-based management plan. The cod population responded faster then anyone would have expected. Just three years later, the population had increased so much that even the scientists were surprised. This rapid recovery was primarily attributed to more fishers following the rules.

But then the party ran out of steam. The two most recent reports by the International Council for the Exploration of the Sea (ICES) have transformed the success story into a new disaster. The fish stock assessment, the backbone of present-day fisheries management, has not been able to produce reliable estimates of cod abundance. Suddenly, cod growth appears to be the main problem. Fishers report that the majority of the cod caught are so small that they cannot be landed legally. For three years in a row, Baltic fishers have landed less fish than the quotas allow - a real oddity in fisheries today. The imports of cod from the healthy Barents Sea stock, which has flooded the Swedish market and brought down the sales prices for Baltic cod, has also been a contributing factor.

In the meantime, the fishers that switched to sprat and herring some twenty years ago - when the cod started to decline - are doing better than ever. At one point, they had to choose whether to continue with cod fishing or switch permanently to sprat and herring. The most entrepreneurial fishers choose the latter path. After a minor crisis with overcapacity in the pelagic fleet, this sector has entered a regulatory system where fishers are afforded their own private share of the quota, and can thereby plan their fishing more rationally. Importantly, this has also led to a rapid reduction of the fleet size. The sprat and herring fishers are expanding to other countries, and due to the design of the rights provided to them are not threatened by fishers establishing competing activities in the Baltic. Possibly, they also benefit from an ecosystem that has permanently switched to a sprat-dominated state, which may secure good future fishing opportunities into the future[1].

* * *

I present these events in a narrative form because they succinctly illustrates three key challenges in contemporary natural resource management:

1. **The interactions between social and ecological factors.** The Swedish North Sea pelagic fleet moved to the Baltic Sea and participated in the cod bonanza, then switched to sprat, and eventually created their own management system where they enjoy individual harvesting rights. Other fishers continued to fish cod fishing despite declining profitability. Improved international management in the mid 00s increased the compliance of the fishing industry, which contributed to the rapid recovery of the cod stock. Apparently, human actors are dynamic, heterogeneous, and change their behavior for various reasons.

   Research questions:

   How can such dynamic human behavior be explained and studied in a NRM context? (Papers I and IV)

   How can qualitative social data be methodologically integrated with quantitative social and ecological data? (Papers II and III)

2. **Complex adaptive system features of fisheries.** Cod was extremely abundant in the 1970s and this phase in history is today widely considered the desired state of the Baltic Sea ecosystem. The cod collapse appeared to lead to a sprat increase, whereas the role of herring is less well understood. These findings challenge the assumption that nature exists in equilibrium, upon which management focusing on optimal harvest levels for single species is based. For the moment, Baltic Sea cod is in a situation of distress, which has greatly surprised management authorities. This illustrates that even in a seemingly well-understood system, new uncertainties can arise - with profound ecological and economic consequences. The current cod fishery problems are also due to Barents Sea cod flooding the market, showing the importance of interactions that operate across geographical scales. The possible nonlinearities, uncertainties and interactions across scales suggest that social-ecological systems may behave as complex adaptive systems.

   Research questions:

   How do processes operating across different temporal and spatial scales affect the behavior of social-ecological systems? (Paper II-IV)

   How can non-linear and non-equilibrium dynamics be studied empirically? (Paper V)

3. **Governing social-ecological systems.** Over the course of around forty years, the Baltic Sea cod fishery has gone from being virtually unregulated (but stimulated by generous subsidies) to strongly regulated at both national and international levels. The sprat and herring fishery has recently undergone a transformation to a more self-organized individual quota system.

[1] This narrative is based on the following references: SOU 1977, EC 2007, Casini et al. 2008, 2009, Eero et al. 2012, 2015, Berggren 2013, Lade et al. 2015, Paper I and III in this thesis.

Research questions:

Can the effects of different types of management be empirically evaluated with regard to sustainability of fish stocks, and more broadly to the resilience of social- ecological systems? (Papers III and IV)

What type of governance is robust to dynamic and changing social-ecological systems? (Papers I-V, Discussion section)

This thesis aims to provide answers to these questions. After theoretically situating this research (Theory section), I describe why fisheries in the Baltic Sea represent a unique case for investigating these broad questions. This uniqueness is based on the: i) Highly variable and well-researched long-term ecological dynamics; ii) Availability of long-term and detailed social-ecological data, iii) Heterogeneity across space and within different groups of fishers, allowing for deep within-case comparisons, iv) Distinct phases of management over time allowing for temporal comparisons. In the Discussion section I reflect on my findings in terms of their generality across in fisheries and social-ecological systems, discuss governance challenges, and suggest areas of future inquiry.

Theory

A brief account of the evolution of *science-based* natural resource management

Natural resource management (NRM) has developed as a discipline from a growing recognition of the importance of natural resources for human well-being. Although there are many examples of historical animal population collapses due to overexploitation (Jackson et al. 2001, Pauly et al. 2002) and other type of natural resource misuse leading to devastating consequences for humans (e.g. Janssen and Scheffer 2004), the increasing human population and the globalization of technologies and trade, has transformed NRM from being a primarily local to a global challenge.

The fundaments in traditional science-based NRM build on earlier mathematical work on the dynamics of animal populations. The interest in this subject was triggered in the 1950s in the search for ways to maximize nature's benefits to the human society (e.g. Borgström 1966). Early population ecologists developed simple mathematical models to understand how species productivity was related to abundance and mortality, and produced the first quantitative propositions on the optimal population levels (and later, mortality levels) in order to maximize long-term harvest of a species (Beverton and Holt 1957). This number became known as the Maximum Sustainable Yield (MSY). In short, MSY management is based on the insight that growth of a harvested population is highest at intermediate population levels (B), or at certain levels of fishing mortality (F). The calculation of management targets for MSY-type management tends to assume that populations are separate and have single population equilibrium levels (Larkin 1977).

The idea that a maximal harvest level could be mathematically established using relatively simple calculations, and managed for maximum benefits to people, proved to be extremely powerful. MSY is today integrated across all levels of fisheries management worldwide, here exemplified in the UN Convention of the Law of the Seas (Article 61, Paragraph 3):

> Such measures [i.e. management measures to prevent overexploitation] shall also be designed to maintain or restore populations of harvested species at levels which can produce the maximum sustainable yield, as qualified by relevant environmental and economic factors, including the economic needs of coastal fishing communities and the special requirements of developing States, and taking into account fishing patterns, the interdependence of stocks and any generally recommended international minimum standards, whether subregional, regional or global.

This has been implemented in the European Union Common Fisheries Policy (EC 2013) in the following way (Article 2, Paragraph 2):

> The CFP shall apply the precautionary approach to fisheries management, and shall aim to ensure that exploitation of living marine biological resources restores and maintains populations of harvested species above levels which can produce the maximum sustainable yield.

And in the United States in the Magnuson-Stevens act (NOAA 1996) as follows (Article 104-297):

> (5) Fishery resources are finite but renewable. If placed under sound management before overfishing has caused irreversible effects, the fisheries can be conserved and maintained so as to provide optimum yields on a continuing basis. (paragraph 5)

> (28) The term "optimum", with respect to the yield from a fishery, means the amount of fish which [...] is prescribed as such on the basis of the maximum sustainable yield from the fishery, as reduced by any relevant economic, social, or ecological factor (paragraph 33 B)[2]

Nevertheless, despite being a dominant paradigm in western natural resource policy, the MSY concept has always been controversial, as exemplified by the famous critique from the prominent fisheries ecologist Peter Larkin in the mid 1970s (Larkin 1977). Without going into a review of the debate and evolution of the MSY concept, the next sections summarize some of the scientific advances since the 1960s (modern population and ecosystem ecology, social-ecological systems research, resilience) that constitute important building blocks for contemporary and future NRM, and that forms the theoretical foundations of this thesis.

New NRM perspectives - modern population and ecosystem ecology

Mathematical work by Robert May in the 1970s on the dynamics of animal populations started to challenge some of the fundaments that had informed earlier approaches to NRM. May showed that very simple mathematical models (1-2 difference equations representing different species) could produce very complex behavior, including stable limit cycles of different periods, and chaos (May and Oster 1976, May 1976). He also showed that only two interacting species are required for a system to exhibit multiple equilibriums - i.e. stable states in terms of population abundances to which a system would return after a small disturbance (May 1977). C.S. Holling, a theoretical ecologist and a contemporary of May, followed up early theoretical and empirical work on different forms of functional responses between species - showing different non-linear shapes (Holling 1959) - to investigate the dynamics of insect outbreaks. He linked an extensive empirical study to mathematical models and again showed, together with his co-authors, again the existence of multiple stable states (Ludwig et al. 1978). What was new in this analysis was the separation in the modeling of slow (tree cover) and fast processes (insect abundance) as a key to understanding long-term dynamics of the coupled system. Under some circumstances, reaching a critical levels of a slow variable may create a rapid shift in the state of a system. These points are referred to as thresholds or tipping points.

The theoretical motivation behind tipping points, alternative stable states and transient behavior in food-webs and ecosystems has consequently been around for nearly 40 years. In the last 15 years or so, this has been complemented by increasing empirical evidence of tipping points and multiple stables states, in the context of food-webs (Price and Morin 2004, Persson et al. 2007, Ives et al. 2008, Fauchald 2010) and whole ecosystems (Scheffer et al. 2001, Scheffer and Carpenter 2003, Folke et al. 2004, Scheffer 2009).

This theoretical and empirical basis for nonlinear and non-equilibrium dynamics motivates why I in this thesis have tried to apply analysis procedures that do not assume linearity and stability.

The importance of social-ecological interactions

NRM developed from theoretical understanding of ecological dynamics, treating human influence as an external and typically one-directional impact (such as harvest level of a resource). More recent research on ecosystem perspectives in NRM also tends to treat humans as factors that are external to the system (Garcia and Charles 2008). This under-appreciation of social dynamics may be partly due to the influential idea from economics on NRM that individually rational human actors will inevitably overexploit common pool resources under open-access conditions (Hardin 1968) - which has focused research efforts towards developing tools that may mitigate human impacts

[2] Larkin (1977) discusses the idea of replacing "maximum" with "optimum" in order to silence all sorts of criticism of the MSY concept without changing the fundaments. According to Larkin, “optimum” makes the whole definition essentially meaningless. The result of the first deliberations to find alternatives to MSY, became "an eclectic mishmash that was all things to all people" (cf. definitions in the current CFP and in the Magnuson-Stevens fisheries act).

I see mainly two general, related problems with the analytical separation of nature and humans. First, evidence has accumulated suggesting that societies, counter to predictions, do not always over-exploit natural resources in the absence of strong economic incentives or government regulations (Ostrom 1990). This has created a stream of research investigating conditions under which people collectively solve commons problems (Hanna et al. 1996, Berkes and Folke 1998, Berkes et al. 2003, Ostrom 2009). Second, state regulation and privatization has not always managed to solve commons problems, despite good intentions (Ludwig et al. 1993, Walters and Maguire 1996, Myers and Worm 2003, Worm et al. 2006, MacKenzie et al. 2009, Österblom et al. 2011). One of the pressing issues has been to achieve compliance with regulations by the actors involved, but also to provide good enough scientific data and design appropriate measures to limit over-exploitation. Scientists have consequently investigated possible alternative pathways to achieve sustainability focusing both on issues of compliance (e.g. Sutinen and Kuperan 1999), improving the science-base for decisions (Botsford et al. 1997, Pikitch et al. 2004), and identifying alternative approaches such as co-management (Jentoft et al. 1998, Jentoft 2007) and rights-based management approaches (Hannesson 1991, Costello et al. 2008).

Further, there is a more practical argument for turning scientific attention to the dynamics of human-nature couplings. Today, there are very few pristine ecosystems (Ellis and Ramankutty 2008, Halpern et al. 2012). Human influence is everywhere and has influenced the dynamics of ecosystems for decades or even centuries (before scientific studies) (Pauly 1995, Jackson 2001), which means that understanding sustainability challenges requires paying attention to both current and past social dynamics. One illustrative example is the Maine fishery, where the collapse of the groundfish populations has led to increased lobster abundance and thereby a switch in the fishery. Lobster fishers are now making much money in this degraded ecosystem and have a strong stake in maintaining the current system state despite its vulnerability (Steneck et al. 2011). The perceptions of the actors in this system clearly matter if the fishery is to be managed sustainably in the future. More generally there is a need to understand drivers and motifs of human behavior and how these relate to current contextual factors such as the ecosystem state, economic and policy conditions (Branch et al. 2006, Fulton et al. 2011, van Putten et al. 2012), but also how they are shaped by historical legacies.

In order to achieve greater understanding of coupled humans-nature dynamics in NRM, it is necessary to bridge the rich knowledge obtained in ecological studies with the increasing interest in understanding how ecosystem change relates to social factors. Overcoming the current epistemological and methodological gap between social science and natural science research on sustainability could potentially lead to more in-depth and practically useful scientific knowledge. In this thesis I explicitly integrate social-ecological data in the analyses and attempt to bridge different scientific traditions by using novel methods and research designs.

Resilience thinking

Resilience perspectives on social-ecological systems have made significant contributions to sustainability science in recent decades. According to a recent definition (Folke et al. 2010), resilience is:

> The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks, and therefore identity, that is, the capacity to change in order to maintain the same identity.

A key tenet of resilience research is that humans and nature constitute linked and dynamic social-ecological systems (SES). Such systems are argued to function as Complex Adaptive Systems (CAS) based on the following theoretical propositions (Levin et al. 2012):

- SES consist of several hierarchical scales. Those scales could be individual fish, schools, fish populations, or individual fishers to fleets up to a fishery. Systems tend to self-organize based on low-level processes, creating so called emergent properties at a higher level of the system. For example, schooling behavior in fish arises from simple rules of movement in individual fish, and the individual decision-making of fishers creates higher-level system outcomes such as an over-harvested fish stock, which again feed back into a new decision-making situation for the individual fisher.

- Interactions in ecosystems and social-ecological systems can create nonlinearities, as shown in population and ecosystem ecology. A system can have multiple states, each of them reinforced by stabilizing feedbacks.

- Social factors such as policy, technology and communication make social-ecological systems more complex than ecosystems (Holling 2001). This level of complexity suggests that social-ecological relations will be highly dynamic and unpredictable, posing significant challenges for knowledge about and management of natural resources.

Promisingly, indication is that there seem to be generic properties of CAS (including ecological, economic and social systems) (Gunderson and Holling 2002, Scheffer and Westley 2007, Scheffer 2009) that provides a possible basis for developing the basic understanding needed for managing such complex systems.

Specifically, accumulated resilience research over the past few decades suggests several key aspects of sustainable ecosystem management. A recent synthesis of insights from resilience in SES identified seven principles (Biggs et al. 2015b):

1. Maintain diversity and redundancy
2. Manage connectivity
3. Manage slow variables and feedbacks
4. Foster complex adaptive systems (CAS) thinking
5. Encourage learning
6. Broaden participation
7. Promote polycentric governance

Principles 1-3 are most relevant for this thesis. I briefly review the theory underlying them below.

Diversity and redundancy

Diversity denotes several related but distinct properties of a system: (i) the number of different components (such as species); (ii) the evenness in the frequency of such components (such as abundance of different species), and; (iii) the difference in character between those components (with difference denoting for example properties of species such as diet or habitat requirement) (Kotschy et al. 2015). The differences between these properties are captured in the term *response diversity* (Elmqvist et al. 2003), denoting the different ways species - including humans in a SES - will respond to a given stressor. Redundancy denotes a system property related to diversity: the degree to which similar system components, such as species, are fulfilling the same function (Walker 1992). For example, if energy from zooplankton to upper trophic levels in an ecosystem is performed by only one planktivore fish species, there is lower redundancy than in a more species-rich food-web.

Ecologists have debated the relationships between diversity, stability and productivity in ecosystems for decades (Yodzis 1981, McCann 2000, Montoya et al. 2006, Tilman et al. 2006). The definition of stability appears to be one of primary the reasons for disagreement. One of the most important contributions to this debate from an SES perspective is the adaptive cycle for CAS introduced by Gunderson and Holling (2002) in the book "Panarchy. Understanding Transformations in Human and Natural Systems". Gunderson and Holling suggest that CAS move through ever-changing phases of growth, stagnation, release and renewal, and that stability is a system property that changes as a part of an evolving system. In short, the adaptive cycle proposes that stability decreases with accumulating potential and connectivity (such as in an old-grown forest), increasing the likelihood of a sudden collapse such as an insect outbreak or a forest fire. This collapse then releases "capital" (e.g. carbon, nutrients, space) and creates a new path for the system, in a similar or different trajectory (Gunderson and Holling 2002).

Defining stability and relating it to ecosystem service provisioning in a SES is likely an even more delicate question than in a purely ecological sense, because the definition of stability and desirability of ecosystem service production from SES are inherently normative questions (Steneck et al. 2011, Schoon et al. 2015). Here, response diversity of humans may be an important measure to identify whether a SES is resilient or vulnerable to change (Elmqvist et al. 2003). The evidence so far from the resilience literature suggests that an intermediate level of diversity and redundancy is desirable, because an overly connected and redundant SES becomes inefficient, with large amounts of energy required to maintain existing structures such as parallel (i.e. redundant) bureaucracies (Kotschy et al. 2015).

Recently identified research gaps include: i) finding ways to (empirically) measure diversity and redundancy in SES, ii) exploring how different aspects of diversity such as variety and evenness are related, and, iii) examining how different levels of diversity and redundancy affect the sustainable production of ecosystem services (Kotschy et al. 2015).

Furthermore, a relatively neglected area of research is how aspects of diversity and redundancy evolve over time in relation to internal and external processes impacting SES. Much of the ecological literature treats diversity and redundancy as a static system feature rather than a characteristic that constantly evolves (but see Gunderson and Holling 2002). Treating diversity and redundancy as dynamic properties possible to manage for, being at the same time closely linked to the development of a SES as a whole, will likely help identify ways to manage for desired levels of diversity in order to sustain ecosystem service flow in SES.

Connectivity

Connectivity refers to the interactions between different elements in a system, such as how species interact in a food web or how humans are connected different ways through, for instance, direct communication or business relations. Connectivity has been identified as a critical feature that affects the resilience of ecosystems (Nyström and Folke 2001) and SES (Dakos et al. 2015). Theoretical work, complemented by a small number of empirical studies, has identified two contrasting faces of connectivity: i) High connectivity can risk the spread of collapse (Gunderson and Holling 2002, Satake et al. 2007, May et al. 2008, Bodin and Prell 2011); ii) High connectivity may enhance recovery after disturbance – a dynamic well-known from population ecology (Hanski 1991) but also seen in recovery of ecosystems (Nyström et al. 2008, Brudvig et al. 2009, Dakos et al. 2015). One critical aspect appears to be the type of connectivity, which could be operationalized as the structural configuration of the network of interactions. Modularity (also termed compartmentalization) refers to the degree of connection between sub-parts within a larger network. High modularity appears to increase system resilience (Stouffer and Bascompte 2011), but apparently comes at a cost of lower general connectivity (Levin et al. 2012). Consequently, as with diversity, there is likely not any optimal level in order to maximize resilience, stability or any other system feature. Rather, a management strategy should try to learn about the system and thereby find a suitable balance between diversity, redundancy, connectivity and modularity for sustainable outcomes (Levin et al. 2012).

Slow variables and feedbacks

As discussed above, change in ecosystems and SES does not always happen smoothly. On the contrary, collapses of species or whole ecosystems often occur suddenly, triggered by small changes in driving variables. In such cases a slow variable reaches a tipping point and the system state rapidly changes, creating a qualitatively new system with new stabilizing feedbacks (Carpenter et al. 2001, Folke et al. 2004, Biggs et al. 2009, Nyström et al. 2012, Dakos et al. 2014). Evidence is accumulating that regime shifts have occurred in a broad range of SES, often with significant effects on ecosystem services (Rocha et al. 2015).

Key in managing slow variables is to understand how social-ecological feedbacks operate and to identify system-specific key variables in order to assess resilience. In some well-researched aquatic and terrestrial ecosystems, key feedbacks and tipping points are understood and can thereby be monitored and used in management (Biggs et al. 2015a). In a SES context, however, there is much less research, very few empirical studies, and knowledge is in an early phase of development (but see Steneck et al. 2011).

Consequently, there are research gaps in terms of identifying the feedbacks that maintain desirable states. Identifying these important feedbacks is a first step towards using slow variables and tipping points in management, something that has been acknowledged but seldom operationalized, probably due to the fact that the whole idea of complex feedbacks and nonlinearity goes against current reductionist management approaches (Biggs et al. 2015a). Identifying the feedbacks stabilizing *undesirable* states is of course equally important in order to find leverage points for transformations towards sustainability (Holling 2001, Nyström et al. 2012).

In conjunction with these broad research needs, there is a methodological challenge in how to actually identify social-ecological feedbacks. A feedback is a form of causal (two-way) relationship between two or more variables, and identifying causality in complex systems is a large, yet sometimes ignored research topic (but see Sugihara et al. 2012).

A note on sustainability definitions in relation to current management

The previous sections have discussed the fundamental knowledge requirements and knowledge gaps in order to understand sustainability from a social-ecological resilience perspective. In this section I want to highlight a more practical aspect that this thesis work relates to, namely the policy goals in fisheries (and more broadly, for the marine environment). It is necessary to understand these goals in order to empirically analyze this SES and make sense of current management.

In the European Union Common Fisheries Policy (CFP) the goals are summarized in Article 4 (EC 2002):

> The objective of the Common Fisheries Policy should therefore be to provide for sustainable exploitation of living aquatic resources and of aquaculture in the context of sustainable development, taking account of the environmental, economic and social aspects in a balanced manner.

This text has been re-written in the current version of the CFP (EC 2013), Article 4, and has become increasingly convoluted:

> The CFP should ensure that fishing and aquaculture activities contribute to long-term environmental, economic, and social sustainability. [...] Furthermore, the CFP should contribute to increased productivity, to a fair standard of living for the fisheries sector including small-scale fisheries, and to stable markets, and it should ensure the availability of food supplies and that they reach consumers at reasonable prices. The CFP should contribute to the Europe 2020 Strategy for smart, sustainable and inclusive growth, and should help to achieve the objectives set out therein.

Both quotes illustrate a view of sustainability where social, ecological and economic sustainability are seen as three equally important legs, reflecting the original formulation in the Brundtland report (World Commission on Environment and Development 1987). This type of sustainability definition ignores the fact that ecological sustainability is the fundamental requirement for social and economic sustainability. This has frequently led to policy decisions that have benefitted short-term economic profitability and employment at the expense of ecological sustainability (Daw and Gray 2005, Khalilian et al. 2010, Österblom et al. 2011). Policy driven by such goals has, for example, frequently implemented subsidy programs to sustain struggling fishing industries and thereby effectively funded over-exploitation (Sumaila et al. 2010).

In contrast to the current view on sustainability in European fisheries policy, I would in line with several recent authors argue that ecological sustainability is a fundamental requirement for social and economic development in the long-term (Figure 1). In other words, I suggest that while social and economic processes are often very important to understand in order to assess sustainability and resilience, social and especially economic sustainability of a particular system should not be used to discount the sustainability of the underlying, life-supporting, ecosystem (Folke et al. 2004, Fischer et al. 2007, Rockström et al. 2009).

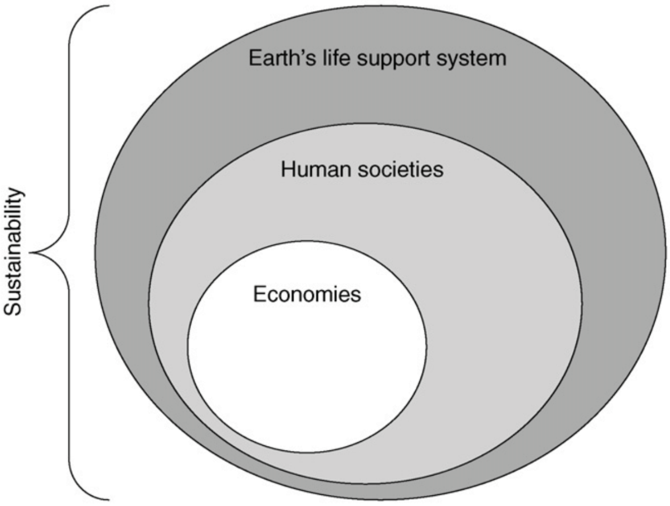

Figure 1. Defining sustainability based on a hierarchical model, were human societies are acknowledged to critically depend on the earth life support system, and where economies are subsets of the social system. Reproduced from (Fischer et al. 2007).

Governance approaches for achieving sustainability

The ultimate goal for the scientific discipline of NRM is to find ways to sustainably govern natural resources. Past governance also influence the observed sustainability outcomes. To conclude the theory section, I want to briefly describe two broad categories of practices with regard to how rules are set and how responsibility is distributed between actors in the system: top-down and bottom-up approaches. I briefly summarize the assumptions upon which each approach is based and the type of knowledge that is required for their implementation. As I will show later there also exist combinations of top-down and bottom-up governance approaches.

Top-down approaches

Hardin (1968) described open access situations of common pool resources as an example of the 'tragedy of the commons,' where individually rational behavior will inevitably lead to over-exploitation. This leaves managers with two options: state-control or private ownership.

Out of these two, state-control has arguably been the dominating paradigm in fisheries management, usually in conjunction with some sort of scientific stock analysis in order to ensure sustainable exploitation. Measures taken to limit exploitation have included combinations of fishing license requirements, catch quotas, fishing effort limitations, closed areas and technical measures, such as gear restrictions.

Key for success in an approach relying on state control is ensuring compliance with regulations, which usually requires significant resources for surveillance (Arnason et al. 2000). This requirement is relaxed in approaches relying on ownership, such as individual quotas or catch shares, because they intrinsically solve the commons problem by aligning personal (economically rational exploitation) and system-wide (stock persistence) incentives. There is empirical evidence suggesting that privatizing ownership in terms of stock sustainability can produce positive outcomes (Costello et al. 2008).

The merits of top-down approaches to management rely on the scientific capacity to predict the complex behavior of ecosystems. In current fisheries management, the models of fish stocks that inform decision-making are often heavily simplified, ignoring possible tipping points and species interactions (Larkin 1977). Management based on this scientific approach will focus on optimal control and, it has been suggested, may decrease resilience by limiting natural variability (Holling and Meffe 1996, Carpenter et al. 2015).

Bottom-up approaches

Bottom-up approaches to NRM acknowledge the self-organizing features of CAS. Proponents of bottom-up driven governance have showed that over-exploitation is not always the rule in cases where state-control is absent or when resources are not privately owned (Ostrom 1990). Research have found several ecological (size, productivity and predictability of the resource system, and mobility of the resource units), governance (existence of collective decision rules) and social (number of users, social capital, leadership, knowledge and resource reliance) features that contribute positively to the self-organizational capacity of SES (Ostrom 2009).

Yet it is clear that many local successes of bottom-up management are successful precisely because they are local, with few users in a relatively small resource system and with high level of social capital (Berkes and Folke 1998, Ostrom 2009). The challenge is therefore to investigate the circumstances under which such local successes can be scaled up, and how their future sustainability can be secured in a globalized world with increasing teleconnections linking local resources to global drivers such as trade (Crona et al. 2015a, 2015b, Eriksson et al. 2015) and even financial markets (Galaz et al. 2015).

Combinations

Integrative frameworks that combine top-down and bottom-up approaches are emerging. In a framework that explicitly acknowledges the CAS properties of fisheries (Mahon et al. 2008), the term 'fisheries chain' is used to describe the level of complexity of the fishery in terms of, among others, target species (multi-species fisheries are more complex than single-species fisheries), system boundaries (more complex when there is poor correspondence between ecosystem and administrative boundaries) and number of fishing units (more fishers makes it more complex). This framework promotes a mix of top-down and bottom-up approaches, with a larger emphasis on bottom-up approaches in the more complex fisheries chains.

Integration of top-down and bottom-up approaches has also been discussed within the frameworks of adaptive management and adaptive governance, and although the focus has been on tools to build self-organizational capacity for bottom-up management (Folke et al. 2005), research has also explored strategically combining optimization with resilience thinking in the context of conservation planning (Fischer et al. 2009).

Research approach

In the Introduction section, I presented the Baltic Sea cod fishery, which illustrates that NRM challenges are dynamic, ever-changing and on-going. The theory section then identified a range of outstanding applied and theoretical questions that need to be addressed in order to improve knowledge towards the achievement of sustainability goals in marine ecosystems. Building on this, my research approach analyses natural resource dynamics in the following ways:

1. *Empirically*, motivated by a theoretical and an applied argument. The theoretical motivation is that the resilience literature, to which this thesis contributes, has identified a range of principles to increase sustainability, but for which there is limited (but accumulating) empirical evidence (Biggs et al. 2015b). The applied motivation is that the Baltic Sea is heavily managed, but many of the underlying assumptions in management are seldom or never tested. The key assumption is that it is possible to identify and manage for optimal population levels and that this approach will produce long-term maximum harvest and sustainable fish populations. This thesis is motivated by a desire to empirically study the dynamic development of a SES with as few assumptions as possible. This has required the development of new methods and application of existing methods on novel types of data.

2. *An integrated social-ecological system perspective*. The biosphere is the life support system that we are all connected to and dependent on, thus ecological sustainability is the fundamental component of sustainability (Folke et al. 2011). Yet, outcomes in SES are heavily dependent on interactions between social and ecological factors, and our perception of sustainability and ecosystem services are also shaped by changing societal norms, related to the type of ecosystem services that are most desirable in a certain context (Schoon et al. 2015). This has resulted in a determination to integrate social data into study frameworks that have previously dealt only with ecological questions.

3. *An explicit complex adaptive system perspective*. My adoption of a CAS perspective is based on several related points: i) contemporary ecological science suggests that ecosystems are much more dynamic than previously thought, including rapid re-organizations, multiple stable states and chaos; ii) resilience science suggests that social-ecological interactions can be conceptualized in a similar way, with feedback mechanisms acting either to strengthen or to erode resilience of particular system configurations; iii) empirical evidence relating to the Baltic Sea indicates the importance of such feedback mechanisms for outcomes in SES (Österblom et al. 2011, Boonstra and Österblom 2014). Consequently, I have applied methods that do not disguise complexity, dynamics and uncertainty, but instead critically examine propositions from CAS theory for SES.

4. *An explicit management perspective*. The dynamics of natural resources do not play out in a vacuum. Instead, they are heavily influenced by current and previous management interventions (Bohensky et al. 2015). This thesis aims to make suggestions for improving management. I have consequently found it reasonable to explicitly include management as a factor in my analyses. This contrasts to more ecology-focused studied of fisheries that often treat humans as predators in a social vacuum or as external to the ecosystem. Operationalizing this in the thesis has required analysis of the management history of the Baltic Sea, but also how current regulations shape patterns of resource use from the individual up to the system level.

A summary of how the research questions presented in the Introduction section have been investigated in the different papers of this thesis using the below-described data and methods is conceptually presented in Figure 2.

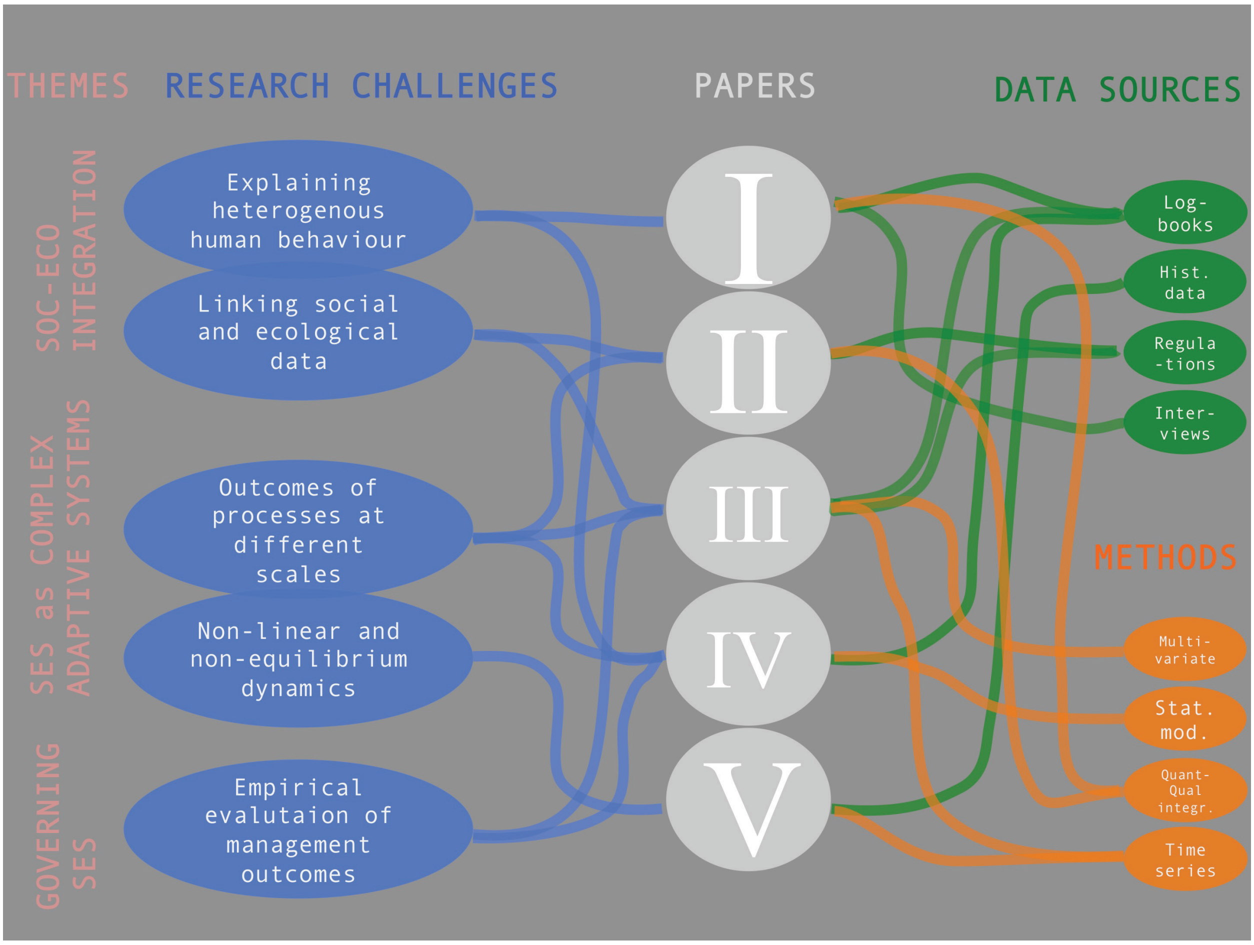

Figure 2. The different research challenges addressed in this thesis, and how they have been approached in the different papers with respective methodologies and data.

Study area

The work presented in this thesis focuses on fisheries in the Baltic Sea (Figure 3). Due to its large catchment area with extensive agriculture and a large human population, the Baltic Sea supplied by an excess of nutrients, creating widespread eutrophication and resulting in one of the largest dead anoxic bottom zones in the world (Diaz and Rosenberg 2008). But although there are interesting interactions between eutrophication and fish (e.g. Hansson and Rudstam 1990, Österblom et al. 2007), this thesis focus on social and ecological aspects related to fisheries.

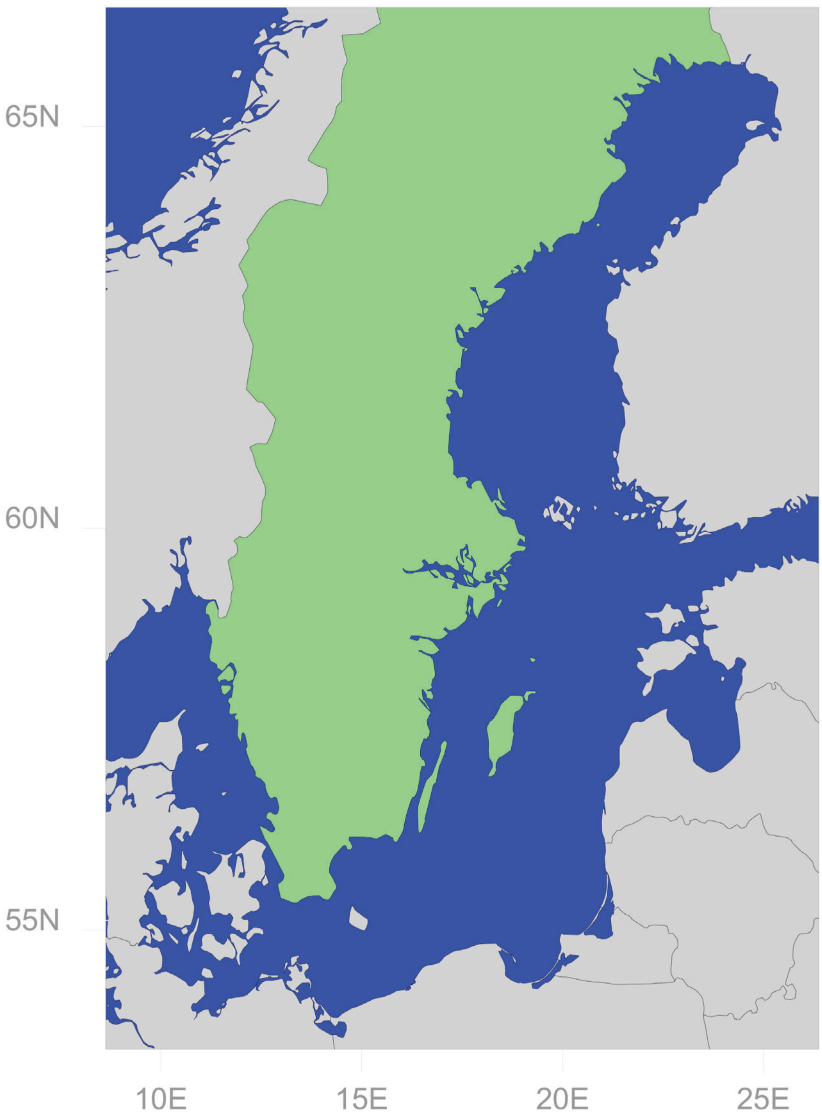

Figure 3. The Baltic Sea, with Sweden indicated in green. It is a relatively large (415 000 km^2) but shallow (mean depth 55 m) semi-enclosed brackish water body in northern Europe. It is a young sea which has switched from freshwater to saline, back to freshwater again and most recently to brackish when the last ice sheet retreated from northern Europe about 10 000 years ago. Saltwater enters the Baltic Sea on an irregular basis through the shallow straits between Sweden and Denmark, creating a salinity gradient from about 20 ‰ in Southern Kattegat (i.e. close to the North Sea) to 7 ‰ in central Baltic Sea and 3 ‰ in the far north (Gustafsson et al. 2012). These special hydrographic conditions lead to an unusual combination of freshwater and marine species, and a species diversity that is significantly lower than the nearby North Sea (Elmgren and Hill 1997).

A fishery is an illustrative example of what could be conceptualized as a SES, because it includes purely social factors (market demand, technology, management), purely ecological factors (fish stocks, other ecosystem components, species interactions) and factors that link the two together (catches, market prices). Fisheries in the Baltic Sea target the whole range of marine, freshwater and anadromous species, using a variety of technologies. In recent years the most economically important fisheries have been the mixed pelagic trawl fishery for sprat and herring (mainly targeted for the fish meal industry), demersal trawl fisheries for cod, and passive gear (mostly gillnet) fishing for cod (Blenckner et al. 2011). The Baltic Sea fisheries are regulated at the international level by legislation produced by the Council of Ministers of the European Union, complemented by national regulation (which often derive from implemented EU legislation), usually in the form of statutes from the Swedish Board of Fisheries (and, following a governmental re-organization in 2011, the Statutes from the Swedish Agency for Marine and Water Management).

Data sources

I have primarily built my analyses on two fisheries datasets complemented with various types of other quantitative data, policy documents and interview material.

Logbook data for 1996-2009

Logbooks contain data collected on the level of individual vessels, covering the whole Swedish fishing fleet. Depending on the size of the vessels the logbooks report catch per species and various aspects of fishing effort – at least every fishing day for vessels over ten meters, and aggregated per month for smaller vessels. In **Paper I** and **III** I use the logbook data to quantitatively describe fishing patterns, using various univariate and multivariate statistical techniques. In **Paper IV**, I use the same data when I investigate the Catch-per-Unit-Effort relationship in the Baltic Sea pelagic fisheries. All data used were anonymized to ensure that personal integrity for included individuals would not be compromised.

Historical statistical records of Swedish fisheries 1914-1980

Early on in my work, I realized that understanding the social-ecological dynamics of fisheries would benefit immensely from expanding the time scope of analysis. The work conducted by the History of Marine Animal Populations (HMAP) project (e.g. Eero et al. 2007, Ojaveer et al. 2007) helped me realize that there is an underutilized source of historical information that can put the current status into a historical context. Historical information of fisheries can thereby facilitate an understanding of the present. I discovered the statistical yearbooks of Swedish fisheries, built a database, and spent many hours digitizing historical material of catches, sales prices, number of fishers and number and value of different types of vessels and fishing gear (see Figure 4 for an example of one of the hundreds of original data tables). This data was available at regional level (Swedish county; *län*), and sometimes with even higher spatial resolution. Unfortunately, the system of collecting regional-based fisheries information ceased in 1980 and I had to use other sources to obtain data reaching into the present day. In **Paper V** I use this data together with modern data to investigate nonlinear dynamics of catches and prices over a 100-period.

Logbooks and prices for 1980-1993

This data fills the gap between the historical statistics and the modern logbook data. The logbook was gradually introduced for certain segments of the fishery and the coverage was thus not complete. Therefore, I had to assign catches to regions (i.e. the same spatial division as for the historical records) and then complement reported catches with catches reported from another system (based on fish sales along different sections of the coast) to obtain total figures. Unfortunately, this was only possible for catch quantities and not for sales prices. I use this data along with the historical statistical records in **Paper V**.

Fisheries regulations for 1994-2009

I was interested in investigating the role of management regulations on the development of fishing strategies. I used this qualitative material to make a quantification of regulatory pressure. The analysis is presented in **Paper II** and the results are used in **Paper III**.

Tab. 1. Fiskare, redskap och båtar vid saltsjöfisket,¹) länsvis, år 1936 samt i hela riket åren 1930—1936.

	1	2	3	4	5	6	7	8	9	10	11	12
	Län (område)	Antal yrkesfiskare	Antal personer med fiske som binäring	Fiskeredskapens antal och anskaffningsvärde: Notar²) Antal	Notar²) Värde kr	Nät Antal	Nät Värde kr	Skötar, sill- och strömmingsgarn Antal	Skötar, sill- och strömmingsgarn Värde kr	Ryssjor, hommor och bottengarn Antal	Ryssjor, hommor och bottengarn Värde kr	Långrevar och annan krokredskap Värde kr
1	Norrbottens	233	445	19	25 200	10 988	143 190	2 531	115 225	2 474	577 885	1 865
2	Västerb. .	191	489	43	4 385	6 312	99 420	3 379	184 910	1 808	155 585	875
3	Västernorrl.	618	359	91	16 967	5 232	62 335	10 922	508 584	1 233	99 478	7 719
4	Gävleborgs .	834	139	84	17 860	4 133	54 583	10 344	792 517	2 178	151 367	2 997
5	Uppsala . .	215	143	28	3 875	2 825	30 675	1 646	186 745	1 785	50 464	955
6	Stockholms	716	1 657	554	226 405	15 161	164 541	12 005	570 009	15 592	243 331	18 858
7	Södermanl.	66	221	141	59 250	6 315	46 318	2 702	138 770	2 773	27 088	3 488
8	Östergötl. .	221	901	372	212 600	5 815	67 415	4 658	184 770	8 648	131 980	8 431
9	Kalmar . .	1 279	2 163	453	144 315	32 911	581 679	15 097	513 680	13 584	1 588 811	93 592
10	Därav n:a del.	311	459	339	99 115	8 086	97 329	5 097	180 180	6 975	154 181	10 777
11	» s:a del.	968	1 704	114	45 200	24 825	484 350	10 000	333 500	6 609	1 434 630	82 815
12	Gotlands . .	272	899	63	5 325	13 262	311 153	7 011	284 460	1 263	95 535	41 948
13	Blekinge . .	1 121	613	301	66 350	20 778	618 280	16 395	573 625	2 469	846 900	50 000
14	Kristianst. .	301	291	140	16 255	3 979	94 050	3 764	151 550	1 125	573 377	13 573
15	Malmöhus .	1 077	243	134	16 380	18 938	485 970	20 463	926 505	14 945	847 175	40 660
16	Hallands . .	531	209	194	52 190	6 380	145 165	4 975	158 250	376	47 380	30 699
17	Göteb. o. Boh.	6 084	1 351	3 309	2 298 035	23 991	592 341	5 810	351 260	16 328	213 140	249 892
18	Ostkusten	4 760	7 543	1 892	725 582	104 404	1 595 809	71 495	3 521 670	51 915	3 503 274	184 628
19	Sydkusten	1 558	755	506	84 355	27 127	747 640	24 651	883 090	3 263	1 473 310	69 390
20	Öresund o. Skälderviken⁷)	826	265	30	5 230	15 118	416 160	14 771	726 590	14 699	412 392	30 943
21	Västkusten	6 615	1 560	3 503	2 350 225	30 371	737 506	10 785	509 510	16 704	260 520	280 591
22	Hela riket år: 1936	13 759	10 123	5 931	3 165 392	177 020	3 497 115	121 702	5 640 860	86 581	5 649 496	565 552
23	1935	13 519	10 279	5 874	3 259 921	169 574	3 262 432	128 980	5 967 450	78 178	5 642 170	494 798
24	1934	13 346	10 093	5 772	3 307 975	167 861	3 253 450	128 361	5 932 364	76 789	5 580 615	548 015
25	1933	13 414	10 176	5 708	3 238 476	173 582	3 279 415	129 692	6 085 564	75 223	5 302 315	475 713
26	1932	13 212	10 036	5 405	3 185 099	166 557	3 154 332	129 876	6 078 620	74 566	5 337 358	444 976
27	1931	12 953	9 672	5 316	3 134 151	158 214	2 863 262	128 012	6 018 644	72 642	5 673 148	459 846
28	1930	12 923	9 214	5 105	3 156 065	151 023	2 852 585	127 209	6 034 676	69 669	5 386 876	493 943

	1	13	14	15	16	17	18	19	20	21	22	23	24	25
	Län (område)	Annan redskap Värde kr	Tågvirke m. m.³) Värde kr	Hela värdet kr	Fiskebåtarnas antal och anskaffningsvärde: Däckade⁴) båtar med motor⁵) Antal	Däckade⁴) båtar med motor⁵) Värde kr	Däckade⁴) båtar utan motor Antal	Däckade⁴) båtar utan motor Värde kr	Öppna båtar med motor⁵) Antal	Öppna båtar med motor⁵) Värde kr	Öppna båtar utan motor Antal	Öppna båtar utan motor Värde kr	Hela värdet kr	Totalvärdet av redskap och båtar kr
1	Norrbottens	5 020	18 820	887 205	3	6 500	—	—	488	374 305	210	38 720	419 525	1 306 730
2	Västerb. .	2 220	15 755	463 150	1	800	—	—	269	213 400	337	31 850	246 050	709 200
3	Västernorrl.	4 587	19 003	718 673	—	—	—	—	605	537 353	318	54 698	592 051	1 310 724
4	Gävleborgs .	—	42 443	1 061 767	1	3 300	—	—	535	791 740	392	46 265	841 305	1 903 072
5	Uppsala . .	—	24 980	297 694	9	29 200	—	—	170	239 825	218	18 310	287 335	585 029
6	Stockholms	10 295	34 907	1 268 346	1	1 200	—	—	949	1 252 865	1 704	165 790	1 419 855	2 688 201
7	Södermanl.	4 210	22 810	301 934	1	3 000	—	—	193	270 225	463	57 355	330 580	632 514
8	Östergötl. .	175	—	605 371	13	36 900	—	—	298	464 200	851	101 580	602 680	1 208 051
9	Kalmar . .	490 370	124 350	3 536 797	120	355 900	—	—	913	1 137 450	3 000	414 000	1 907 350	5 444 147
10	Därav n:a del.	4 970	36 250	582 802	48	129 400	—	—	308	517 150	1 002	89 000	735 550	1 318 352
11	» s:a del.	485 400	88 100	2 953 995	72	226 500	—	—	605	620 300	1 998	325 000	1 171 800	4 125 795
12	Gotlands . .	3 828	30 384	772 633	201	304 900	—	—	266	186 375	698	56 295	547 570	1 320 203
13	Blekinge . .	68 150	87 780	2 311 085	334	1 202 500	—	—	226	188 100	838	139 900	1 530 500	3 841 585
14	Kristianst. .	17 335	31 850	897 970	84	352 600	—	—	55	43 725	282	48 735	445 060	1 343 030
15	Malmöhus .	98 420	73 280	2 488 390	337	1 088 400	15	8 100	192	176 750	456	140 565	1 413 815	3 902 205
16	Hallands . .	34 645	21 900	490 229	116	993 200	1	1 000	62	39 100	224	26 525	1 059 825	1 550 054
17	Göteb. o. Boh.	509 939	1020095	5 234 702	⁶)1251	⁶)18706710	11	5 800	385	436 285	1 984	293 921	19 442 716	24 677 418
18	Ostkusten	554 705	372 952	10 458 620	379	816 700	—	—	4 734	5 518 738	8 341	1 003 863	7 339 301	17 797 921
19	Sydkusten	123 865	132 365	3 514 015	449	1 652 000	—	—	308	254 600	1 061	207 915	2 114 515	5 628 530
20	Öresund o. Skälderviken⁷)	26 040	21 025	1 638 380	277	916 500	15	8 100	117	102 975	365	102 285	1 129 860	2 768 240
21	Västkusten	544 584	1041995	5 724 931	1 367	19 699 910	12	6 800	447	475 385	2 208	320 446	20 502 541	26 227 472
22	Hela riket år: 1936	1249194	1568337	21 335 946	2 472	23 085 110	27	14 900	5 606	6 351 698	11 975	1 634 509	31 086 217	52 422 163
23	1935	1320620	1316252	21 263 643	2 366	21 791 148	21	18 004	5 227	5 981 257	12 076	1 686 271	29 476 680	50 740 323
24	1934	1281781	1183721	21 087 921	2 322	20 876 602	31	25 404	4 994	5 779 453	11 856	1 686 165	28 367 624	49 455 545
25	1933	1145625	1191824	20 718 932	2 259	20 544 486	42	35 828	4 851	5 674 981	11 733	1 712 293	27 967 588	48 686 520
26	1932	960 016	1132657	20 293 058	2 203	19 450 376	33	34 328	4 604	5 460 161	11 761	1 731 019	26 675 884	46 968 942
27	1931	919 159	1045937	20 114 147	2 088	17 773 892	52	93 026	4 314	5 223 742	11 679	1 762 010	24 852 670	44 966 817
28	1930	459 902	980 933	19 364 980	2 013	16 931 896	67	110 266	4 047	5 015 425	11 698	1 760 955	23 818 542	43 183 522

¹) Uppgifterna avse även sill- och strömmingsfisket. — ²) Under notar upptagas notar och vadar av alla slag samt trålar. — ³) Ej inräknat i värdet av de särskilda redskapen. — ⁴) Hit räknas även halvdäckade båtar. — ⁵) I värdet inräknas jämväl värdet av icke fasta motorer. — ⁶) Häri ingå även ångtrålare (20 st). — ⁷) Jämte sträckan Torekov-Båstad. Denna jämte Skälderviken t. o. m. år 1933 räknade till västkusten.

Figure 4. Example of an original data table, in this case various data relating to fishing effort such as number of fishers, and number and value of fishing vessels and various types of fishing gears, in different Swedish regions in 1936. All these data back to 1914 are now compiled in a MS Access database.

Wholesale prices for 1995-2009

This dataset contains the original sales notes for the sales of fish from the fisher to the fish auction or any other buyer. It was used to calculate average sales prices per species and was used in **Paper III**.

Fishing quotas

The actual Swedish fishing quotas, as decided by the council of the European Union, was used to calculate yearly overcapacity (fleet size in relation to fishing quota) in **Paper IV**. A complicating factor exists in figures for country-specific fishing quotas in the European Union: after the decision in the council, countries can trade quotas that are not reported in the official journal. Fortunately, I could get access to working documents from the Swedish Board of Fisheries to take this into account.

Interviews with fishers

Although I didn't do any interviews myself, **Paper I** builds on interviews performed by my co-author Wijnand Boonstra and two Masters students, Emma Björkvik and Maja Berggren, both of whom Wijnand and I co-supervised.

Methods

This thesis is written from the starting point that social and ecological factors may interact and that linked social-ecological systems may be complex, adaptive and dynamic. Selecting methods to empirically analyze SES dynamics is a significant challenge. Social science has often been more willing to link various types of data and attempt to provide holistic representations of social phenomena, whereas the widespread influence of reductionist approaches in the natural sciences has often provided limited answers to limited questions (Myrdal 2005). With a background in natural science, and convinced about the value of figures produced in quantitative analyses using data, I have tried to bridge a wide systems view with detailed, quantitative and empirical analysis. I will here briefly summarize the methods I have used in this thesis. More detailed methods descriptions are available in the respective papers and in their attendant appendices.

Multivariate statistics and multi-methods integration

In **Paper I** and **Paper III** we were interested in describing the diversity of fisheries, and explaining how this diversity has emerged and changed over time. The basis for the two papers builds on the same multivariate statistical analysis. I had access to raw data on fishing operations (logbooks) – in total more than 600k individual observations – in which I first used Principal Component Analysis (PCA) and k-medoids cluster analysis (the CLARA algorithm) to identify typical catch compositions, then Multiple Correspondence Analysis (MCA) and another cluster analysis on a combination of catch and effort data to identify what we called *fishing tactics*. This analytical procedure builds on earlier work in fisheries on similar type of data (Pelletier and Ferraris 2000). In the next step, we grouped those fishing tactics depending on who performed them (the data was linked to the individual fishers), into what we called *fishing strategies*. From there, we took two different approaches in the two papers. In **Paper I** we investigated how those strategies (what fishers did) were linked to social and physiological factors. We did this by interviewing fishers representing different strategies, asking them "why" type questions, and came up with the concept of *fishing style*, integrating qualitative and quantitative understanding of fishing diversity. In **Paper III** we used time series analysis to investigate how three contextual factors – ecological, economic and management change – had influenced individual fishing strategies over a period of 15 years, and found that management was the strongest driver. Together, the two papers thus gave quite deep insights into why fisheries diversity exists, how it changes over time, and the factors that can drive changes in diversity.

Multiple General Linear and General Additive models (GLMs and GAMs)

In **Paper IV** we wanted to investigate whether we could find signs of misreporting in the Swedish pelagic (two-species) fishery - the largest Baltic Sea fishery measured in landing quantities. Part of that work was to develop a statistical model for the relationship between catch and effort. There was a range of factors we wanted to control for, such as vessel size, season, area and gear. In addition, we constructed two variables: overcapacity (which would incentivize overfishing), and skewness of the quotas (which would incentivize misreporting of species composition). The idea behind this analysis was that if including overcapacity and species skewness improved model performance, it would indicate misreporting. We used both linear (GLM) and additive models (GAM), but report the results from the linear models as we found that the relationships in this case were predominantly linear.

Quantification of qualitative data

To analyze the drivers of fishing strategies (**Paper III**), we wanted to have comparable data on fish stocks, prices and regulations. The problem was that while the two first were quantitative and readily available for an integrated analysis, no one seemed to have a good overview of the regulations. I therefore made a systematic analysis of all regulatory changes in the Swedish fishery since Sweden entered the European Union in 1995 and until 2009 (**Paper II**). Regulation included restrictions on specific fishing gears and other technical regulations, fishing quotas, fishing effort restrictions and fishing licenses. After obtaining a complete overview, we made a judgment on whether each regulatory change would restrict or open up for more fishing. To explain this procedure, consider the case of catch allowances, which are subsets of the total fishing quota given to individual fishers. We considered a yearly allowance less strict than a weekly allowance because it gives higher flexibility to the fishers to plan their activities. Another example is minimum size limits for target species that are put in place to protect juvenile fish from being caught. We here considered a higher minimum size limit less strict than a lower one, simply because a fisher can land a broader range of sizes. We considered all new introductions of regulation as restrictive of fishing, and removal of regulations as opening up for more fishing. This classification was done for each fishing strategy (**Paper I** and **III**), for which we developed an aggregate regulatory score. Thereby, we could compare fish stocks, prices and regulations in the same, integrated analysis.

Empirical Dynamic Modeling

From the outset of my PhD studies, I wanted to do a "whole systems, total analysis" of the Baltic Sea fishery over a long time period, looking at drivers of change and integrating various types of biological, abiotic, social and economic data. Although collecting data was easier than I had thought (see data section) I struggled to find the appropriate methods for conducting such an analysis. What I found especially challenging was to identify a method that could work on a system where drivers might have changed over time, i.e. not assuming state-independence. About halfway through my PhD, I discovered a set of methods under development within a framework called Empirical Dynamical Modelling (EDM), which I used in **Paper V**. I summarize EDM in Box 1 in **Paper V** and will not repeat this description here, but in short observed time series are used to reconstruct an attractor of the system, and that attractor is used for prediction. By studying the shape of the attractor, one can estimate the dimensionality of a system, whether or not it is state-dependent, and analyze causality between interacting variables. EDM methods appear well suited for analysis of SES because they build on a notion of SES as CAS with non-linear and non-equilibrium dynamics. However, to my knowledge this is the first analysis where EDM methods have been used to investigate the dynamics of a SES.

Summary of results

New ways of empirically studying coupled social-ecological dynamics

In the introduction I described the North Sea fishing fleet switching to Baltic Sea cod fishing, and later to industrial herring and sprat fishing, as an example of substantial fisher adaptation that can drive unexpected outcomes. Other Baltic Sea fishing activities seem surprisingly static, continuing for decade after decade despite changing conditions. How can such differences be understood and in what ways does it matter for management? There is a scientific divide between qualitative studies of fishing communities (often performed by ethnologists, anthropologists and sociologists) and quantitative studies by economists and ecologists. These two realms of science rarely communicate. This is unfortunate, because each can provide partial answers to questions with relevance for understanding sustainability challenges. Fisheries management has primarily been informed by quantitative research, often focusing on static (generalizable) descriptions of fisheries in terms of, for example, scale of operations (small-scale vs. large-scale), profitability, target species, gear and fishing areas. We wanted to bridge the two research traditions and began by performing the first extensive ($n_{fishers}$ = 1905) quantitative study of fishing patterns in the Swedish Baltic Sea commercial fishery using PCA, MCA and cluster analysis (**Paper I** and **III**). We found a striking diversity in fishing patterns, from small-scale gillnet and trap fishing for eel and freshwater species in the archipelagos of southern Sweden, to large-scale industrial trawl-fishing for sprat and herring, primarily supplying the fish meal industry. The existence of this diversity could not be explained by simple factors such as location. In the next step we therefore investigated *why* this diversity existed, and hypothesized that historical, social and psychological factors could play an important role. We conducted semi-structured interviews with over forty active fishers, representing different fishing patterns, and asked questions about their motifs, drivers, beliefs and perceived future prospects. As a qualitative analogue to cluster analysis, we grouped fishers based on characteristics revealed by the interviews, and compared those groupings to the grouping based on fishing patterns (**Paper I**). We found a striking coherence between the groupings based on the statistics and those based on the interviews, and we termed the combination of practice and mentality a *fishing style*. One extreme was the small-scale archipelago fishers that had inherited their practices (gears, fishing areas) from earlier generations, and perceived their activity as important cultural heritage. They were bound to a certain location, and often expressed a feeling of disempowerment due to rigid regulation, declining catches and competition with seals and cormorants. Despite this, they were generally unwilling to change practices even if they could make more money by doing so. The other extreme were the industrial trawl fishers. They described themselves as entrepreneurs and risk-takers, constantly on the move and pushing the limits with new technologies. These actors resemble most of all fishers the image of the *Homo economicus,* a commonly used model for humans in resource economic analyses. Fishing practices and mentalities did not however map 1:1 – a similar mentality could be shared by several fishing practices. We think the fishing styles concept could be a useful middle-ground of studying fishers in the context of SES and NRM, by combining some level of empirical detail on social and psychological characteristics of different fishers while at the same time not loosing the generalizability provided by quantitative analysis.

The next example of the importance of linked social-ecological dynamics comes from our detailed study of one of these fishing styles. Fishers in the Swedish two-species (sprat and herring) mixed pelagic fishery had been reporting their catches just in line with their assigned quotas for many years, but anecdotes from the processing industry and sporadic landing controls suggested a widespread misreporting of both species composition and total quantities. Applying an economic lens to this problem, we soon realized that management authorities had created economic incentives for species misreporting (by setting quotas that didn't match abundance) and catch quantity (by allowing a large and increasing overcapacity). Modeling catch per unit effort without these incentives created large time-dependent residuals, indicating systematic errors, but including these incentives in the model drastically improved its performance. In other words, we found that fishers had adapted their *reporting*, not their fishing, to the regulations (**Paper IV**).

This finding however left us with an unresolved question. Being economically rational actors relying on a potentially very profitable fishery, misreporting would be a maladaptive strategy in the long-term as it negatively affects the scientific base for management and thereby increases the risk of insensible political decisions. In the end, future fishing opportunities would be at stake. So what did the actors do? The key underlying problem in this fishery was the over-capacity caused by the large fleet. Earlier governmental buy-back programs had not led to any significant reductions in the fleet size, and the authorities instead responded through increased micro-management of fishing activities, seriously threatening fisheries profitability. At this point, some of the most proactive fishers began to lobby the government and managed to transform the whole fleet management into an Individual Transferable Quotas (ITQ) system (**Paper II** and **IV**). This drastically reduced the fleet, released fishers from micro-management and increased profitability (**Paper II** and **IV**). This example suggests that a detailed understanding of linkages between dynamic human actors, authorities and ecosystems is key to understanding outcomes in SES.

Paper IV identified specific management interventions (or lack thereof) as a key component in shaping a fishery over time. But how can knowledge about fisheries management be more generally integrated in a quantitative systems analysis? As explained in more detail in the Methods section, we approached this question by carefully analyzing and classifying all management changes applying to the different Baltic Sea fisheries, from the Swedish entry to the EU in 1995 until 2009 (**Paper II**). Knowledge about regulations and their effects on fishing is often of an anecdotal nature, but we found that it was possible to condense the complicated regulatory landscape experienced by fishers into a simple aggregate, quantitative score. This score had an interesting temporal component in our study, suggesting a trend towards increasingly detailed regulations. We termed this trend micro-management. But not all fishing strategies were becoming increasingly micro-managed; the pelagic fishers from **Paper IV** stood out as a group which had become less regulated in recent years. The explanation is the ITQ transformation, with management shifting from top-down regulation by authorities to more self-organization by the fishers themselves.

The quantification of the data on regulation was ultimately a step towards integrating various social and ecological data, in order to understand what was driving change in this fisheries system over time. In **Paper III**, we operationalized three main categories of drivers – management, ecology and markets – as regulation, fish stock status and fish prices, and used them as possible explanatory factors for change in the number of fishers using different fishing strategies. We found that regulation was the dominating factor explaining change in the number of fishers using a particular strategy over time. The impact of fish stocks was particularly weak, whereas there was a mixed pattern for fish prices. We concluded that regulation at the current level of detail restricts fishers from responding to change in fish stocks or markets. For example, cod fishers that were previously doing very well have over a number of years suffered from declining profitability due to declining stocks and increased regulation. However, as owners of a cod fishing license they are not allowed to fish sprat and herring under current regulations. Thus, an increase in abundance sprat or herring (or a price increase) would make no difference for these fishers as no direct feedback exists between, on the one hand, fish stocks and prices, and on the other, fishing strategies (due to the design of the regulatory system). Implications for the CAS behaviour of fisheries in general are discussed in the next section.

Insights on social-ecological systems as complex adaptive systems

The introductory section suggested that complex ecological dynamics (exemplified by a proposed ecological regime shift in the Baltic Sea), the inherent uncertainty of SES (exemplified by the current, unexpected distress of the Baltic cod population), and the linkages between geographical scales (profitability of local fishers depending on globalized fish markets) represent outstanding challenges for regional resource management.

To begin with the issue of scale, Figure 5 summarizes the approximate scale of operation for the different processes I have studied in this thesis, in the context of Baltic Sea fisheries. To explain how interactions between scales take place, consider the daily or weekly fishing activities performed by individual fishers denoted *fishing tactics* in **Paper III**. Decisions about where to fish, which gears to use and when to go fishing are decisions taken at the level of the individual fisher (or perhaps on a corporate level) based on some rules (for example, to maximize profit), and a number of factors, such as economic (expected fish price, operating cost), abundance of different species, technology available and the differing regulation of various fishing activities. The behaviors stemming from each individual fisher decision will then affect the higher-level contextual factors that conditioned the decisions in step one (such as fish abundance and fish prices), creating a feedback. In the next round, there is a new decision situation, where the same rules will apply but with a new level of the factors.

This is a fairly general description of fisheries that should apply in many cases. What my study contributes is the role of fisheries management in creating another level in this system. Many Baltic Sea fisheries, particularly the cod fishery, have over the past few decades suffered from overfishing and fleet overcapacity. In order to control fishing, authorities have applied a strategy that gradually increases control, a strategy we term micro-management (**Paper II**). The ultimate goal of this strategy is to control fishing effort, and has included various measures to limit movement between fisheries, such as requiring licenses for individual target species with restrictions on combinations. Over a period of 15 years (1996-2009) we found that this management strategy has led to a significant specialization in individual fishing strategies (**Paper III**). Thus, there has been a decline in diversity at the fisheries system level over a long time period, as a gradual effect of the actions of individual fishers. Along with the decline in diversity, we also observed a decrease in flexibility (fewer fishers switching between strategies between years). In essence, decision-making at individual fisher level, contextual factors such as fish abundance and fish prices, and policy-making interact across scales to produce higher-level emergent properties that would not be seen if the analysis was restricted to a single geographical or temporal scale.

Another example of cross-scale interactions is the case of the small pelagic fisheries discussed in the previous section. As explained above, these fishers systematically misreported their catches due to unreasonably set fishing quotas and fleet overcapacity, risking the sustainability of this fishery (**Paper IV**). What adds another dimension is that the data reported by the individual fishers are used in the stock assessment (the scientific procedure of calculating stock size), which is the basis for the fishing quotas. Thus, the whole scientific base for management becomes biased, and can even deteriorate over time. This is an example of a social-ecological feedback mechanism involving fishers, science and regulation (**Paper IV**). In this case, luckily, the fishers themselves identified this looming problem and took steps to escape this unsustainable situation (described further below).

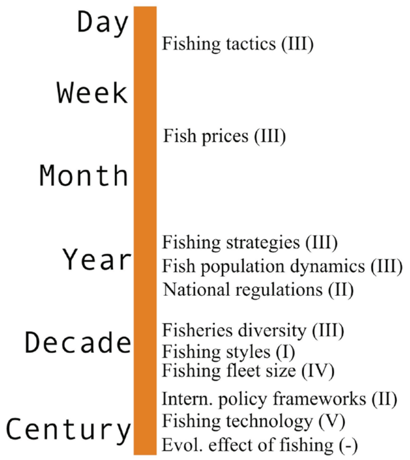

Figure 5. Processes at different temporal scales studied in this thesis (with paper numbers in parentheses). Localized interactions influenced by and influencing other scales may give rise to complex adaptive systems behavior.

Theory suggests that complex systems, due to the above-described cross-scale interactions, can behave nonlinearly. As outlined in the theory section above, nonlinear changes have been increasingly shown in ecosystems. Yet the frequency of nonlinearities in ecosystems and SES is unresolved, partly because of a methodological gap, and partly because current fisheries management practices often build on the assumption of linear relations between, for example, harvest and stock size. To investigate the features of the possible linked social-ecological dynamics of fisheries, I used the long-term data of catches and prices that I had compiled from historical sources, and applied a novel form of non-parametric time series statistics, Empirical Dynamical Modeling (EDM).

In my analysis using 96 years of catch data and 67 years of price data for cod and herring across 14 regions of the Baltic Sea, I first showed that it was possible to predict observed time series using neighboring regions (**Paper V**). What this demonstrates is that there are similar (deterministic) dynamics in different regions. Importantly, the predictions were independent of time, hence this pattern did not emerge from temporal correlation but from similar dynamic features across regions. Second, I compared state-independent (linear) non-parametric time series models with state-dependent (nonlinear) models and found that the latter performed significantly better, indicating nonlinearity. I validated this finding by comparing EDM performance to a standard parametric time series model (ARIMA). The latter had significantly lower predictive performance. Third, I found that prediction for restricted time periods had better predictive power than predictions for the full study period, indicating that the dynamics of the system were changing over time.

By showing deterministic dynamics in catches and prices, my study demonstrates that the Baltic fishery in fact behaves like a coupled SES. It further shows nonlinearity (state-dependence) and change in dynamics over time. Earlier research on the Baltic Sea ecosystem has focused on an ecological *regime shift*, which could be conceptualized as a special form of state-dependent dynamics where two distinct states exist, separated in time by a rapid shift (Casini et al. 2009, Möllmann et al. 2009). Although my analysis does not directly reject such a hypothesis, the system trajectory rather appears to be continuous, gradually changing feedback strength and thereby eventually ending up as a very different system (**Paper V**). Future research should focus on categorizing different types of state-dependent dynamics in SES, and also empirically investigate how feedbacks change over time, which is another possible application for EDM methodology in the context of complex systems (Sugihara et al. 2012).

Empirical analyses of outcomes in state-of-the-art management

The introduction section flagged the influence and effectiveness of management as a black box in many studies of fisheries and ecosystems. One first and basic thing was to understand the changes in fisheries management over time. By compiling and classifying all national fishing regulation statutes since the Swedish EU entrance (1995) we developed an aggregate score of regulatory strictness for each fishing strategy over time (**Paper II**). We found a general trend towards increased micro-management, but that some fisheries, notably the industrial fisheries that transformed into an ITQ system, were less regulated in 2009 than in 1995. Micro-management may be described as an "emergent property" of the regulatory system, arising from individually reasonable decisions or regulations, but eventually producing an incomprehensible mishmash where flexibility for individual fishers is strongly limited (**Paper II**). We argue that this background knowledge (preferably quantified in some sense) is an essential ingredient to understand development of fisheries, but also important for managers to understand the full picture of regulation.

In our analysis of the Swedish Baltic Sea pelagic fishery, we found that regulations perceived as unreasonable can drive misreporting (**Paper IV**). The narrow single-species focus of current management, ignoring the multi-species character of the fishery as well as economic aspects (i.e. fleet overcapacity), was the prime reason behind fishers not reporting what they actually caught, but what they were allowed to. More generally, this illustrates a problem that could potentially be widespread beyond the Baltic Sea: how does bias in catch data influence stock assessment? Stock assessment outcomes are currently used both for decision making on catch quotas and also, increasingly, in applied analyses of ecosystem dynamics (Lindegren et al. 2009, Casini et al. 2009), illustrating the fundamental importance of this issue.

Discussion

The case

To what degree can the findings of this thesis be generalized to other marine SES? From a biological perspective the Baltic Sea is clearly a special system, with a food web consisting of few species, creating strong inter-specific relations (such as those between cod and sprat). The Baltic is also heavily influenced by land-based processes, such as nutrient run-off leading to eutrophication, and climate variation leading to salinity fluctuations, affecting different commercially exploited fish species in a non-random way (Niiranen et al. 2013). All this makes the Baltic Sea a system under strong human influence from multiple sources (Österblom et al. 2007).

Fisheries in the Baltic Sea today largely resemble other fisheries in developed countries at northern latitudes, with specialized technology, and linked to dynamics in other areas through mobile actors (moving between Baltic Sea and other areas) (Lade et al. 2015) and to regional and global food markets through trade of fish products including fish meal (Deutsch et al. 2007). In addition to such large-scale actors, which could be seen as the archetypical modern-day fishing operators (Berkes et al. 2006, Österblom et al. 2015), there is a great variety of other kinds of fishing activities that takes place at the same time. The SES lens lets us view and investigate this remarkable diversity, and helps in understanding its causes and consequences. By looking at several different fisheries, several different fleets within these fisheries, and the evolution of these over a period of up to hundred years, the single case of the Baltic Sea fishery effectively becomes a social-ecological mesocosm, where events happening simultaneously have sometimes played out differently for different groups of fishers depending on contextual ecological and social factors. From the literature, this diversity appears to be a general feature of fisheries systems (Wilson 2006, Mahon et al. 2008), but scientific studies have often analyzed single fisheries, focusing on either small-scale fisheries and their importance for coastal livelihoods, or the environmental sustainability of large-scale fisheries.

Interest has grown in fisheries management in response to increased technological sophistication (raising the risks of over-exploitation), and the nation state's ability to limit access since the introduction of the Exclusive Economic Zones (EEZs) in 1982. Today there are not many open-access fisheries within EEZs, and nation states have adopted various strategies to achieve ecological sustainability and profitable fishing industries. The goals of the Europan CFP and the United States' Magnuson-Stevens Act are similar (see Theory section) – but the outcomes of each differ. European fisheries are underperforming in comparison to North America and other regions globally, with regard to both status of the stocks and current exploitation patterns (Österblom et al. 2011, Ricard et al. 2012). Yet the tools in fisheries management are the same: TACs, technical regulations, and more recently a move towards ITQs, including catch shares. This indicates that although interesting performance differences exist, the results in this thesis should have general relevance for managed fisheries systems in developed countries.

Studying linked human-ecosystem dynamics in a NRM context

Humans have often been treated as external factors in research on ecosystem interactions and sustainable use of marine resources, whose impacts must be controlled through various management interventions in order to achieve ecological sustainability (e.g. Hilborn 2007, van Putten et al. 2012). In this thesis I show, however, that humans (operationalized as fishers) interact with the ecosystem, the economy and management in a deeply interconnected way. This clearly suggests that taking human behavior into account is absolutely key to understanding sustainability.

Previous research has provided evidence about how different drivers affect fisher behavior in a social-ecological context, highlighting factors such as the phase of development of the fishing, type of management, enforcement level, economics of the fishery as well as social and psychological factors (Branch et al. 2006, Fulton et al. 2011, van Putten et al. 2012). We add to this literature by introducing the integrative concept of *fishing styles*. A fishing style is a combination of what fishers do and why they do it, drawing from progress in fisheries science on multivariate classification of fishing patterns as well as sociological tools for describing patterns and diversity in human behavior. The styles concept (which in fact originated from the farming literature and could easily be applied to other types of natural resource uses) could be a fruitful middle-ground concept for studying humans and their interactions with the environment.

The theory section discussed a tension between those advocating top-down control or privatization of resource use (Hardin 1968), and those highlighting that humans, when provided with the right conditions, have a remarkable capacity to self-organize (Ostrom 1990). Our identification of different fishing styles showed that these two (extreme) positions may apply for different styles, and under different social-ecological conditions. The large-scale pelagic fishers were strongly driven by profit and they misreported their catches under a situation of overcapacity and poor enforcement. However, they managed to bring about a transformation of the management system towards individual ownership (ITQs), limiting entry and providing economic incentives for reducing the fishing fleet. In Hardin's logic, rigid enforcement or privatization are the two options to achieve sustainability, and here privatization became the solution. But the shift to ITQ could also be interpreted in line with Ostrom’s (2009) framework, as evidence that the fishers managed to self-organize to bring about the ITQ transformation, and thereby ensure exclusive harvest rights. In contrast, the archipelago fishing styles were not particularly profit driven but rather emphasized historical and cultural motivations for fishing. This group has increasingly faced top-down regulatory pressure over time, limiting the flexibility that has historically characterized their activity. Self-organization is poor in this group due feelings of disempowerment, and perhaps releasing some of the (often inefficient) top-down regulation could enable a more bottom-up type of governance.

As the fishing styles concept highlights, an increased level of insight into the dynamics of SES require linking human behavior, the economy, the ecosystem and management to understand the conditions under which we can achieve sustainability. In this thesis I take one step to empirically integrate social, ecological and economic data with fishing behavior to understand drivers of change in a particular fisheries system. Further such analyses are needed for identifying generalities (Rochet et al. 2012, van Putten et al. 2012). One problem with such analyses is that for each successive level of detail the data requirement grows rapidly. One fruitful way forward could therefore be to combine detailed empirical analyses with analyses using more general systems descriptions such as scenario analyses (Österblom et al. 2013), Generalized Modeling (Lade et al. 2013, 2015) or analyses of social-ecological network topologies (Bodin and Tengö 2012).

Social-Ecological Systems as Complex Adaptive Systems

The Theory section summarized resilience theory, which suggests that SES can behave as CAS because they have interactions at multiple scales, significant uncertainties and possible nonlinearities. In this thesis, I provide empirical evidence for these three aspects. First, this thesis identifies a few empirical examples (individual regulations, individual fishing strategies) where local processes create emergent properties at a higher level of the system (regulatory landscape, fishing specialization). These examples illustrate cross-scale interactions, a key component of CAS (Levin 1998, Levin et al. 2012). This is a largely unexplored and very challenging area of inquiry. Possible future research questions include: (i) On which geographical and temporal scales do the processes that determine decision-making in fishers operate (Schlüter et al. 2012)?, (ii) How do larger scale processes influence the sustainability of local fisheries (Crona et al. 2015b, Eriksson et al. 2015)?, (iii) What type of social-ecological conditions are necessary for creating local self-organization in order to achieve higher-level sustainable outcomes (Ostrom 2009)?

As already elaborated, resilience theory further suggests that SES consist of feedbacks between social and ecological factors, which can create unexpected and possibly nonlinear effects (Folke 2006). Key in resilience thinking is to not manage for static targets but rather to investigate the conditions under which a SES will continue to produce benefits under significant uncertainty (Holling and Meffe 1996, Folke et al. 2005, Folke 2006). A key ingredient of understanding resilience is to understand the diversity and connectivity of a system, and how a system's dynamics are determined by slow variables and feedbacks. This thesis contributes to this literature by measuring social-ecological diversity (rate of fisheries specialization and flexibility that is related to response diversity) and connectivity (how fishing strategies are linked) and by identifying factors that determine change in diversity and connectivity, notably management regulations. In resilience language the current situation in the Swedish Baltic Sea fishery, characterized by declining social-ecological diversity, a rigid regulatory framework and low flexibility within actors, can be conceptualized as a rigidity trap (Carpenter and Brock 2008). A somewhat similar conclusion has been made in the analysis of the Maine lobster fishery, where Steneck et al. (2011) suggest that although current profits are high and fishers are happy, the high level of specialization, low response diversity and partly impoverished (at least simplified) underlying ecosystem, make the SES prone to collapse (with potentially devastating socio-economic consequences).

As balancing flexibility, diversity, redundancy and connectedness appears to be a key for resilience of social-ecological systems (Elmqvist et al. 2003, Levin et al. 2012, Dakos et al. 2015, Kotschy et al. 2015), it would be an interesting next step to compare those aspects of the Baltic Sea fisheries system with other SES, preferably in a similar framework. For the Baltic case in particular, this would be a way to clarify whether the observed specialization and decrease in connectedness is close to a critical system boundary, or if it remains within the safe operating space for social-ecological stability (cf. Carpenter et al. 2015).

Many of the theories around CAS have arose from the study of natural systems such as foodwebs. Although there is some evidence for dynamic similarities between human and natural systems (Gunderson and Holling 2002), there are also factors unique to humans such as strategic planning, technology and communication (Holling 2001). Thus, in order to achieve an integration between social and ecological, we need to answer the question: How different are SES to ecosystems? We found in our long-term time-series study that there were clear similarities to previously studied ecosystems: dynamics of fish catches and fish prices were deterministic and nonlinear just as previously studied ecological time series (Hsieh et al. 2005, Deyle et al. 2013, Glaser et al. 2014, Ye et al. 2015). This is promising for the integration of social data into analyses of social-ecological systems. However, when investigating dynamic change over short time periods, we also found an interesting difference: whereas the dynamics of the ecological time series were constant (measured as maintained predictability over long time frames), predictability of the social-ecological data rapidly declined with time. We speculate that this difference arises from the fact that fundamental change in SES (such as feedback strength) can come about on a much shorter time scale than for ecosystems. One example of this is the introduction of a new catch technology, which can spread rapidly over a time span of one or a few generations of the targeted species, completely changing the game that will be seen in observed time series. On the other hand, this difference is conceptually not essentially different from evolutionary change in ecosystems, which will also change the rules of the game. Theoretically and possibly empirically investigating similarities between outcomes of evolution in complex systems and change in SES would be of great interest.

On a more general note, I think the EDM methodology, which is here used for the first time in an analysis of a SES, has great potential in empirical analysis of SES.

Governance implications

This thesis includes both explicit analyses of the current NRM paradigm and also insights into the dynamics of SES that can help to design a governance system that has a better chance of achieving sustainability.

The basic paradigm in European fisheries is managing for MSY building on single-species stock assessments. This paradigm contains a number of assumptions that have been previously challenged (Larkin 1977), including (from a purely ecological point of view) the idea that the fish population can be treated in isolation, will strive towards equilibrium abundances and will respond linearly to changing harvest. My research proposes some new reasons why – from a SES perspective – such a non-systemic approach will have intrinsic problems: (i) Uncertainty in human behavior may be significant, but is currently largely ignored. Although there have been efforts to incorporate catch uncertainty in stock assessment models (Patterson et al. 2001), our finding of deliberate systematic misreporting in a multi-species context adds a new dimension to this problem. (ii) Related to uncertainty in human behavior is the switching of fishing practices due to changing regulation. Stock assessment for Baltic Sea sprat around 1980 indicates a very small population, which rose rapidly as the cod declined throughout the 1980s. The problem is that this event was concurrent with a switch in the fisheries - few fished for sprat around 1980 because of the high cod abundance and no developed market for sprat. These fisheries-specific dynamics influence stock assessment as such methodology largely relies on reported catches (no fishery independent abundance data exists for this period). In summary, by employing a SES perspective new possible biases of the current management approach were identified. In hindsight, it would have been interesting to evaluate the possible effects of misreporting and species switches on stock assessment reliability. One reason why I have not done this is because I focused primarily on Swedish fisheries, providing only a partial picture of the system as a whole. This was largely because of data availability, yet understanding the role of different regulatory and other social contexts on the same ecosystems would have greatly increased the generality of my findings. Looking beyond the Baltic Sea, a question that would be interesting to investigate is: What are the effects of various types of reporting errors and other fisheries dynamics on stock assessment? Are some tools more robust than others with regard to social dynamics and imperfect information?

Managing fish is managing people (Hilborn 2007) but human behavior still remains a key uncertainty in fisheries management (Fulton et al. 2011). We think our new concept of fishing styles can help to design better fishing policies by paying closer attention to human motivations and drivers. In fisheries today, despite the good intentions of authorities, compliance with regulation is a widespread and much-debated problem (Raakjær Nielsen 2003, Sumaila et al. 2006, Agnew et al. 2009, Österblom et al. 2010). Our study suggests that different groups of fishers will have very different drivers to comply or not to comply with regulations. Compliance among archipelago fishers is linked to the legitimacy of regulation and can be achieved through greater levels of co-management, whereas compliance among entrepreneurial fishers is rather linked to economic incentives and enforcement efforts. Fisheries governance that splits up different fisheries depending on their socio-economic characteristics is a subject under intense scientific discussion (Kooiman et al. 2005, Mahon et al. 2008). We think fishing styles could be useful concept when applying such governance models.

European fisheries policy is currently moving towards cross-scale approaches that may indeed be a step from top-down management towards a broader governance approach. For example, regional bodies have an increasing role in negotiating implementation of policies decided at the European level (Symes 2012, Linke and Jentoft 2013, Soma et al. 2015). Further, the fishing industry has been given a more significant role in implementing policy through, for example, the ITQ system, which has been introduced in parallel with the removal of several detailed regulations. It appears as if this type of distribution of responsibility and power could increase the prospects for sustainability, as *polycentricity* is known to encourage learning, increase participation and promote diversity and redundancy (Ostrom 2009, Schoon et al. 2015, Soma et al. 2015). An interesting and at this point unanswered question, I think, is the role of science in a regionalized governance system with distributed responsibility. Some initial ideas on this issue have been presented by Mahon et al. (2008), suggesting a governance mix where a set of guiding principles and values (cf. Schoon et al. 2015) are achieved through a mix between regulative actions and enabling inputs to promote self-organization. In such a system, the main role of science would be to propose and evaluate different types of guiding principles based on an understanding of the system to be governed.

Conclusion

In 1778 S.T. Schultze, a member of the Royal Swedish Academy of Sciences, optimistically stated in "Den swenske fiskaren" ("The Swedish Fisherman") that Sweden, thanks to its location and diverse habitats, might have the most superb fishing waters in the world. While not exactly true (according to 2012 FAO statistics, Sweden ranked roughly seventieth in the world) there was and still remains a great richness and variety in target species, harvest technologies and modus operandi in Swedish fisheries.

The most important target species listed by S. T. Schultze in 1778 are strikingly similar to the species targeted today. Other things have changed profoundly. A lack of advanced processing capabilities at the end of the 18th century created a great interest in keeping fish alive in ponds and pools. In order to protect his or her fish, a competent fisher was able to shoot dead or scare away swans, herons, cranes, storks (now extinct), fish eagles, kites, sea gulls, geese and wild and captive ducks. Witchcraft was another threat to fishing luck, according to Schultze, as it could render fishing gear completely ineffective.

At the beginning of the 20th century (the starting point for this thesis) there was still great optimism about the future of Swedish fisheries. The steam engine had a dramatic influence on catch rates and great subsidies were paid for the establishment of modern harbors, more efficient vessels and processing and distribution infrastructure. For most of the century, the fishing industry was a piece in the larger puzzle of creating modern Sweden, and in 1977 the goals of the national fishing policy were to produce fish for domestic consumption, provide fishers with an income in parity with other groups in society, provide consumers with nutritious food to reasonable prices, to manage this efficiently, and to provide jobs in rural regions. Still relying on the same underlying ecosystem as in 1778, but with modern technologies and increasing demands, these ideas were unfortunately far from sustainable, despite good intentions. In fact, Swedish catches had already peaked thirteen years earlier, in 1964, largely because of the collapse of North Sea herring due to over-fishing.

Same ecosystem, changing societies. Or is it really the same ecosystem? Some species in the Baltic have become extinct over the past 250 years, while new species have arrived due to natural or human-aided expansions. Primary production is higher today because of the nutrients added by humans, creating widespread dead bottom zones. But profound variation also characterizes ecosystems without human influence. The Baltic Sea has had earlier phases of stagnation, with species appearing and disappearing along with variations in climate..

In the first act of "The Tempest", one of the last plays written by William Shakespeare, the sorcerer Prospero commands a storm. The shipwrecked Alonso, king of Naples, drowns, and his body lies on the sea floor. There, at five fathoms depth, something spectacular happens: his eyes turn into pearls, and his bones turn into coral. He suffers a *sea change*. Ever since, sea change has been a metaphor for a profound, un-anticipated change – a change to something beyond recognition.

As a present-day ecologist, I recognize the species and habitats S. T. Schultze described in 1778. Cod still swim in the southern Baltic and salmon spawn in the rivers of the northern Baltic. Perch and pike are found in the archipelagos and eels leave in the autumn – it is now known – for their spawning habitats on the other side of the Atlantic. I would recognize the late 18th century Baltic Sea ecosystem.

However, there has been a *sea change* in the relationships between humans and the Baltic. It was impossible for S. T. Schultze to anticipate fishing vessels with motors, dragging nets across the seafloor. Likewise, politicians in the late 20th century were unable to anticipate human-driven fish collapses. Yet these events have happened nonetheless, and have profoundly and irresistibly changed the conditions under which humans live with and benefit from Baltic nature.

What changes lie ahead? Can we learn anything from history? The development of the Swedish Baltic fishery over the last fifty years has been tightly interlinked with ecological, political and technological change. The leading group of Swedish fishers today target Baltic sprat and herring, but has, at different periods over the last forty years, focused primarily on both North Sea herring and Baltic cod. They currently benefit from high Baltic sprat abundance, high demand from the fishmeal industry and favorable regulations limiting access for competing fishers. We might conclude that the race for fish has ended and that the fishers are increasingly becoming stewards of their resource, as their long-term profit maximization incentives appear to align with ecological sustainability. Science has an increasingly important role in providing the knowledge base for management, but the impact of science reaches far beyond annual stock size estimations. The large and specialized fishing companies are continuously investing, supported by banks, under the presumption that harvest levels will remain stable for many years. Even though some simple ecological models suggest that long-term stable stocks and high-maintained harvest are achievable, other evidence suggests that ecosystems are chaotic and unpredictable. How can we best know? What will happen if the current path proves to be wrong? Might the current "sustainable" fishing patterns and fisheries management represent, rather, a straight path to collapse?

I think we have to explore these questions with different time scales in mind. There are many natural resource management problems that require immediate action. Such action must be informed by existing scientific tools. Other problems allow us to be a little more forward looking, to produce good science that seeks to inform action over a time frame of one, two or even three decades. Yet other problems are more fundamental and may need completely new scientific approaches. This will require brave scientific endeavor by researchers able to see beyond disciplinary boundaries, curious to find answers to questions yet-to-be-asked, embarking on trips to unknown destinations and crossing stormy waters - just like the sailor on the cover of this thesis.

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