

The Economics of Regime Shifts in Marine Ecosystems

Inauguraldissertation zur Erlangung des akademischen Grades
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vorgelegt von

Diplom-Volkswirtin Lorena Fricke

aus Ulm

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To Daniel

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1. GENERAL INTRODUCTION



Trinity Bay, Newfoundland

This thesis contains the following papers:

Fricke, L., Quaas, M.F. (2015), The Economic Causes of Regime Shifts in Marine Ecosystems, *unpublished manuscript*

Fricke, L., Quaas, M.F. (2015), The Economic Consequences of Regime Shifts in Marine Ecosystems, *unpublished manuscript*

Fricke, L. (2015), Economic Drivers of Regime Shifts in Optimally Managed Fisheries, *unpublished manuscript*

Section 1.2 contains a short description of my contribution to each of those papers.

The following paper is not part of this thesis:

Doering, R. Goti, L., Fricke, L., Jantzen, K. (2015), Equity and ITQs: About fair distribution in quota management systems in fisheries, forthcoming in *Environmental Values*

1.1 Motivation

Natural systems are often characterized by limited resilience and the possibility of regime shifts as a consequence of exogenous shocks (Scheffer et al., 2001). Examples include populations with a minimum population size below which extinction is inevitable (e.g., Gould 1972; Berck 1979; Bulte and van Kooten 2000), and ecological systems with complex interactions between the various components of the system such as shallow lakes and semi-arid rangelands (e.g., Mäler et al. 2003; Anderies et al. 2002).

The ecological literature typically considers regime shifts to be undesirable or even 'catastrophic' (Scheffer et al., 2001; Scheffer and Carpenter, 2003). This implies that strengthening resilience of natural systems should be a precondition for sustainability (Arrow et al., 1995; Levin et al., 1998; Perrings, 2006).

This thesis takes a new look at this issue by investigating the economic causes and consequences of regime shifts in marine ecosystems. In the following three chapters I study (a) the underlying economic causes of fishery collapse when fishing is unregulated,

(b) the implications for efficiency when an ecosystem experiences a shift, and (c) how an optimal management by itself can lead into regime shifts and species collapse.

The thread connecting the three articles in this thesis is not exclusively the overall topic 'regime shifts' but also the theoretical ecological-economic model that my supervisor Martin Quaas and I developed over the last years. It proved to be not only enduring but also versatile. I save details for later.

Rather I want to focus here on the motivation behind looking further into the economics of regime shifts. In particular I want to describe the famous case of a collapsed fishery and what it meant for an entire region in the North-West Atlantic: Newfoundland and Labrador. In my opinion, the case of Newfoundland is exceptionally well suited to explain the economic and ecologic reasoning behind many ideas in my thesis. Although I was only able to use this case study in the very last chapter of this thesis, Newfoundland provides anecdotal evidence for most of the modeling choices we made in the following articles.¹

Newfoundland holds some of the poorest, most fishery dependent provinces of Canada (Hamilton and Butler, 2001). Historically the cod fishery has been economically immensely important for Newfoundland & Labrador, and attracted an international fishing fleet for almost five centuries. By the late 1960s foreign overfishing had already severely depleted the Newfoundland cod stocks. The International Commission for the Northwest Atlantic Fisheries (ICNAF) first established quotas and total allowable catches (TACs) in the early 1970s but severely overestimated stock levels. Canada established an extended 200 mile exclusive economic zone in 1977 leading to a boom period for the local cod fishery. The number of registered fishermen in Newfoundland increased from 14.000 in 1976 to 34.000 in 1981 (Schrank, 2005).

In the early eighties catches fell dramatically and by the early 1990's the northern cod stocks finally collapsed. In 1992 Canada imposed a moratorium of the northern

¹ Additionally, I was lucky enough (thanks to Martin's generosity) to travel to Newfoundland in autumn 2011 and discover for myself the consequences of a massive ecosystem regime shift that resulted in the collapse of the northern cod stocks in the early 1990s.

cod fishery. The fishery was reopened on a small scale in the late 1990's but closed again shortly after. Directed fishing through stewardship and recreational fisheries was reopened on a very small scale in 2006 (DFO, 2014).

Although the story of the Newfoundland cod fishery plays only a minor part in the following three chapters, it brings up a number of issues that we used to motivate 'our' theoretical model of a fishery. The first and most important one is the dependency of a local economy on fish. This includes factor markets for both workers and capital such as fishing vessels and gear. The number of fishermen along with the whole branch of fish processing and trading that depends on a fishery does not only play a big part when assessing consequences of regime shifts and fishery collapses but may as well be one of their main causes. The same may be true for the demand for fish: If a local economy heavily depends on a fish species as a source of protein one would assume that pressure on stocks remains high even when stock levels are decreasing. The idea that both factor markets and output markets are possible causes of regime shifts is the main focus of the article in chapter 2 of this thesis.

Today, it is generally accepted that the main reason for the collapse of the Newfoundland cod is overfishing (Walters and Maguire, 1996; Myers et al., 1996, 1997).² Invertebrates (northern shrimp, snow crab, american lobster) increased in abundance after the Newfoundland cod stocks collapsed (Worm and Myers, 2003; Frank et al., 2005; Boudreau et al., 2011). It is suspected that the ecosystem at the Canadian east coast shifted towards a new stable equilibrium, where cod stocks remain at a low level while other species biomass levels, especially cod prey, including forage fishes, shrimp and large crustaceans remain high (Bundy, 2001; Worm and Myers, 2003; Rice, 2002; Bundy and Fanning, 2005).

Predator-prey relations similar to the ones described above can be found in virtually all fisheries around the globe. They are important determinants of system dynamics and stability. In Chapter 3 and 4 predator-prey relations between different species play an important role in determining management choices and consequences in the presence of

² Other theories included increased natural mortality due to environmental factors, harp seal predation, competition by pelagics and inaccuracy in stock estimation(Myers et al., 1996).

regime shifts.

The cod moratorium in Newfoundland set around 30 000 people (around 12% of the labor force) out of work immediately. Many outport populations are declining and depend increasingly on governmental transfers (Hamilton and Butler, 2001). However, after the cod moratorium the cod fishery was replaced by shellfish, caplin, halibut and other fisheries. The lobster fishery was already an established tradition but grew increasingly important after the cod moratorium. By the mid 1990s shrimp and snow crab landings quadrupled (tripled) compared to 1990. By 2002 the total value of Newfoundland landings increased about 60% in real terms compared to 1990 (Schrank, 2005). In 2008, these fisheries provided direct employment for about 25,000 workers.

From the description above we take that the idea of local factor and demand markets, and interactions between harvested species may complicate the assessment of management decisions, and consequences of regime shifts in a marine setting. Corresponding to that, chapter 3 of this thesis particularly focuses on dealing with the question who gains and who loses from a fishery collapse.

All of the presented work is just a first step in understanding the economic factors behind regime shifts. While the case of Newfoundland may appear as outdated, today's fisheries in the developing world are often managed poorly and many species are at the brink of collapse. At the same time, many regions are still strongly dependent on fisheries as the main source of food and employment. Hence, the question how to deal with possible and actual shifts is more pressing than ever. This thesis contributes to the discussion by exposing the relationship between the resource dependency of local economies and regime shifts. It specifies ways to assess the aftermath of regime shifts on the local economy, i.e. the changes in economic benefits for different stakeholders.

1.2 *Contributions*

Here I briefly describe my contribution to the individual chapters.

- Chapter 2: This paper is joint work with Martin Quaas. Martin Quaas came up with the general idea to use local input and output markets to explain fishery collapse. We worked together on the technical implementation. The analysis, the empirical part and most of the writing, were done by myself.
- Chapter 3: This paper is joint work with Martin Quaas. The theoretical part stems mostly from our previous work in Chapter 2. The empirical part and the writing were mostly done by myself.
- Chapter 4: The theoretical part stems mostly from our previous work in Chapter 2. I am the single author of this paper although it benefited from extensive discussions between Martin Quaas and myself.

2. THE ECONOMIC CAUSES OF REGIME SHIFTS IN MARINE ECOSYSTEMS

with Martin F. Quaas



St John's, Newfoundland

2.1 *Introduction: Regime Shifts and Fishery Collapses*

Many natural systems are characterized by limited resilience and the possibility of regime shifts as a consequence of exogenous shocks (Scheffer et al., 2001). Evidence for regime shifts in the late 1980s and early 1990s has been documented for marine ecosystems all across the Northern hemisphere (Choi et al., 2004, 2005; Beaugrand, 2004; Weijerman et al., 2005; Kenny et al., 2009; Moellmann et al., 2009; Hare and Mantua, 2000; Overland et al., 2008; Conversi et al., 2010). In the scientific literature it is assumed that these almost synchronous events were triggered by common drivers associated with climate variables, but trophic cascades caused by overfishing have been observed as well in many marine ecosystems that experienced a regime shift (Moellmann, 2011). In this vein, Neubauer et al. (2013) show that prolonged intense exploitation reduces resilience of harvested fish stocks. Additionally, it has been shown that consumer preferences for variety, or technical progress in harvesting, may trigger or hasten stock collapse (Squires and Vestergaard, 2013; Quaas and Requate, 2013). Thus, while overexploitation impedes the resilience of the system, another external driver (i.e. changing climate variables) may give the final impulse for the marine ecosystem to shift to another state (Moellmann, 2011).

We contribute to the discussion on the reasons of fisheries collapse by looking at local economic drivers (i.e. input and output market conditions) and derive conditions under which stock collapse is or is not an equilibrium outcome of unregulated fishing. We explain how input and output market conditions shape the open-access harvest function and, by that, affect the resilience of a fishery. To derive an empirically applicable form of the open-access harvesting function, we specify iso-elastic market supply functions for capital and labor, and derive the open-access catch quantity in market equilibrium as a function of the current stock size. We find that collapse is an open-access equilibrium under the following conditions: (i) the supply of labor and capital to the fishery is inelastic. This is the case for example if coastal economies have few employment alternatives outside the fishery. (ii) Consumer demand for fish is inelastic. This means that there are few close substitutes available for fish harvested from the corresponding stock (Quaas and

Requate, 2013). (iii) Harvesting costs do not depend strongly on the stock size. This latter effect has been discussed previously in resource economics (Clark, 1990) and known in the fisheries literature as hyperstability (Harley et al., 2001).

We apply our theoretical model using stock assessment data for 179 fisheries for which we estimate open-access harvest functions. We employ a stock-based indicator for stock collapse that is a modification of the classifications proposed by Worm et al. (2006) and Costello et al. (2008). Using estimated values for the model parameters and classification of stock collapse, we show that the probability of a fisheries collapse is affected by the shape of the open-access harvest function in the predicted way.

The remainder of this paper is organized as follows: In section 2.2 we set up our theoretical bioeconomic fishery model and derive the non-linear open-access harvest function. In section 2.3 we present estimates for open-access harvest functions for several fisheries using a global database for harvest and stock estimates. We then link our findings about the open-access harvest structure to observed fishery collapses using a non-linear probability estimation approach. The final section briefly concludes.

2.2 *A Model of an Open-Access Fishery*

In the following we set up the model for an open-access fishery. In everything that follows we consider a fishery on a single stock, abstracting from any biological, technical, or market-interactions between fisheries. Ecological factors driving population dynamics (and collapse) are diverse and often controversial. We aim at finding economic mechanisms that may contribute to stock collapses, and thus adopt a fairly general model on the ecological side. Biomass growth \dot{x} depend on stock growth before harvest $g(x)$ and harvest quantity h :

$$\dot{x} = g(x) - h . \tag{2.1}$$

We assume that stock biomass growth is zero at a zero stock size, $g(0) = 0$, and that marginal growth of the stock is finite and positive for very small stock sizes, $0 < g'(0) < \infty$. These assumptions suffice to show the principal results from our theoretical model.

Many fisheries focus on a species with no close substitutes, are sufficiently large to affect the world price or simply serve local markets. Constant output prices are not a reasonable assumption for any of these. We thus assume an iso-elastic inverse demand function for the harvest,

$$p(h) = \bar{p} h^{-\nu}, \quad (2.2)$$

where ν is the inverse price elasticity of demand, where we assume $0 \leq \nu < 1$. The restriction $\nu < 1$ means that revenues $p h$ will increase with harvest.

Harvesting is described by the generalized Gordon-Schaefer industry production function (Gordon, 1954; Schaefer, 1957),

$$h = q(x) E, \quad (2.3)$$

where $q(x) > 0$ denotes the ‘catchability’, which depends positively on stock size, $q'(x) > 0$. As common in the literature, we use the specification $q(x) = q \exp(\rho t) x^\chi$, where $q > 0$ is the productivity parameter, $\rho \geq 0$ is the rate of exogenous technical progress, and $\chi > 0$ is the stock-output elasticity or schooling parameter (Clark, 1990). We use E to denote the fishing effort, which can be thought of as an intermediate product that itself is produced by means of labor l and capital k input. We follow Hannesson (1983b), and assume a constant-returns-to-scale Cobb-Douglas production function

$$E = l^\varphi k^{1-\varphi} \quad (2.4)$$

with $\varphi \in (0, 1)$.

Fisheries often do not only provide an important source of protein for the local population, but are major sources for employment and foster local capital markets for vessels, gear etc. We assume that the production input, capital and labor, are supplied on local

markets. We furthermore assume upward sloping iso-elastic inverse supply functions,

$$w(l) = \omega l^\zeta, \quad (2.5)$$

$$r(k) = \kappa k^\psi, \quad (2.6)$$

with $\omega, \kappa, \zeta, \psi > 0$. For capital, this captures that fishing capital may be only partially malleable (Clark et al., 1979). One cannot easily use gear and vessels employed in one fishery in a fishery for a different species. For labor, an upward sloping supply curve translates into differences in employment alternatives for workers in the fishing industry that could be explained by different skill sets. When labor and capital supply is perfectly elastic, $\zeta = 0$ and $\psi = 0$, the wage and capital rental rates are fixed at some ‘world market’ levels, $w = \omega$ and $r = \kappa$.

We assume that fishermen minimize their costs, taking factor market prices as given. Because of constant returns to scale in effort production, harvesting cost is a non-linear function of factor prices w and r and a linear function of harvest, and given by

$$\tilde{C}(h, w, r; x) = \frac{w^\varphi r^{1-\varphi}}{\varphi^\varphi (1-\varphi)^{1-\varphi}} \frac{h}{q x^\chi \exp(\rho t)}. \quad (2.7)$$

Because of this linearity, marginal cost are equal to average cost. Under conditions of open access, fishermen will increase their harvest level until marginal profit is zero, and also the level of profit is zero – for given prices on factor and output markets. The resulting open-access condition is

$$p = \frac{w^\varphi r^{1-\varphi}}{\varphi^\varphi (1-\varphi)^{1-\varphi}} \frac{1}{q x^\chi \exp(\rho t)} \quad (2.8)$$

If prices on output and factor markets were constant, as in the Gordon-Schaefer framework, this condition determines a unique open-access stock size.

With imperfectly elastic supply of factors l and k , their prices depend on the effort level in factor market equilibrium, however. We show in Appendix 2.5.1 that factor prices increase in the harvest level, and that the market equilibrium cost function is the

following non-linear function of harvest and current stock biomass:

$$C(h, x) = C \left(\frac{h}{x^\chi \exp(\rho t)} \right)^{e+1}, \quad (2.9a)$$

with $C > 0$, and

$$e = \zeta \frac{\varphi(1 + \psi)}{1 + \zeta(1 - \varphi) + \psi\varphi} + \psi \frac{(1 - \varphi)(1 + \zeta)}{1 + \zeta(1 - \varphi) + \psi\varphi} > 0. \quad (2.9b)$$

The equilibrium cost function decreases with stock size and increases over-proportionally with harvest quantity, leading to unit costs that are increasing in harvest. This specific characteristic of the cost function results from the term $e > 0$. The expression for e in equation (2.9b) consists of two parts: The first part is derived from the equilibrium in the labor market, and the second part from the equilibrium in the capital market. The input market effect e is increasing in the elasticities of both labor and capital supply (ψ and ζ). The more elastic the supply of inputs, the more elastic the equilibrium cost function reacts to changes in the harvest level. For a perfectly elastic labor supply ($\zeta = 0$), the first term of (2.9b) vanishes, for a perfectly elastic capital supply ($\psi = 0$), the second term disappears. For perfectly elastic factor supply, the cost function (2.9) reduces to $C(h, x) = chx^{-\chi} \exp(\rho t)$, and the fishery experiences constant unit costs.

In an open-access situation, fishermen will enter the fishery when profits are positive and leave the fishery if profits are negative. Thus, using the open-access condition (2.8), we obtain the open-access harvest level as an iso-elastic, monotonically increasing function of stock biomass:

$$h_{oa} = \left(\frac{\bar{p}}{c} \right)^{\frac{1}{(e+v)}} x^{\chi \frac{(e+1)}{(e+v)}} \exp \left(\rho \frac{(e+1)}{(e+v)} t \right) \equiv a x^b \exp(ct). \quad (2.10)$$

Open-access harvest (2.10) is concave or convex in x depending on the elasticity b of open-access harvest with respect to the stock size. The size of b depends on the schooling behavior χ , the demand elasticity $1/\nu$, and the elasticity of input supply via term e . For

$x \in (0, \infty)$, we identify following cases

$$b \begin{cases} \geq 1 \\ \leq 1 \end{cases} \quad \text{for} \quad \frac{\chi - \nu}{1 - \chi} \begin{cases} \leq \\ \geq \end{cases} e. \quad (2.11)$$

For a concave open-access harvest function it must hold that e is sufficiently large. As e increases in both, ζ and ψ , this is true for sufficiently inelastic capital and/or labor supply. While in open-access fisheries no profits are gained by fishermen (cf. Eq. 2.8), producer surpluses do exist for $e > 0$ on account of the non-linear cost structure (cf. Eq. 2.9).¹

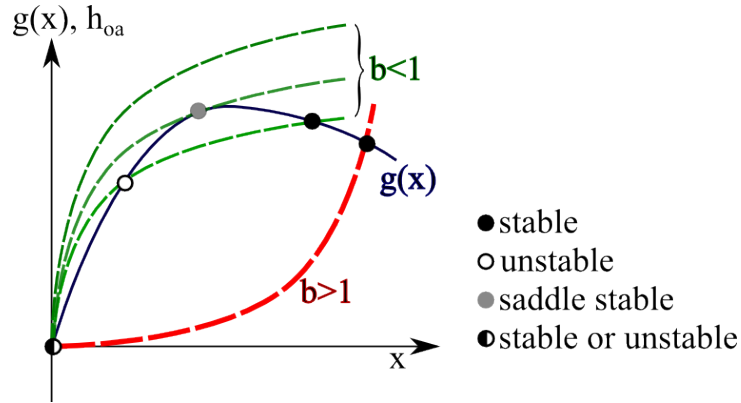


Fig. 2.1: Phase diagram and equilibria for the open-access fishery under different assumptions on the shape of the open-access harvesting function. The green and red curves depict open access harvest functions for different levels of b . The blue curve sketches a stock growth function. Steady states are depicted as colored dots, where stability is characterized in the legend.

Using the derived open-access harvest function (2.11) along with the assumptions on the biomass growth function, we now turn to analyze the resilience of the stylized system (illustrated in Figure 2.1). Stock growth and harvest are assigned to the vertical, stock size to the horizontal axes. Intersections of harvest (green and red) and stock growth (blue) curves represent equilibria of the open-access fishery that may differ in their stability properties. The effect of the concavity of open access harvest on the resilience is can be described by the effect on the stability of the equilibrium in the origin:

¹ One can easily rewrite equation (2.11) in terms of schooling (χ), resulting in the (well known) result, that open-access harvest adapts less elastic to changes in stock size, when the targeted fish species tends to form dense, stock-independent schools, i.e. if χ is small. When rewriting equation (2.11) in terms of the inverse elasticity of demand (ν), we find that for sufficiently inelastic demand, the open-access harvest function is concave. A shock on the fish stock leads – in case of an inelastic demand function and thus $b < 1$ – to a less than proportional change in open-access harvest, see equation (2.10).

- If $b > 1$, collapse ($x = 0$) is not an open-access equilibrium.
- If $b < 1$, collapse ($x = 0$) is always a stable open-access equilibrium.

By assumption, the slope of the population growth function (blue curve) in the origin is positive and finite (cf Eq. (2.1)) The concave open-access harvest functions (dashed green curves) lie always above the growth function for very small stock sizes. Stock collapse is therefore always a stable open-access equilibrium.

If the open-access harvest function and the growth function do not intersect, harvest always exceeds population growth, and the sole equilibrium at $x = 0$ is stable. If the open-access harvest function and the growth function intersect, there will be stable/saddle stable equilibria at positive stock levels $x > 0$. However, the collapsed stock equilibrium will remain locally stable. We draw concave harvest functions for several levels of a that scale the slope of the open access harvest function. Both, increasing prices (\bar{p}) and increasing technological progress (ρ) shift the concave harvest function upwards, leading to the disappearance of intersection points, thus, decrease the resilience of the system.

The slope of a convex harvest function (red curve) is always zero at the origin ($h'_{oa}|_{x=0} = 0$). As the slope of the growth function is positive at the origin, the stock collapse $x = 0$ always remains unstable.

Economically, the result illustrates that when coastal communities are especially fishery dependent, that is, if there are few employment alternatives for labor and capital outside the fishery, and thus the supply functions are inelastic, unregulated harvest will not adapt sufficiently to decreasing stock sizes. Harvest quantities will be unsustainable for small stock sizes (i.e. they lie above stock growth) and the fishery might collapse. Similar arguments hold with respect to the elasticity of demand for fish and the schooling behavior.

2.3 *Empirical Evidence*

We do not require detailed information on local capital and/or labor supply, or output demand to verify the effect of local, fishery-dependent input and output markets on

the resilience of a marine ecological-economic system. Instead, we employ a two-stage estimation procedure: The first stage includes the estimation of the open-access harvest function (2.10) for several fisheries to derive information about differences in the stock elasticity of open-access harvest b . In the second stage, we feed estimates from the first stage estimation into a regression model that explains the probability of fishery collapse.

2.3.1 First Stage: Open-Access Harvest Function

The estimation of an open-access harvest function (2.10) is based on the assumption that the fisheries are (at least de facto) unregulated, where management regulations are absent or ineffective.

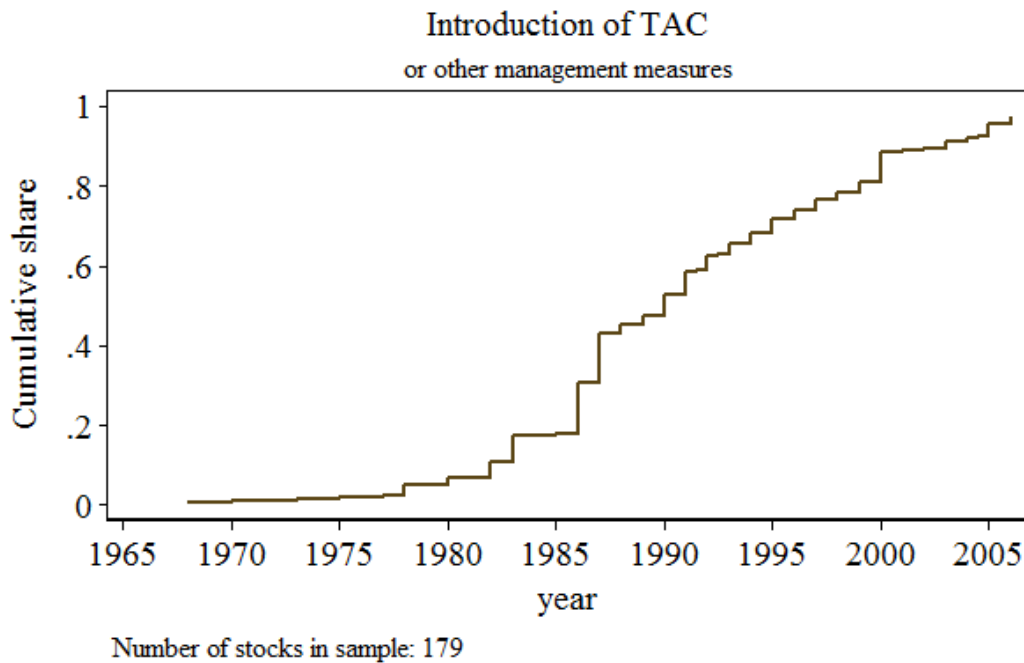


Fig. 2.2: The introduction of management over time. The figure depicts the cumulative share of fisheries managed by TAC or other measures over time in the RAM legacy database (Ricard et al., 2012).

We employ data on stock biomass and harvest quantity from Ricard et al. (2012), making use of the static copy of the RAM legacy database.² It contains time series of harvest (h) and spawning stock biomass (SSB) estimates from stock assessments for 331

² Available at <http://ramlegacy.marinebiodiversity.ca/ram-legacy-stock-assessment-database/how-to-access-the-ram-legacy-database> (accessed: Sept 2013).

marine fish and invertebrate stocks (Ricard et al., 2012). We combine this data with information on the year $T_{mgm,i}$ in which management systems have been introduced for each stock.³ We make use of only data on harvest and SSB when assigned to a year before $T_{mgm,i}$, and when a minimum of 10 observations is available.⁴ This reduces the number of fisheries to $N = 179$.

Figure 2.2 displays the cumulative share of management fisheries in out sample over time. We observe a steady increase in the share of managed fisheries since the late 1970s. While by 1990 only about half of the sample fisheries were at least de-facto managed, this number increases to almost 100% in 2007.

We estimate a logarithmic harvest function assuming log-normally distributed errors, and, by that, making sure that estimated harvest cannot be negative. The open-access harvest function is estimated for each fishery i separately using OLS, treating each stock as independent time series data set:

$$\ln(h_{i,t}) = \ln(a_i) + b_i \ln(x_{i,t}) + c_i t + \epsilon_{i,t} \quad \forall t < T_{mgm,i}, \quad (2.12)$$

where $\epsilon_{i,t}$ are Newey-West standard errors that may be heteroskedastic and possibly following an AR(1) process.⁵ We estimate (2.12) using the harvest data for $h_{i,t}$ and SSB for $x_{i,t}$ for 179 stocks. A more detailed description of the data and the regression results can be found in Table 2.2 in Appendix 2.5.2.

Figure 2.3 displays a histogram for estimated stock output elasticities. We find 136 positive point estimates for the stock output elasticity \hat{b} , 73 of them lie below unity.⁶ We cannot reject the null hypothesis $H_0 : b = 1$ at a 5% level for only 87 fisheries. This is strong evidence for the non-linear relationship between unregulated harvest and stock

³ Information on management is compiled from stock status and fishery management reports from the concerned advisory boards and/or management agencies.

⁴ Results remain robust with respect to varying the requested number of observations. See Appendix 2.5.2

⁵ Endogeneity issues may arise from estimating (2.12) as stock size in period t may depend on harvest in period t . Robustness checks of the second-stage results with respect to a possible endogeneity of the regressor in the first stage are performed. We use lagged stock size as instrument for stock size and estimate (2.12) using *Instrument Variable* (IV) regression. Results remain robust. See Appendix 2.5.4.

⁶ We also find 39 negative stock output elasticities (8 significantly negative at a 5% level). Second-stage results are robust with respect to inclusion or exclusion of these fisheries (see Appendix 2.5.4).

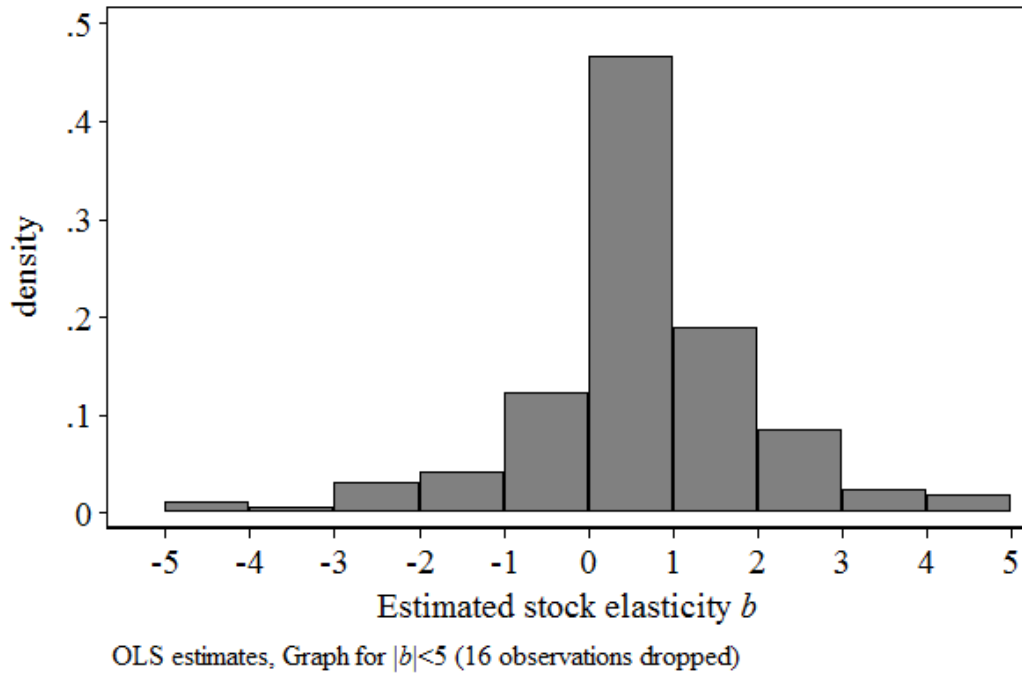


Fig. 2.3: Histogram of estimated stock elasticities \hat{b} from OLS estimation. Estimates with $|b| > 5$ are excluded in the figure.

size. Our theory states that the non-linearity stem from a combination of inelastic input supply, output demand, and the species' schooling behavior.

A 5% significant estimate for technological progress is found in 99 fisheries (84 of them positive). This effect varies considerably between fisheries. We also find differences in the remaining parameter, \hat{a} , even for same-species fisheries in nearby geographic area where technology can be assumed to be quite similar.⁷

2.3.2 Second Stage: Do Local Markets Influence Stock Collapse?

In the second stage we verify whether a concave harvest function indeed impairs the resilience of fish (or invertebrate) stocks by increasing their probability of collapse.

Classifications of collapse for fisheries have been proposed by Worm et al. (2006) and Costello et al. (2008). They are based on the relation of current harvest levels to former maximum harvest levels. According to these measures, a fishery is considered to be collapsed when the harvest level falls below a certain percentage (typically 10%-1%) of a previous maximum. It has, however, been stated that solely harvest based measures

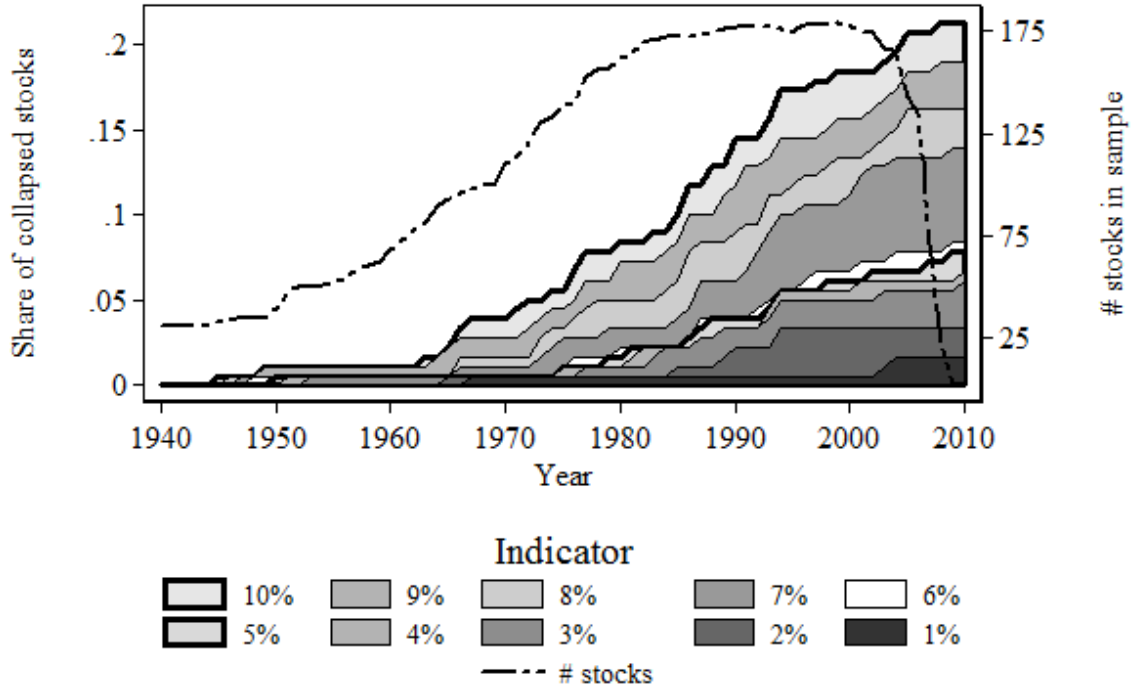
⁷ For more details on the first stage regression see Table 2.2 in Appendix 2.5.2.

may be misleading as landings data alone will not adequately reflect changes in fish populations and communities .

Here, we employ a modification of the collapse indicators by applying similar criteria to the stock sizes. The reason is that we want to explain that the stock may have collapsed because of a particular shape of the open-access harvesting function. When analyzing the stock effect on open-access harvest, as we do here, a solely harvest based approach may be misleading. One would suspect that in case of a convex open-access harvest function, harvest levels react strongly to changes in biomass, leading to a well-defined harvest based indicator for collapsed fish stocks. For concave functions, however, harvest reacts less drastically to changes in biomass, somehow diminishing the explanatory power of harvest based indicators. As Figure 2.3 shows the stock elasticity of open-access harvest varies considerably. We thus conclude that pure harvest based indicators for stock collapses are not suitable for our approach. We therefore apply the proposed indicators to actual stock size x (measured in SSB) instead of harvest. Additionally, we are not interested whether a stock can be categorized as collapsed only in a specific year but if it has been categorized as collapsed until the year T . By that we include the possibility of recovery through changes in the ecosystem. The applied indicator of collapse $D_{i,T_{coll,i},y\%}$ thus states whether a stock i can be classified as being collapsed until time $T_{coll,i}$:

$$D_{i,T_{coll,i},y\%} = \begin{cases} 1 & \text{if any } x_t \leq y/100 \cdot x_{s,max}; s < t \leq T_{coll,i} \\ 0 & \text{else,} \end{cases}$$

where y denotes the chosen percentage level, and $x_{s,max}$ the maximum observed stock level before time t . Figure 2.4 displays the share of collapsed fisheries in our sample using this indicator. For the calculation of the share we use the total number of fisheries $N = 179$. The dashed curve, however, depicts the total number of fisheries in sample at any given point in time. All 179 fisheries of the sample are only jointly observed in the period between 1980 and 2000. Using different indicator levels y naturally leads to differences in the classification. A 10% indicator eventually leads to a more than 20% share of collapsed fisheries by 2010, while the more conservative 3-6% indicators



Share calculated using the total number of stocks (179).

Fig. 2.4: Collapsed stocks in the sample. On the left side the figure depicts the share of stock in the sample that can be considered collapsed for a year using the indicator below. The 10% and 5% indicators are highlighted. The axis on the right side of the figure - corresponding to the dashed line - indicates how many stocks are observable for a given year in the sample.

yield in a share below 10%. In the following, we restrict the analysis to a 'lax' 10%, a conservative 5% indicator for collapse. To guarantee the connection between open access harvest and collapse we restrict the time of collapse to the start of the management year $T_{coll,i} = T_{mgm,i}$.⁸

To determine the influence of a concave open-access harvest function on the probability of a collapse, we are not interested in the influence of the exact value of the estimated parameter \hat{b} , but in the information whether it is smaller or larger than unity. A shock on either stock size, stock growth or harvest may lead to a fishery collapse if the harvest function is concave, but not if it is convex (given the fish stock is not characterized by a minimum viable population level). We thus generate a dummy variable, $D_{b<1}$ that takes

⁸ Results are robust with respect to other values of T_{coll} . Significance decreases only when using a lag between the year of the introduction of management and the year of collapse of more than 15. See Appendix 2.5.3 and 2.5.4.

the value one if the estimated stock elasticity \hat{b}_i lies below unity:⁹

$$D_{b<1} = \begin{cases} 1 & \text{if } \hat{b}_i < 1 \\ 0 & \text{else.} \end{cases}$$

We treat each stock as a separate cross-sectional unit, and employ a probit model to estimate the probability of a collapse:

$$P(D_{\text{collapse}} = 1) = \Phi(X'\beta + Z'\alpha), \quad (2.13)$$

$$\text{with } D_{\text{collapse}} \in \{D_{10\%}, D_{5\%}\},$$

where X are economic factors influencing the harvest function and Z ecological factors influencing the stock growth. Among the economic factors we add the dummy for concavity of the harvest function $D_{b<1}$ as well as the estimated intercept ($\ln \hat{a}_i$), and the estimated trend parameter (\hat{c}_i). Both $\ln a$ and c influence the steepness of the open-access harvest function (2.10): $\ln \hat{a}$ includes information on the output price level while the trend parameter is proportional to the rate of technological progress.¹⁰ Our model states that the increase in the output price level and in technological progress increases the probability of collapse (see Figure 2.1).

Ecological factors and shocks (Z) that cause changes in biomass growth are indisputably important reasons for regime shifts in marine ecosystems. Modeling these changes, however, goes beyond the scope of this study. We furthermore assume that these ecological factors are independent from the utilized economic factors that shape open access harvest ($X \perp Z$). A changing climate variable, for example, will shock the system independently of the shape of the harvest function.

Wooldridge (2002) demonstrates that unobserved heterogeneity caused by omitting independent variables from a probit model will bias the estimated regression coefficients

⁹ The 39 estimated \hat{b}_i that lie insignificantly below zero are included in that classification. The 8 estimated elasticities that lie significantly below zero are included as well. A robustness test with respect to the exclusion of these estimates is performed, and results remain robust. See Appendix 2.5.4.

¹⁰ It has previously been suggested that technical progress may increase harvesting pressure and hasten fisheries collapse (Squires and Vestergaard, 2013).

but does not affect the average marginal effect. Cramer (2003) suggests that same is true for logit models. However, the significance of estimates might be biased downwards (Ramalho and Ramalho, 2010). We thereby conclude that omitting ecological factors from equation (2.13) will still yield in consistent estimates on the average marginal effect of a concave harvest function on the probability of fishery collapse.¹¹

Results from the second-stage regression (2.13) are listed in Table 2.1 for the two collapse indicators and with economic control variables only.¹²

	$P(D_{5\%} = 1)$		$P(D_{10\%} = 1)$	
	Coef./s.e.	M.E./s.e.	Coef./s.e.	M.E./s.e.
$D_{b<1}$	0.938***	0.048***	0.695*	0.138*
	0.32	0.01	0.41	0.06
$\ln \hat{a}$	-0.020*	-0.001*	-0.016	-0.004
	0.01	0	0.01	0
\hat{c}	0.789	0.047	1.411	0.313
	1.15	0.07	1.11	0.24
Constant	-2.625***		-1.625***	
	0.27		0.36	
$\ln L$	-25.03		-72.965	
χ^2	9.312		4.193	
p-value	0.025		0.241	
N. of replications	650		1000	
N	179		179	

1st stage OLS, 2nd stage Probit with bootstrapped standard errors,
 $T_{collapse,i} = T_{mgm,i}$, Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Tab. 2.1: Second stage regression results for two collapse indicators (10% right and 5% left). Next to the coefficients (Coef.) the corresponding average marginal effects (M.E.) are listed.

The overall significance of all regressions (p-value) is satisfactory for the conservative but not the 'lax' indicator. The parameter of interest ($D_{b<0}$) is positive in both regressions and significant at a 1% level for the conservative and at a 10% level for the lax indicator.

¹¹ We additionally attempt to instrument ecological factors by including characteristics of fish species (habitual area) and a regional dummy D_{north} that equals one if the stock occupies the northern hemisphere. This large scale regional effect may control for an ecosystem effect such as the observed regime shifts in several ecosystems. However, results remain quite robust and almost all estimated ecological parameters remain insignificant. See Appendix 2.5.4 for more details on the regressions.

¹² We use bootstrapped standard errors to account for the *Error-in-Variables* (EIV) issue created by using the generated regressor $D_{b<1}$ in the estimation (Efron and Tibshirani, 1994; Matei and Meer, 2000). The number of bootstrap replications is given below estimates.

However, we cannot directly interpret the coefficients. Corresponding average marginal effects are listed next to the estimated coefficients. A concave open access harvest function thereby leads to a significant increase in probability of fishery collapse of 4.8%-13.8% depending on the employed indicator. The less-than-proportional adaptation of harvest to changes in stock size is thus clearly a risk factor concerning the collapse of fisheries. The result for the 5% indicator is remarkably robust with respect to changes in control variables, regression methods, changes in T_{coll} , and the number of observations we use (see Appendix 2.5.4).

The marginal effects of the economic controls $\ln a$ and c remain mostly insignificant for both regressions. For the 5% indicator we find a negative effect of the slope $\ln a$ that is significant at a 10% level. However, the marginal effect is quite small. Caused by the complex composition of the term a (see equation (2.11)) we are not able to interpret the average marginal effect of $\ln a$. Term c , however, is proportional to the rate of technological progress (ρ): an increase in technological progress by one percent point does not significantly change the probability of collapse.

Using a global data set and different indicators for fishery collapse, we find clear empirical evidence for our thesis that local input and output markets (that is sufficiently inelastic factor supply and output demand) as well as increasing schooling behavior of stocks decreases the resilience of an unregulated fishery. The probability of stock collapse positively depends on the the concavity of the open access harvest function. Results are mostly significant at least at a 1% level for a conservative 5% indicator, and quite robust with respect to changes in estimation method, time frame and other variations.

2.4 *Discussion*

In this paper we investigated the economic conditions under which an unregulated exploitation of a marine ecosystem is prone to collapse. We develop a theoretical model of an open-access fishery with two input markets for capital and labor, and one output market for the harvested product, and derive conditions for the existence of one or more open-access equilibria. Our results show that an unregulated fishery is particularly vul-

nerable to collapse if the supply elasticities for labor and capital are low, if the demand elasticity for fish is low, and if the fish species tends to form schools.

While the latter result is well known in the theoretical literature (Clark, 1990), the effects of input and output market structure on the resilience of a fishery have not yet been analyzed in such a formal setting. Bjørndal et al. (1993) suggested that in fisheries, capital with few employment alternatives as well as low opportunity costs of labor, that is, few outside options for fishermen, may lead to overexploitation and possible extinction. In our model these effects are formally linked to the open access harvest function via the non-linearity of the cost function. Producer surpluses gained from employing production factors lessen the adaptation of open-access harvest quantity to changes in stock size. Thus, the existence of “local” input markets leads to a decrease in stock elasticity of open-access harvest, and, by that, unsustainably high harvest levels especially for small stock sizes.

On the consumer side, we allow demand to be less than perfectly elastic. Given fish stocks decrease and supply for fish shifts down, the increasing equilibrium price level for fish may lead to only an insufficient adaptation of harvested quantity to the falling stock sizes. Again, this effect on its own – given the demand function is sufficiently inelastic – may lead to unsustainable harvest levels and possible collapse.

Clearly other factors, in particular natural and environmental events, are likely to also play a part in the collapse of fish stocks. Our theoretical model is highly stylized. We abstract from any species as well as industry interactions to allow for an analytical identification of certain market effects. Clearly in fisheries, biological interactions between species do exist and will influence the resilience of fisheries. Since we only impose very few assumptions on the biological part of the model, interactions between species would not lead to different results.

We test our theoretical results using a global data set of fisheries (Ricard et al., 2012). We use a classification for stock collapse that is based on the well known harvest-based indicator by Worm et al. (2006) and Costello et al. (2008) but applied to stock size instead of harvest. While we do not find support for technological progress affecting species

collapse, we do find that an open access harvest function that is inelastic with respect to stock size increases the probability of a fish stock collapse. We also show that the stock elasticity of open access harvest varies strongly between fisheries – and vary considerably from previous estimated schooling effects – indicating that differences in output and input markets indeed shape open access harvest. The resilience of marine fisheries thus seems indeed to be dependent on local economic conditions in fishing communities.

Our analysis is focused on unregulated fisheries – a type of management system that officially seems to become extinct in recent years. However, there are still many de-facto open-access fisheries around the globe, not only in the developing world but also within the regulated EU fisheries (Quaas et al., 2012).

Our empirical sample is mostly drawn from developed countries as there is no systematic database for harvest and stock levels for fish stocks in the developing world. However, management effectiveness, especially concerning the implementation and enforcement of regulations, seems to be lower in low-income than in high-income countries (Mora et al., 2009). Development countries additionally seem to be more at risk from illegal and unregulated fishing (Agnew et al., 2009). Thus, it seems that many fisheries, especially in the developing world are at least de-facto open access to date. Our theoretical model as well as the historical correlation drawn from mostly high income countries in our sample, may serve as an indicator on how de-facto unregulated fisheries in the developing world today are at risk of collapse depending on local labor, capital markets and markets for fish produce. Additionally, the effect of climate change on marine ecosystems will most likely not vanish, adding to the necessity of understanding marine ecological-economic systems and their vulnerability to collapse.

2.5 Appendix

2.5.1 The Market Equilibrium Cost Function

Using w to denote the wage rate and r to denote the rental rate for capital, the representative firm's cost minimization problem

$$\begin{aligned} \min_{l,k} \quad & wl + rk \\ \text{s.t.} \quad & \text{Eqs. (2.3), (2.4)} \end{aligned}$$

yields the factor demand functions

$$l = \frac{h}{q x^\chi \exp(\rho t)} \left(\frac{\varphi}{1-\varphi} \frac{r}{w} \right)^{1-\varphi} \quad (2.14)$$

$$k = \frac{h}{q x^\chi \exp(\rho t)} \left(\frac{1-\varphi}{\varphi} \frac{w}{r} \right)^\varphi \quad (2.15)$$

and a cost function that is linear in harvest, given by (2.7). In labor and capital market equilibrium, we find (using (2.14) in (2.5), (2.15) in (2.6) respectively)

$$w = \omega l^\zeta = \omega \left(\frac{h}{q x^\chi \exp(\rho t)} \right)^\zeta \left(\frac{\varphi}{1-\varphi} \frac{r}{w} \right)^{\zeta(1-\varphi)}, \quad (2.16)$$

$$r = \kappa k^\psi = \kappa \left(\frac{h}{q x^\chi \exp(\rho t)} \right)^\psi \left(\frac{1-\varphi}{\varphi} \frac{w}{r} \right)^{\psi\varphi}. \quad (2.17)$$

With (2.16) in (2.17) ((2.17) in (2.16) respectively) we derive the equilibrium wage and capital rental rate

$$w_{eq} = \left(\omega^{1+\psi\varphi} \left(\frac{h}{q x^\chi \exp(\rho t)} \right)^{\zeta(1+\psi)} \left(\frac{\kappa\varphi}{1-\varphi} \right)^{\zeta(1-\varphi)} \right)^{\frac{1}{1+\psi\varphi+\zeta(1-\varphi)}}, \quad (2.18)$$

$$r_{eq} = \left(\kappa^{1+\zeta(1-\varphi)} \left(\frac{h}{q x^\chi \exp(\rho t)} \right)^{\psi(1+\zeta)} \left(\frac{\omega(1-\varphi)}{\varphi} \right)^{\psi\varphi} \right)^{\frac{1}{1+\psi\varphi+\zeta(1-\varphi)}}. \quad (2.19)$$

Substituting (2.18) and (2.19) in (2.7), we obtain the equilibrium cost function

$$C(h, x) = C h^{e+1} x^{-\chi(e+1)} e^{-\rho(e+1)t},$$

with

$$C = q^{-(e+1)} \left(\frac{\omega}{\varphi} \right)^{\frac{\varphi(1+\psi)}{1+\psi\varphi+\zeta(1-\varphi)}} \left(\frac{\kappa}{1-\varphi} \right)^{\frac{(1-\varphi)(1+\zeta)}{1+\psi\varphi+\zeta(1-\varphi)}}, \quad (2.20)$$

and the "local" market term

$$e = \zeta \frac{\varphi(1+\psi)}{1+\zeta(1-\varphi)+\psi\varphi} + \psi \frac{(1-\varphi)(1+\zeta)}{1+\zeta(1-\varphi)+\psi\varphi}. \quad (2.21)$$

The local market term e increases in both, ζ and ϕ .

2.5.2 First Stage Regression Results and Data Summary

Table 2.2 summarizes the employed data set as well as some results from the 1st stage regression of the open access harvest function. The data set consists of 179 fisheries in 10 regions, the majority of them in the Pacific and Atlantic ocean. The minimal number

Number of stocks in sample	$N =$	179	
Number of observations for 1st stage regression	$\bar{T} =$	32	
	$T_{min} =$	10	
	$T_{max} =$	107	
Regions in sample:			
Atlantic Ocean (49), Arctic Ocean (5), Pacific Ocean (79), Indian Ocean (2), Antarctic Ocean (2), Bering Sea (11), North Sea (11), Baltic Sea (7) Gulf of Mexico (3), South Africa (10)			
1st stage Regression (OLS)			
Stock elasticity b	$\bar{b} =$	0.805	
Stock elasticity b	$b \in (0, 1)$	736	cases
	$b < 0$	40	cases
	$b^{**} < 0$	8	cases
Time trend c	$\bar{c} =$	0.047	
	$c > 0$	129	cases
	$c^{**} > 0$	85	cases
Constant $\ln a$	$\ln \bar{a} =$	-1.624	
Stocks with $b^{**} < 0$:			
Arrowtooth flounder , Gulf of Alaska ($T_{mgm} = 1990$)			
Dusky rockfish , Gulf of Alaska ($T_{mgm} = 1988$)			
School whiting, Southeast Australia ($T_{mgm} = 1992$)			
Albacore tuna, Northern Atlantic ($T_{mgm} = 2001$)			
Longspine thornyhead, Pacific Coast ($T_{mgm} = 1991$)			
Pacific hake, Pacific Coast ($T_{mgm} = 1999$)			
Gopher rockfish, Southern Pacific Coast ($T_{mgm} = 1982$)			
Mackerel, ICES IIa-IIIabd-IV-Vb-VI-VII-VIIIabcde-XII-XIV-Ixa ($T_{mgm} = 1987$)			

Tab. 2.2: Data summary and 1st stage regression results. The top part of the table contains information on the utilized data set including the number of observations and the covered regions. The second part summarizes estimated parameters b , c , and $\ln a$. The bottom part list all cases where the stock elasticity of open access harvest lies significantly (5% level) below zero.

of observations used for the 1st stage OLS regression is 10, the mean number 32. A Hausman test for exogeneity of the regressor x_t is performed for all regressions. The H_0

of exogeneity is rejected for 75 regressions. Robustness checks of second stage results with respect to using IV regressions in the first stage are performed and listed in Table 2.4 in 2.5.4.

2.5.3 Different Collapse Indicators

	#	$(T_{coll} - T_{mgm})$			
		0	5	4	15
Indicator	1%	1	1	1	2
	2%	4	4	5	5
	3%	6	6	7	10
	4%	6	6	7	11
	5%	6	8	9	12
	6%	6	8	9	14
	7%	9	17	19	23
	8%	14	22	25	26
	9%	19	25	29	30
	10%	27	31	35	36

Tab. 2.3: Variation in the collapse indicators. This table lists the number of 'collapsed' stocks in the sample when employing the $x\%$ indicator regarding a collapse that happened within $(T_{coll} - T_{mgm})$ years after management was introduced.

Table 2.3 lists the number of collapsed stocks for different levels y for the index of collapse (2.13), and different levels of $T_{coll} - T_{mgm}$, i.e. the maximum distance between the introduction of management measures and the fisheries collapse. Medium level indicators (3%-6%) yield in very similar results. For most indicators the number of collapses almost doubles when increasing the distance from 0 years to 15 years. This may indicate that introduced management measures are not very effective especially in the first years after introduction.

2.5.4 Second Stage Robustness Checks

Table 2.4 lists results using IV instead of OLS estimates in the first-stage regression. Estimated parameters remain positive and robust in magnitude and significance for the 5% indicator, but decrease both for the 10% indicator.

	$P(D_{5\%} = 1)$		$P(D_{10\%} = 1)$	
	Coef./s.e.	M.E./s.e.	Coef./s.e.	M.E./s.e.
$D_{b<1}$	0.792***	0.049***	0.234	0.054
	0.27	0.02	0.27	0.06
$\ln \hat{a}$	-0.004	0	0	0
	0.01	0	0	0
\hat{c}	0.162	0.009	0.165	0.038
	0.5	0.03	0.51	0.12
Constant	-2.383***		-1.166***	
	0.18		0.17	
$\ln L$	-24.661		-75.289	
χ^2	9.933		0.907	
p-value	0.019		0.824	
N. of replica-	650		1000	
tions				
N	179		179	
1st stage IV, 2nd stage Probit with bootstrapped standard errors, $T_{collapse,i} = T_{mgm,i}$, Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$				

Tab. 2.4: Robustness check: First stage IV regressions for two collapse indicators (10% right and 5% left). Next to the coefficients (Coef.) the corresponding average marginal effects (M.E.) are listed.

Table 2.5 summarizes results for the regression where stocks are excluded when the stock elasticity lies significantly below zero (first regression), and regressions using different control variables.

The second listed regression attempts to instrument ecological effects (Z) by using a dummy for northern hemisphere D_{north} , where ecosystem regime shifts have been observed in the 1990s. The third regression attempts to control for a management effect, that is a dummy that equals one if the fish stock is managed and fished multilaterally. We do not find significant effects for both control variables. The effect of a concave harvest on the probability of collapse remains robust.

$P(D_{5\%} = 1)$	Excl. $\hat{b}^{***} < 0$		Incl. D_{north}		Incl. $D_{multimgm}$	
	Coef./s.e.	M.E./s.e.	Coef./s.e.	M.E./s.e.	Coef./s.e.	M.E./s.e.
$D_{b<1}$	0.941*** 0.29	0.052*** 0.01	0.961*** 0.3	0.047*** 0.01	0.854*** 0.31	0.043*** 0.01
$\ln \hat{a}$	-0.019* 0.01	-0.001* 0	-0.021* 0.01	-0.001* 0	-0.017 0.01	-0.001 0
\hat{c}	0.777 1.09	0.049 0.07	0.967 1.3	0.056 0.07	0.625 1.24	0.037 0.07
D_{north}			0.298 0.29	0.015 0.01		
$D_{multimgm}$					0.467 0.35	0.042 0.04
Constant	-2.603*** 0.25		-2.886*** 0.32		-2.588*** 0.28	
$\ln L$	-24.767		-24.829		-24.75	
χ^2	10.945		12.928		10.096	
p-value	0.012		0.012		0.039	
N. of replica- tions	676		430		430	
N	171		179		179	

1st stage OLS, 2nd stage Probit with bootstrapped standard errors,
 $T_{collapse,i} = T_{mgm,i}$, Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Tab. 2.5: Robustness check: Control variables

Table 2.6 summarizes results changing the relevant time frame of species collapse ($T_{coll} - T_{mgm}$). Increasing the lag between the introduction of managements and the species collapse does not have a large effect on magnitude and significance of the average marginal effect for up to 10 years. An increase to $T_{coll} - T_{mgm} = 15$ however yields in a decrease of significance of all effects. This effect is suspected as more and more fisheries moved towards an effective management over time.

$P(D_{5\%} = 1)$	$T_{coll,i} = T_{mgm,i} + 5$		$T_{coll,i} = T_{mgm,i} + 10$		$T_{coll,i} = T_{mgm,i} + 15$	
	Coef./s.e.	M.E./s.e.	Coef./s.e.	M.E./s.e.	Coef./s.e.	M.E./s.e.
$D_{b<1}$	1.342 *** 0.45	0.074 *** 0.01	1.478 *** 0.45	0.086 *** 0.01	0.942 0.62	0.089 0.04
$\ln \hat{a}$	-0.027 ** 0.01	-0.002 ** 0	-0.029 ** 0.01	-0.002 ** 0	-0.017 0.01	-0.002 0
\hat{c}	1.255 1.28	0.082 0.08	1.311 1.36	0.091 0.09	1.347 1.52	0.150 0.15
Constant	-2.87 *** 0.44		-2.938 *** 0.44		-2.298 *** 0.59	
$\ln L$	-30.184		-32.618		-41.694	
χ^2	9.241		11.161		2.358	
p-value	0.026		0.011		0.501	
N. of replica- tions	685		678		886	
N	179		179		179	

1st stage OLS, 2nd stage Probit with bootstrapped standard errors,
 $T_{collapse,i} = T_{mgm,i}$, Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Tab. 2.6: Robustness check: Varying T_{coll}

Table 2.7 summarizes changing the minimum number of observations used in the 1st stage regression. We vary the number between 5 and 15. Again, the magnitude remains robust, while the significance decreases for both levels.

$P(D_{5\%} = 1)$	≥ 5 obs. In 1st stage		≥ 15 obs. In 1st stage	
	Coef./s.e.	M.E./s.e.	Coef./s.e.	M.E./s.e.
$D_{b<1}$	0.609*	0.03*	0.766**	0.047
	0.32	0.01	0.31	0.01
$\ln \hat{a}$	-0.009	-0.001	-0.04*	-0.003
	0.01	0	0.02	0
\hat{c}	-0.077	-0.004	-2.635	-0.193
	0.64	0.04	2.19	0.15
Constant	-2.377***		-2.266***	
	0.25		0.28	
$\ln L$	-26.42		-22.909	
χ^2	3.848		6.939	
p-value	0.278		0.074	
N. of replica- tions	662		660	
N	212		131	

1st stage OLS, 2nd stage Probit with bootstrapped standard errors,
Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Tab. 2.7: Robustness check: Number of observations

3. THE ECONOMIC CONSEQUENCES OF REGIME SHIFTS IN MARINE ECOSYSTEMS

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3.1 Introduction

Natural systems may be characterized by limited resilience and the possibility of regime shifts as a consequence of exogenous shocks as well as internal forces (Scheffer et al., 2001). The ecological literature typically considers regime shifts to be undesirable or even “catastrophic” (Scheffer et al., 2001; Scheffer and Carpenter, 2003). Put the other way around, strengthening resilience of natural systems is perceived to be a precondition for sustainability (Arrow et al., 1995; Levin et al., 1998; Perrings, 2006).

We understand regime shifts as drastic changes in the composition of marine ecosystems over a large time and space scale. In the Baltic sea two major regime shifts concerning local fisheries have been identified. One shift from seal to cod domination due to the virtual elimination of marine mammals in the Baltic, and another from cod to sprat domination in the late 1980s. The latter regime shifts has been explained by overfishing and climate change and accompanied by additional food-web changes (Österblom et al., 2007; Moellmann et al., 2009; Lindegren et al., 2009).

In this paper, we study an ecological-economic fishery model and investigate the economic consequences of regime shifts, such as observed in the late 1980s for the Baltic sea, to which we apply our model. We consider an open access fishery, and analyze the distributional implications of a regime shift, i.e. the distribution of benefits for different functional interest groups using the ecosystem, and looking at situations with and, hypothetically, without a regime shift. The regime shift is triggered by an exogenous shock on the predator population dynamics, with internal economic processes playing an important role for the (in-)stability of the coupled ecological-economic system. We consider an imperfectly elastic demand for landed fish and a non-linear fishing cost function, which may be due to imperfectly elastic supply of production factors employed in the fishery in a similar fashion than in chapter 2 of this thesis (Fricke and Quaas, 2015a). These non-linearities influence the shape of the relationship between open access harvest and the current stock size and, by that, affect the resilience of the open-access fishery. The non-linearity of the cost function allows for positive factor rents in an unregulated fishery even if profits are zero. We show that, under the assumptions of iso-elastic cost

and demand functions, factor surplus and consumer surplus vary with the stock size in a parallel fashion. Thus, for an individual fishery, factor owners are positively affected by a regime shift if and only if consumers gain from the regime shift. In a multi-species setting, however, as present in the Baltic cod, herring, and sprat fisheries, a regime shift may affect the stakeholders in the fisheries differently.

To study these effects quantitatively, we apply our model to the Baltic sea sprat, herring and cod fisheries. We investigate the surpluses generated in the Baltic fisheries for the various functional interest groups and analyze how they are affected by the ecosystem regime shift. The parametrization of the cost and demand functions are empirically highly uncertain. We take this uncertainty into account by conducting a thorough Monte-Carlo sensitivity analysis of the model. We find that the stakeholders in the cod and herring fisheries most likely have incurred a loss from the regime shift. For the herring fishery the loss depends on whether or not the regime shift triggered a stock collapse, which depends on the exact economic parameters. The stakeholders in the sprat fishery, by contrast, most likely have benefited from the regime shift, but the magnitude of the benefit is much lower than the loss incurred by the two other fisheries.

The paper is organized as follows. In the following section, we develop our ecological-economic model and derive analytical results. In section 3, we present the quantitative results for the Baltic sea. The final section briefly concludes.

3.2 *A Coupled Ecologic-Economic Model*

In the following, we sketch the coupled ecological-economic model starting with the ecological part. Population dynamics are modeled as a biomass model that is based on logistic growth and possible interactions that enter the dynamics linearly, as previously used for fisheries (Flaaten, 1991; Brown et al., 2005) and grazing systems (Walker et al., 1981). The growth function of a fish stock x is furthermore specified as:

$$g(x) = r x \left(1 - \frac{x}{K}\right) + \mu x y, \quad (3.1)$$

where $x \geq 0$ the species biomass, $r > 0$ is the intrinsic growth rate, $K > 0$ the capacity limit, and $h \geq 0$ the harvest rate. The interaction parameter μ may be positive or negative, depending on the specification of the triggering variable y .¹

We thus think of y as a place holder for either predator, prey, competition or another exogenous effect such as climate change.

In our model interactions between fisheries only exist on the ecological side. Costs, harvest, input and output markets are assumed to be independent for the different fisheries. In the following we set up the economic part of the model without writing an index for the particular species to the cost and demand functions. All parameters are conceived to differ with the fish species under considerations.

Harvesting is described by the generalized Gordon-Schaefer production function,

$$h = q E x^\chi, \quad (3.2)$$

where $q > 0$ denotes the productivity parameter, and $\chi > 0$ the stock-output elasticity, sometimes referred to as ‘schooling’ parameter. In the Gordon-Schaefer framework, which assumes $\chi = 1$, q is the ‘catchability’ coefficient. Fishing effort E can be thought of as an intermediate product that itself is produced by means of labor l and capital k according to some production function (Hannesson, 1983a; Squires, 1987).

Fishermen are assumed to minimize their costs to determine their optimal harvest quantity in each period. Cost minimization gives rise to factor demand for labor and capital employed in the fishery. If the supply of these factors is imperfectly elastic, their price in factor market equilibrium, and thus marginal fishing cost, will increase with harvest quantity. Similarly, if the effort production function exhibits decreasing returns to scale, marginal fishing costs will be increasing with catch. We thus assume a harvesting

¹ The variable y may stand for the stock size of a competing, predator, or prey species. For the predator-prey case, the interaction term that is both linear in prey and predator biomass, reflects the assumption that predator and prey randomly move in a homogeneous environment and the predator’s success rate when meeting a prey is μ . An increase in predator biomass decreases both the growth rate for a given biomass level and the maximal achievable biomass level of the prey by shifting the growth function down.

cost function of the following iso-elastic type

$$c(h, x) = c \left(\frac{h}{x^\chi} \right)^{e+1}, \quad (3.3)$$

with $c > 0$, and $e \geq 0$. A potential non-linearity in the cost function is modeled by the parameter $e \geq 0$. It equals zero if all input factor supplies are perfectly elastic, and if the effort production function exhibits constant returns to scale. If any of the production factors is imperfectly elastic in supply, or if the effort production function exhibits decreasing returns to scale, marginal fishing costs will increase with the catch, $e > 0$. We show in Appendix 3.5.1 how the cost function (3.3) could be derived from assumptions on the inverse supply functions of labor and capital, and a Cobb-Douglas effort production function.

It may be safe to assume perfectly elastic demand for output of a fishery in some cases, for example a small cod or haddock fishery selling fish on a large world market for white fish. However, many fisheries either serve local markets, focus on species with no close substitutes, or are sufficiently large to affect the world price. We assume an iso-elastic inverse demand function,

$$p(h) = \bar{p} h^{-\nu};, \quad (3.4)$$

for the harvest, where $0 \leq \nu < 1$ is the inverse price elasticity of demand. The restriction $\nu < 1$ means that revenues ph will increase with harvest.

3.2.1 The Open Access Fishery

In an open access situation, fishermen will enter the fishery when profits are positive and leave the fishery if profits are negative. Thus, using the zero profit condition, $p(h)h = c(h, x)$, with Eq. (3.3) and Eq. (3.4), we obtain the open access harvest function,

$$h_{oa} = ax^b, \quad \text{with } a = \left(\frac{\bar{p}}{c} \right)^{\frac{1}{(e+\nu)}}, \quad \text{and } b = \chi \frac{(e+1)}{(e+\nu)} \quad (3.5)$$

Open access harvest (3.5) is concave or convex in x depending on the size of the term b . The stock elasticity of open access harvest b depends on the schooling behavior χ , the demand elasticity $1/\nu$, and the input market conditions via term e . For a concave open access harvest function it must hold that e is sufficiently large. We show this in more detail in Appendix 3.5.1.

Figure 3.1 illustrates how both, the limited resilience in an ecosystem changes (by a change in μy), and the limited resilience in an economic system (imperfectly elastic labor and capital supply) may lead to the collapse of the open access predator fishery. Population dynamics are drawn for two levels of μy (the green and red curves). Three different harvest functions are drawn for the concave (Figure (3.1a, numbering (1)-(3)), and one for the convex (Figure (3.1b)) case. Filled circles indicate stable, empty circles unstable, and dashed circles saddle stable equilibria.

By assumption (cf. Eq. (3.1) ff), the population growth function is finite and positive at the origin. The concave open-access harvest function (as in panel (a)) thus lies always above the growth function for very small stock sizes. Stock collapse ($x = 0$) is a locally stable open access equilibrium in this case. If the open-access harvest function and the growth function do not intersect, harvest always exceeds population growth, and the equilibrium at $x = 0$ is globally stable.

The slope of a convex harvest function in Figure (3.1(b)) on the other hand is always zero in the origin. For very small stock levels, the growth function lies always above open access harvest. Stock collapse is therefore always unstable and there is only one unique stable open access equilibrium at a positive stock level.

We can use this result for the stock elasticity of open access harvest along with the population dynamic from Eq. (3.1) to make statements about the resilience of the system:

Proposition 1. *If $b < 1$, collapse ($x = 0$) is always a stable open access equilibrium. If $b > 1$, collapse ($x = 0$) is no open access equilibrium.*

The concavity of the open access harvest function depends on the characteristics of input supply functions. Thus, if the schooling parameter lies between zero and unity and capital and/or labor are sufficiently inelastic, the resilience of the marine ecological-

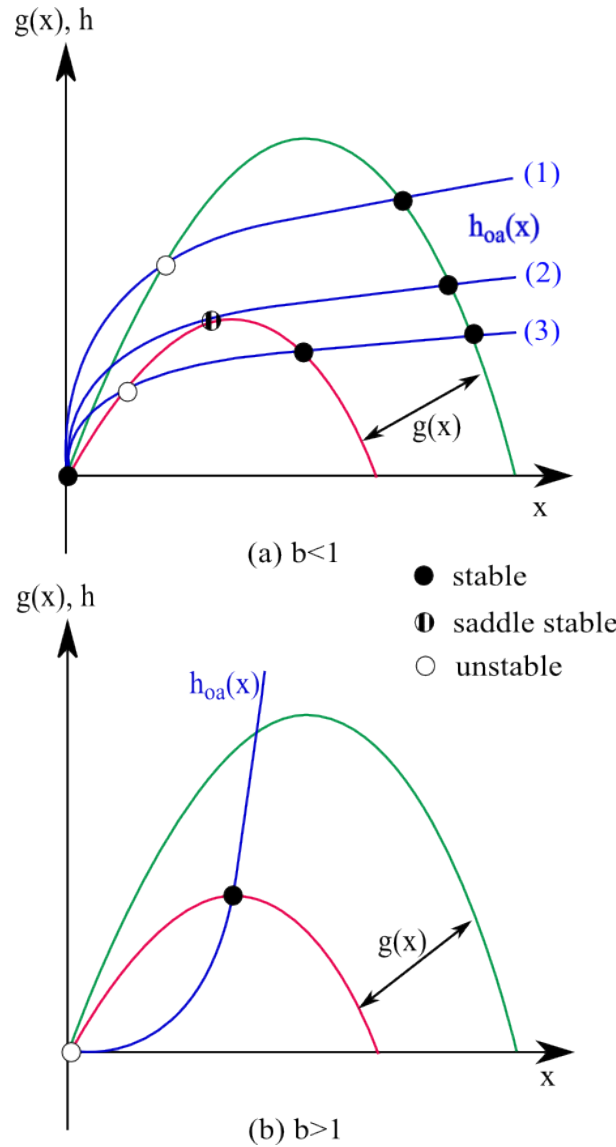


Fig. 3.1: Illustration of potential regime shifts in a fishery. Both figures depict possible growth functions (in green and red), open access harvest functions (in blue), and steady states including their stability characteristics. The top panel illustrates different formations of concave open access functions (1)-(3).

economic system is reduced, i.e. stock collapse is always a stable open access equilibrium. The economic idea behind this mathematical result is not new. Bjørndal et al. (1993) already discuss that “long-lived capital with few or now alternative employment opportunities is more likely to lead to serious overexploitation or even stock extinction than short-lived, mobile capital” (Bjørndal et al., 1993, p 161). A similar line of reasoning applies for labor as fisheries are often seasonal, and employment alternatives for fishermen may be very limited.

We can further determine the tipping point of an open access fishery depending on

the size of μy in the population dynamics (3.1) corresponding to the curve (2) in Figure (3.1(a)).

Proposition 2. *Define*

$$\Theta = \frac{K(r(b-1) + \mu y(b-1))}{r(b-2)}. \quad (3.6)$$

Collapse is globally stable if

$$\mu y < \bar{\mu} y \equiv ab\Theta^{(b-1)} - r\left(1 - \frac{2\Theta}{K}\right) \quad (3.7)$$

Proof. See Appendix 3.5.2. □

Is the interaction effect smaller than a certain value $\bar{\mu} y$ the maximum achievable net population growth lies below zero. In this case the population inevitably collapses.

Rents

The non-linear cost structure allows for a positive factor rents in the open access regime even if there are no profits. These factor rents comprise worker surplus, capital owner surplus, and profits in effort production. We interpret the sum of these rents as fisherman's surplus (FS). It be calculated as the area between the marginal cost curve and the horizontal line at the open access price level,

$$FS = \frac{e}{1+e} c \left(\frac{h_{oa}}{x^x} \right)^{1+e} \quad (3.8)$$

For the proof see Appendix 3.5.3.

The open access consumers surplus can be derived as the area between inverse demand and the horizontal line at the open access price level,

$$\begin{aligned} CS &= \int_0^{h_{oa}} p(h) dh - p(h_{oa}) h_{oa} \\ &= \frac{\nu}{1-\nu} \bar{p} h_{oa}^{1-\nu}. \end{aligned} \quad (3.9)$$

Proposition 3. For given parameter values e , c , χ , ν , and \bar{p} , FS and CS change proportional to each other over time, $FS \propto CS$.

Proof. This is because $h_{oa} \propto x^b$, with b given by (3.5). Thus,

$$\begin{aligned} FS &= \frac{e c a^{1+e}}{1+e} x^{(b-\chi)(e+1)} = \frac{e c a^{1+e}}{1+e} x^{(1-\nu)\chi \frac{e+1}{e+\nu}} \\ &= \frac{e c a^{1+e}}{1+e} x^{(1-\nu)b} = \frac{e c a^{e+\nu}}{1+e} h_{oa}^{1-\nu} = \frac{e \bar{p}}{1+e} h_{oa}^{1-\nu} = \frac{e(1-\nu)}{(1+e)\nu} CS. \end{aligned}$$

□

Since both, consumers and factor owners are affected proportionally, changes of stock size or harvest level lead to no trade-offs within a single fishery. When ecological interactions exist, however, trade-offs between consumers and factor owners of different fisheries may occur.

3.3 The Baltic Sea System

The Baltic Sea is a brackish semi-enclosed sea that is relatively poor in fish species. Its commercial fishery is mainly dominated by cod, with catches in 2012 of around 80 000 t, sprat (190 000 t), and herring (200 000 t). And landed values of around 80 mio€ for cod, 60 mio€ for herring, and more than 40 mio€ for sprat (STECF, 2013, p 233 ff). Cod landings peaked in the late 1970s/early 1980s to around 400 000 tonnes followed by a swift decline in spite of high effort levels (ICES, 2013c). Simultaneously catches of sprat increased substantially in the 1980s and 1990s.

Cod, sprat and herring in the Baltic sea do not exist independently of each other. Suggested interactions include cod predation on both, sprat and herring, while the two prey species themselves prey on cod eggs and larvae and impose food competition for each other, and young cod. Zooplankton abundance may also affect stock size (Lindgren et al., 2009). Since the early 1980s cod biomass decreased, while the development of sprat biomass seemed to be positively affected by the decreasing cod stocks. Herring biomass steadily decreased from the 1970s until 2000. Moellmann et al. (2009) identify

two stable ecosystem states between the 1970s and the 2000s separated by a transition period between 1888 and 1993. Main forces behind the shift from a cod dominated towards a sprat dominated state in the late 1980s have previously been identified as climate change and overfishing (Österblom et al., 2007; Moellmann et al., 2009; Lindegren et al., 2010). This corresponds well to the proposed theoretical model, where both, economic as well as ecological factors influence the resilience of a fishery.

While we explain the regime shift in the 1980s on an aggregate Baltic sea level in the following subsection, we thereafter restrict our analysis of the economic consequences of the Baltic sea regime shift to the interesting case of Finland. Finland is characterized by a long coastline (4600 km, islands not included) and about 81 000 islands with an area of more than 100 sqm in the Baltic sea. It's fishery is almost exclusively located in the Baltic sea area. Especially in rural areas there are only few employment alternatives other than the fishing and there is an ongoing concern for the continuity of employment possibilities in the fishing industry. In 2011 there were around 2800 persons employed in the harvest sector and around 900 in fish processing. The most important commercial fisheries in the Baltic sea by volume are herring and sprat, that latter almost solely used for animal fodder (OECD, 2003, 2014). Cod is traditionally only a minor fishery in Finland since cod fishing grounds are further offshore and thus less accessible.

We restrict our analysis to the case of Finland for two reasons: First, Finland is one of the few countries that fish all three species of interest exclusively in the Baltic sea. Second, Finland is the only state that provides sufficient long time series data on landings, landing values and effort levels which enables us to estimate elasticities of interest (FGFRI, 2014).

3.3.1 *The Baltic: Population Dynamics, Harvesting, and the Regime Shift*

We apply the population dynamics in Eq. (3.1) to the Baltic sea ecosystem, i.e. cod (c), herring (h), and sprat (s). We use data on spawning stock biomass (SSB) from ICES (2013a,b,d) for a period from 1974 (1963 for cod) to 2013. Historical data on aggregate Baltic sea harvest, H , is available for the period from 1950 to 2010 is provided by ICES

	Cod	Herring	Sprat
Population Dynamics: Baltic Sea			
r	0.887***	0.877***	0.647***
K	1.506***	1.997***	2.894***
μ	-0.121*	-0.141**	-0.832**
Harvest Function: Aggregate Baltic Sea			
B	0.865***	0.399***	1.599***
A	0.562***	0.361***	0.221***
Harvesting and Markets: Finland			
c	0.676	0.000	3.709
e	0.261**	-3.844	0.888
q	33.142***	51.962***	61.162***
χ	0.806***	0.265*	0.174**
ν	0.314***	0 ^a	0 ^a
\bar{p}	0.157	0.143***	0.099***
$\Rightarrow b$	1.769***	0.196	0.370
$\Rightarrow a$	0.079	0.090***	0.017***
^a : Restriction $\nu_h = \nu_s = 0$.			
Significance: 1% ***, 5% **, 10% *			

Tab. 3.1: Estimated parameters for the Baltic sea system. The top two section list estimates for the aggregate Baltic sea population dynamics (3.10) and open access harvest functions (3.11). To bottom section lists estimated parameters for the Finnish market equilibrium system (3.13).

(2011).² The growth of each stock in time t is approximated by the difference in stock levels in subsequent years t and $t + 1$ adjusted by harvest in year t .

In the growth function of cod and herring we include an ‘ecosystem dummy’ that accounts for the ecosystem regime shift.³ For sprat, this interaction effect is the cod stock. The formal regression model for the population dynamics separately for cod,

² Cod and herring harvest and stock data is for ICES subdivision 25-32 (IIIId). Sprat stock data is for ICES subdivision 22-32, harvest for IIIId. A detailed description of the utilized data is presented in Appendix 3.5.5.

³ We test other variations of the population dynamics such as including the external effect in sprat. We also try incorporating possible competition between the two prey species, and creating a feed-back loop between prey and predator. Also, effects of changes in zooplankton concentration are investigated. The finally chosen ecological model represents the most parsimonious model that is compatible with previous and more in-depth foodweb models of the area. Results are also quite robust to the choice of the regime shift time point. A summary can be found in Table 3.4 in Appendix 3.5.6.

herring, and sprat (dropping fishery subscripts i) is:

$$g_t(x) = x_{t+1} - x_t + H_t + \varepsilon_t = r x_t \left(1 - \frac{x_t}{K}\right) + \mu x_t y + \varepsilon_t, \quad (3.10)$$

with

$$y_s = x_{c,t}, y_c = y_h = D_{t \geq 1988} = \begin{cases} 1 & \text{if } t \geq 1988 \\ 0 & \text{else,} \end{cases}.$$

including the error terms ε_t .⁴ We make use of the fact the Eastern Baltic fish stock were exploited under conditions close to open access until 2008 on an aggregate Baltic level, and assume that the open-access condition in Eq. (3.5) holds until then.⁵ We estimate the logarithmic aggregate open access harvest function separately for the three fisheries (dropping fishery subscripts i):

$$\ln H_{t,oa} = \ln \hat{A} + \hat{B} \ln x_t + \epsilon_t, \quad \forall t \leq 2008, \quad (3.11)$$

$$(3.12)$$

including the error terms ϵ_t .⁶ The upper case coefficients A , and B denote that the open access harvest function is estimated on an aggregate Baltic level.

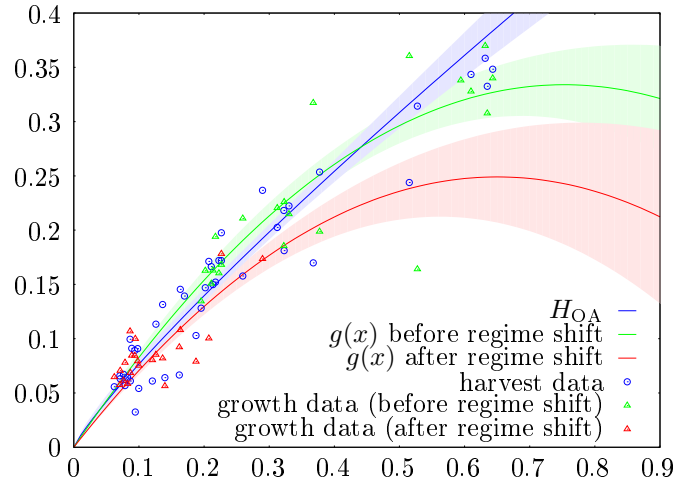
The top to sections of Table 3.1 sum up estimates of population dynamics (3.10), and the aggregate open access harvest function.⁷ Point estimates and standard errors of stock growth functions and open access harvest functions are used to depict possible open access equilibria in the Baltic sea system in Figure 3.2. The colored ' Δ ' are the available observations for each fitted growth curve, the colored 'o' depict observations

⁴ For details on the estimation and the error structure see Appendix 3.5.6.

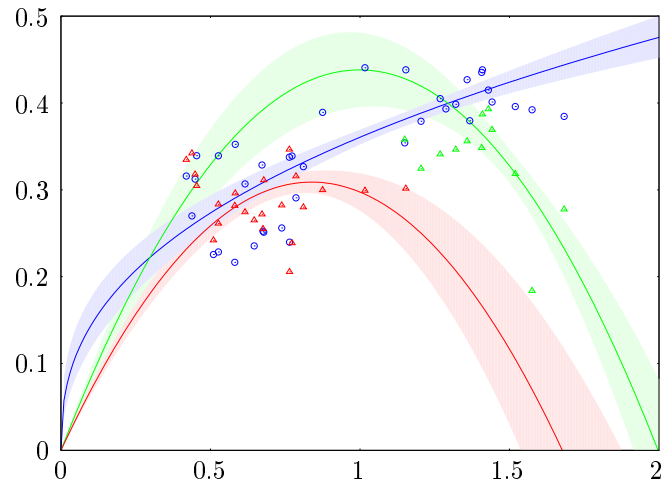
⁵ We employ the criterion for *de facto* open access from Quaas et al. (2012). A fishery is considered *de facto* open-access when in at least three consecutive years between 1984 and 2008 the catch was less than 90% of the total allowable catch (TAC) and no additional management measures are in place. This is true for all considered fisheries (ICES, 2013c).

⁶ For details on this regressions and the error structure see Appendix 3.5.7.

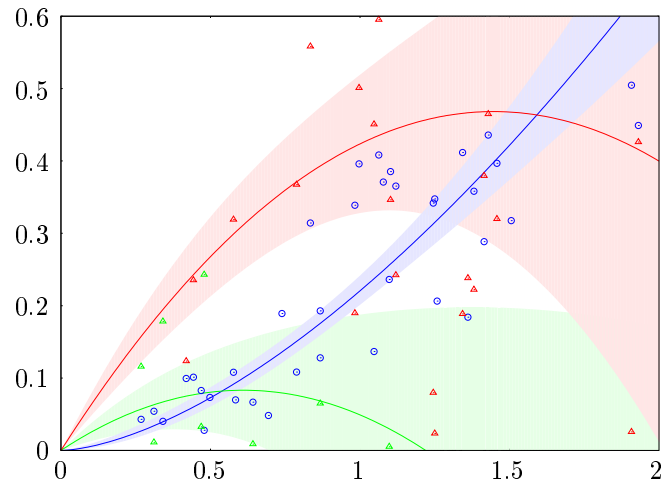
⁷ All estimated intrinsic growth rates and carrying capacities are significant and in a reasonable range. Quaas et al. (2012) estimate $\hat{r}_c = 0.74$ for the Baltic cod. Carrying capacity of cod has been previously estimated at $\hat{K}_c = 2$ million tons by Froese and Proelß (2010), and $\hat{K}_c = 1.875$ by Quaas et al. (2012). Also, Baltic Herring intrinsic growth and carrying capacity have been estimated by Quaas et al. (2012): $\hat{r}_h = 0.28$, $\hat{K}_h = 4.667$. To our knowledge, there are no similar estimates for Baltic sprat population dynamics available.



(a) Cod



(b) Herring



(c) Sprat

Fig. 3.2: Estimated stock growth and open access harvest using parameters listed in Table 3.1. Fitted growth functions are in green (pre-1988) and red (post-1988), and open access functions in blue. The shaded areas around each curve depicts the ± 1 s.e. interval.

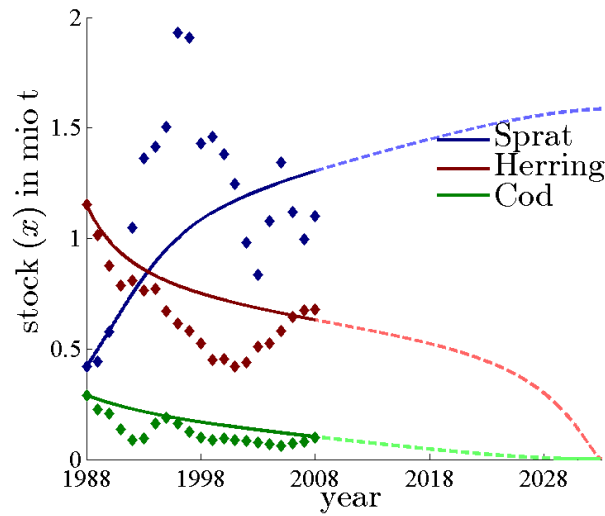
for harvest. The colored curves represent the fitted growth functions pre-regime shift (green) and post-regime shift (orange), and the open access harvest functions (in blue) for each species, and the shaded areas around the curves depict \pm one standard error confidence regions around the estimates.

Estimated Baltic cod (panel (a)) and herring (panel(b)) growth and harvest functions behave similarly. The regime shift leads to a decrease in the growth rates at any particular stock size, and the de-facto carrying capacity of both stocks. The estimated open access harvest function is concave for herring and cod. Pre-1988 growth and harvest function intersect at a positive equilibrium stock level, $x_{c,oa} = 0.45$ ($x_{c,oa} = 1.29$), corresponding to $h_{c,oa} = 0.28$ ($h_{h,oa} = 0.4$). The amplitude of the downward shift of the growth functions after 1988 averts the intersection of the new stock growth functions and the open access harvest functions. The open access equilibrium in both fisheries disappears. Tipping points for the effect of the regime shift μ_c and μ_h (specified in Eq. (3.7)) for which the fisheries would just not collapse are estimated as $\bar{\mu}_c = -0.074$ and $\bar{\mu}_h = -0.125$. Hence, for the de-facto unregulated Baltic herring and cod fishery we find both, an environmental driver, i.e. the ecosystem regime shift, and "local" markets, i.e. the concavity of the open access harvest function affects the resilience of the Baltic system. The interplay between the ecological and the economic factors leads to the collapse of both fisheries in the equilibrium.

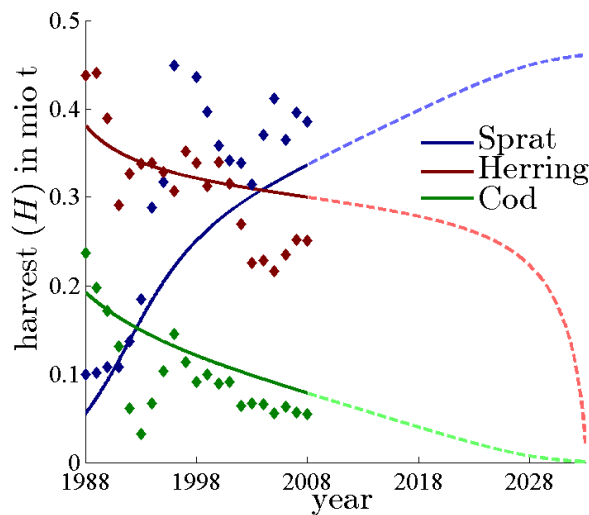
The sprat growth function (in panel (c)), on the other hand, is not directly affected by the ecosystem effect. While the orange curve depicts sprat growth at the pre-regime shift equilibrium cod stock level ($x_{c,oa} = 0.45$), the green shows sprat growth for a collapsed cod population after the regime shift ($x_c = 0$). The growth function shifts up and right, increasing both growth rates at a particular stock size, and the de-facto carrying capacity of sprat. The convex open access harvest function intersects both growth functions close to their maximum.

This results indicate that the regime shift in 1988 affected the Baltic sea equilibrium such that both the herring and cod open-access fishery were not viable anymore. The sprat fishery benefited from the collapse of cod, that led to increasing equilibrium stock

and harvest levels.



(a) Stock



(b) Harvest

Fig. 3.3: Simulated stock (a) and harvest (b) dynamics for cod (green), herring (red) and sprat (blue). Diamonds depict estimated stock and harvest levels from ICES (2013c). Continuous lines depict simulated development until 2008. Dashed lines the simulated development after 2008.

Using the point estimates for growth and harvest function from Table 3.1, Figure 3.3 depicts simulated development of stock sizes (panel (a)) and open access harvest (panel (b)) for all fisheries after the ecosystem regime shift in 1988. We use starting values for fish stock levels in 1988 just at the estimated stock biomass level from ICES (2013c). Diamonds indicate observed values until 2008, continuous lines the simulation given the parametrization in Table 3.1, and dashed lines the hypothetical development if the fish-

eries were continuously de facto open access after 2008. We predict a steady decrease of stock and open access harvest quantity of herring and cod after the shift in the ecosystem at 1988, and a collapse of cod and herring after 45 years – given that harvest remains unregulated. Due to a decrease in predation pressure, sprat biomass steadily increases until it reaches its new open access equilibrium after 45 years.

3.3.2 Finland: Harvesting, Markets, and Rents

In the previous subsection we explained the Baltic sea regime shift by a combination of ecological and economic factors that worked on an aggregate level. We derived new equilibrium levels of fish stocks and simulated the corresponding stock path towards this new equilibrium. In the following we aim at explaining the consequences of this regime shift on the Finnish fishery. Finland is just one among many actors in the Baltic sea fisheries. Hence, it makes sense to regard this shock on the fishery as exogenous for Finland and take the (simulated) development of the fish stocks after 1988 as given.

For Finland, we again assume that the open-access condition in Eq. (3.5) holds until 2008. Using time series of landings and landed values, we derive a time series of prices p_{it} for Baltic cod and sprat (FGFRI, 2014). Catch and stock biomass data is taken from ICES (2013a,b,d) and ICES (2011).⁸ To ensure identification of the model we estimate the simultaneous equations system of market demand and supply jointly with the transformed harvest production function (3.2) in terms of catch-per-unit-effort (CPUE). We approximate CPUE using

$$CPUE_t = \text{number of vessels in } t \cdot \frac{\text{catch value of fishery in } t}{\text{total catch value of all fisheries in } t},$$

where information on the number of vessels and catch values are taken from FGFRI (2014).

⁸ A detailed description of the utilized data is presented in appendix 3.5.5.

The model of the open access market equilibrium is (dropping fishery subscripts i):

$$\begin{aligned}
 \text{demand:} & & p(h_t) &= \bar{p}h_t^{-\nu}\epsilon_{d,t} \\
 \text{supply:} & & uc(h_t, x_t) &= ch_t^e x_t^{-\chi(1+e)}\epsilon_{s,t} \\
 \text{production:} & & \text{CPUE}_t &= h/\bar{E} = qx_t^\chi\epsilon_{c,t} \\
 \text{equilibrium condition:} & & p(h_t) &= uc(h_t, x_t) = p_t
 \end{aligned} \tag{3.13}$$

including the error terms $\epsilon_{s,t}$, $\epsilon_{d,t}$, $\epsilon_{c,t}$.⁹ The bottom section of Table 3.1 sums up estimates of the market equilibrium system (3.13). Interestingly, we find that the cod and sprat harvest functions switch from convex to concave (concave to convex respectively) when looking at the Finish instead of the aggregate Baltic sea fishery (see coefficient b in Table 3.1). Thus, it appears that input and output elasticities in the Finish cod fishery only play a minor role while they grow in importance in the sprat industry. Since traditionally the Finish fishing industry is more focused on small pelagics, the local labor and capital markets may as well be more dependent these fisheries. Hence, open access harvest of sprat and herring is less elastic to changes in stock size. The Finish cod fishery that mainly consist of few trawls does react much more elastic to changes in stock size in comparison.

Estimated economic coefficients are mainly significant, however, far from certain – the number of observations being only $N = 13$ for each equation.¹⁰ The estimated demand elasticity for cod is $\hat{\nu}_c = 0.314$, and we restrict the demand elasticities for herring and sprat to $\nu_h = \nu_s = 0$ to achieve convergence in estimates. This makes sense, as a large percentage of all herring and sprat catches in Finland are used for animal fodder and it seems reasonable to assume a fixed world market price level for the pelagic fisheries (OECD, 2003). The input market effect for the herring fishery is negative, in contradiction to our model assumptions, but insignificant.

⁹ For details on this regressions and the error structure see Appendix 3.5.8.

¹⁰ Comparable estimates from the literature are $\hat{\chi}_c = 0.644$ for the Baltic cod Kronbak (2004), $\hat{\chi}_c$ between 0.22 and 0.58 depending on the fishing technique for the North East Arctic cod Richter et al. (2011), and $\hat{\chi}_h = 0.56$ for the North Sea herring fishery Nøstbakken and Bjørndal (2003). To our knowledge the only relevant available estimate of the inverse price elasticity is for the North East Arctic Cod $\hat{\nu} = 0.5$ by Richter et al. (2011).

To cope with the uncertainty invoked by the estimation of parameters of interest, we refrain from the use of only point estimates but conduct a thorough Monte-Carlo sensitivity analysis, making use of the estimated co-variance matrices of estimates. We draw $N = 10000$ samples from multinomial normal distributions, $\beta \sim \mathcal{N}(\hat{\beta}, Cov(\beta))$, for each of the parameter sets to account for some of the uncertainty evoked by the estimation.¹¹

We calculate the present value of fishermen and consumer surplus for each fishery i from 1988 to 2008 corresponding to predicted stock development for each parameter set,

$$PV_{FS} = \sum_{t=1988}^{2008} \frac{1}{(1+\delta)^{t-1988}} \frac{e_i}{1+e_i} c_i \left(\frac{h_{it}}{x_{it}^{x_i}} \right)^{1+e_i}$$

$$PV_{CS} = \sum_{t=1988}^{2008} \frac{1}{(1+\delta)^{t-1988}} \frac{\nu_i}{1-\nu_i} \bar{p}_i h_{it}^{1-\nu_i},$$

where δ is the discount rate. Present values are calculated for the actual case when the regime shifted in 1988, as well as a benchmark model – that is the hypothetical case where the regime shift did not happen.

We furthermore calculate the effect generated by the regime shift for each fishery i , quantifying the annuities on the change in present values for the fishermen and consumer surplus with the regime shift:

$$\Delta_{FS} = \delta (PV_{FS, \text{with regime shift}} - PV_{FS, \text{no regime shift}}), \quad (3.14)$$

$$\Delta_{CS} = \delta (PV_{CS, \text{with regime shift}} - PV_{CS, \text{no regime shift}}). \quad (3.15)$$

Figure 3.4 depicts the distribution of the effect of the regime shift on fishermen surplus, Δ_{FS} , for the three fisheries: Cod in the top row, herring in the middle, and sprat in the bottom. We only show changes in the fishermen surplus, as the consumer surplus varies in parallel to fishermen surplus (cf. Proposition 3).

These top row in Figure 3.4 indicate that fishermen and consumers in the cod fishery are the clear losers of the regime shifts. The distribution looks almost log-normally

¹¹ For more details on the procedure see Appendix 3.5.9.

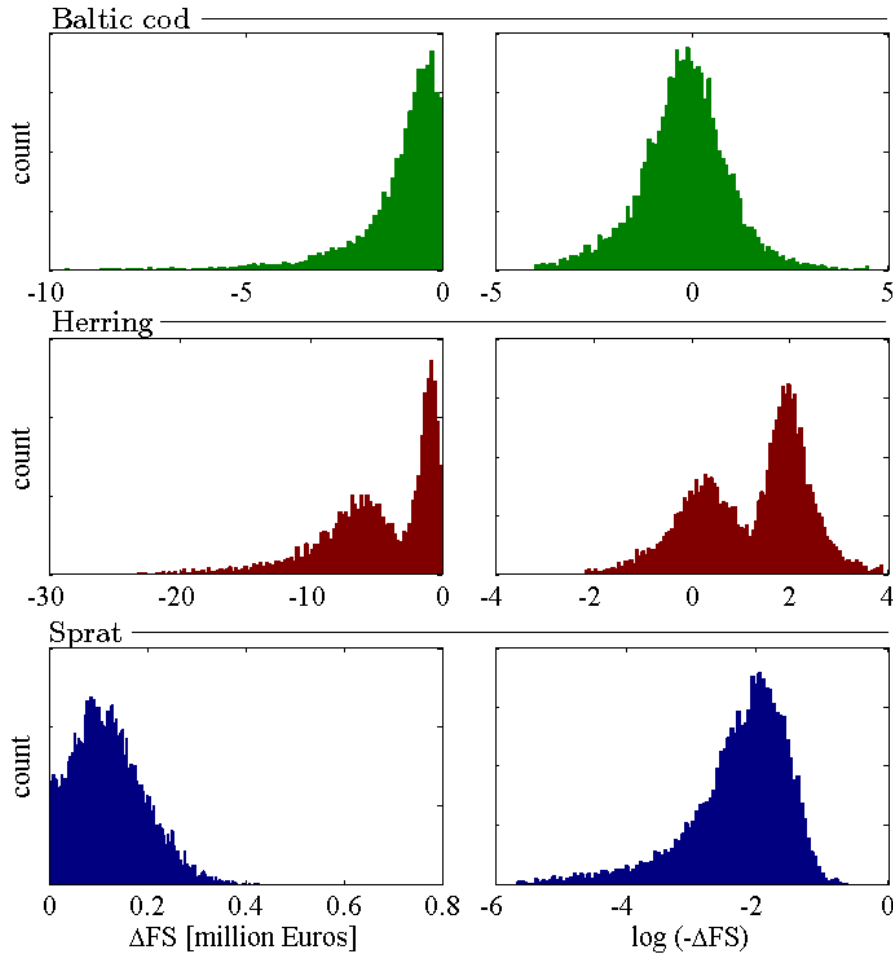


Fig. 3.4: Histogram of the annuities of changes in fishermen surplus for the cod (top row), herring (middle) and sprat (bottom) fisheries using a discount rate $\delta = 0.01$. Panels on the left show the annuities, panels on the right the log annuities.

distributed around a mean of roughly -1 million Euros. As the middle row indicates, also the stakeholders in the herring fishery have incurred a loss from the regime shift. The distribution is bi-modal, with one peak at around -1 million Euros, and another one at around -7 million Euros. This bi-modal shape is a consequence of the uncertainty in economic parameters, which is apparent already in Figure 3.2(b).¹² Depending on the exact constellation of economic and biological parameters, collapse may be globally stable or not after the regime shift. If the regime shift triggers a collapse in the open-access fishery, the loss is much higher than if it doesn't.

Finally the bottom row in Figure 3.4 focuses on effects on sprat fishermen. The

¹² The bi-modal shape is less distinct for larger discount rates δ . Figure 3.6 depicts the histograms above for a discount rate $\delta = 0.1$ where this bi-modality is not detectable anymore. This is because the long term effects of the regime shift are weighted much less than immediate effects for a larger discount rate.

stakeholders in the sprat fishery have gained from the regime shift, with a distribution centered around 0.1 million Euros. The gain for the sprat fishery is thus much smaller than the loss for the two other fisheries. On aggregate, the regime shift thus has caused a substantial loss for the Finnish fisheries.

3.4 *Conclusion*

In this paper, we studied the consequences of a regime shift on the functional interest groups in a multi-species fishery. We have argued that also under conditions of open access the fishery creates welfare in terms of fishermen and consumer surplus, if marginal fishing costs are increasing, and demand for fish is imperfectly elastic. We have shown that the shape of the marginal cost and inverse demand functions influence the shape of the open-access harvest as a function of current stock size and thus the stability of the fishery under open access. We have further shown that under open-access conditions, changes in the stock size affect fishermen and consumers of fish proportionally. Thus, a regime shift will affect the stakeholders in one fishery in a similar way. In a multi-species setting, a regime shift may create winners and losers, though.

To quantify these effects, we have applied the model to the Baltic sea ecological-economic system that is dominated by three major fisheries: cod, sprat and herring. We model an exogenous climate shock that directly affects the cod and herring stocks and indirectly (via its main predator) the sprat population. On an aggregate Baltic sea level, both, the cod and herring fishery are characterized by sufficiently inelastic input and/or output markets such that the response of harvest with respect to changes in stock size is weak (the harvest function is inelastic). This, in combination with the exogenous climate shock leads to a shift in the ecological-economic system.

We furthermore estimate changes in consumer surpluses and factor rents due to the ecological regime shift for the case of Finland. There are winners and losers of the ecosystem regime shift. The stakeholders in the sprat fishery gain from the increased availability of sprat after the regime shift. Consumers and fishermen in the cod and herring fisheries, by contrast, face a net loss after the regime shift, which is much higher

than the gains in the sprat fishery.

It has previously been analyzed how different management strategies for the Baltic fisheries would impose regional trade-offs since quotas for different fisheries are distributed subject to a stability criterion (Voss et al., 2014). Drawing on the EU's annual Baltic quota distribution of sprat and cod in a similar fashion, it is likely that many of sprat producers are located in Estonia, Lithuania and Latvia but also in Poland and Sweden.¹³ Cod quotas are concentrated on mainly Sweden, Denmark, and Poland where the loss for workers and consumers will have been most severe after the regime shift.

There is evidence for similar regime shifts in several other ecosystems. The Newfoundland cod that disappeared in the early 1990s and only very recently seems to return, gave way to a very valuable snow crab and lobster fishery that exceeded the historic cod fishery in terms of annual catch value. For Newfoundland, the consequence of the 1990s regime shift, thus, might be not as unambiguous as it is the case for the Baltic sea.

Since our analysis is focused on unregulated fisheries, the developing world with its many de-facto open access management regimes provides further, more recent, possible applications. Management effectiveness in low-income is often insufficient (Mora et al., 2009), illegal and unregulated fishing very common (Agnew et al., 2009). The proposed theoretical model may not only assess the vulnerability of fisheries of the developing world, but also help estimating the consequences (i.e. the effects on rents) of potential regime shifts.

Applying the proposed model to other ecosystems to analyze changes in realized rents, however, strongly depends on the availability of relevant data. Although data requirements are quite modest, i.e. it is not necessary to acquire detailed data on factor and output markets, experience shows us that in fisheries especially quantifying cost relationships is challenging.

¹³ These quotas can be obtained from http://ec.europa.eu/fisheries/cfp/fishing_rules/tacs/index_en.htm.

3.5 Appendix

3.5.1 The Cost Function and Open Access Harvest

In this section we aim to show how the cost function (3.3) and the open access harvest function (3.5) could be derived using isoelastic supply functions for factor along with a Cobb-Douglas effort production function. In the following we make use of the economic model proposed in chapter 2 of this thesis that explicitly considers markets for inputs in a fishery as well as the output demand to determine open access harvest (Fricke and Quaas, 2015a). Harvesting is described by the generalized Gordon-Schaefer production function $h = q E x^\chi$, where $\chi > 0$ denotes the schooling parameter, and $q > 0$ denotes the ‘catchability’. The fishing effort E can be thought of as an intermediate product that itself is produced by means of labor l and capital k using Cobb-Douglas technology with constant returns to scale:

$$E = l^\varphi k^{1-\varphi} \quad (3.16)$$

with $\varphi \in (0, 1)$. Capital and labor are supplied on local markets. We furthermore assume iso-elastic inverse supply functions,

$$w(l) = \omega l^\zeta, \quad (3.17)$$

$$r(k) = \kappa k^\psi. \quad (3.18)$$

Fishermen minimize their costs to determine their optimal harvest quantity in each period. Thus, they have to take local factor markets into account when they decide on their harvest strategy. The representative firm’s cost minimization problem

$$\begin{aligned} & \min_{l,k} wl + rk \\ & \text{s.t. Eqs. (3.2), (3.16)} \end{aligned}$$

yields the factor demand functions

$$l = \frac{h}{q x^\chi e^{\rho t}} \left(\frac{\varphi}{1-\varphi} \frac{r}{w} \right)^{1-\varphi} \quad (3.19)$$

$$k = \frac{h}{q x^\chi e^{\rho t}} \left(\frac{1-\varphi}{\varphi} \frac{w}{r} \right)^\varphi \quad (3.20)$$

and a cost function that is linear in harvest,

$$\tilde{c}(h, w, r; x) = \frac{w^\varphi r^{1-\varphi}}{\varphi^\varphi (1-\varphi)^{1-\varphi}} \frac{h}{q x^\chi e^{\rho t}}. \quad (3.21)$$

In labor and capital market equilibrium, we find (using (3.19) in (3.17), (3.20) in (3.18) respectively)

$$w = \omega l^\zeta = \omega \left(\frac{h}{q x^\chi e^{\rho t}} \right)^\zeta \left(\frac{\varphi}{1-\varphi} \frac{r}{w} \right)^{\zeta(1-\varphi)}, \quad (3.22)$$

$$r = \kappa k^\psi = \kappa \left(\frac{h}{q x^\chi e^{\rho t}} \right)^\psi \left(\frac{1-\varphi}{\varphi} \frac{w}{r} \right)^{\psi\varphi}. \quad (3.23)$$

The market equilibrium cost function can then be written as

$$c(h, x) = c \left(\frac{h}{x^\chi} \right)^{e+1},$$

with $c > 0$, and

$$e = e(\zeta, \psi, \varphi) \geq 0, \quad \frac{\partial e}{\partial \zeta} > 0, \quad \frac{\partial e}{\partial \psi} > 0$$

The non-linearity is caused by the term e , that decreases in both, the inverse price elasticity of labor and capital. It equals zero if both input factor supplies are perfectly elastic ($\zeta = 0$ and $\psi = 0$). In that case the equilibrium cost function reduces to $c(h, x) = c h x^{-\chi}$, thus, increases linearly in harvest quantity.

We assume an iso-elastic inverse demand function for the harvest, allowing for imper-

fectly elastic demand. The inverse demand function is

$$p(h) = \bar{p} h^{-\nu},$$

where ν is the inverse price elasticity of demand, where we assume $0 \leq \nu < 1$. The restriction $\nu < 1$ means that revenues ph will increase with harvest.

Using the zero profit condition, $p(h)h = c(h, x)$, we obtain the open access harvest level as an iso-elastic, monotonically increasing function of stock biomass,

$$h_{oa} = \left(\frac{\bar{p}}{c}\right)^{\frac{1}{(e+\nu)}} x^{\chi \frac{(e+1)}{(e+\nu)}} e^{\rho \frac{(e+1)}{(e+\nu)} t} \equiv a x^b e^{ct}.$$

For $x \in (0, \infty)$, we identify following cases

$$b \begin{cases} \geq 1 \\ < 1 \end{cases} \quad \text{for} \quad \frac{\chi - \nu}{1 - \chi} \begin{cases} \leq e \\ > e \end{cases}. \quad (3.24)$$

For a concave open access harvest function it must hold that e is sufficiently large. As e increases in both, ζ and ψ , for sufficiently inelastic capital and/or labor supply and a schooling parameter of less than unity the open access harvest function is concave.

3.5.2 Proof of Proposition 2

Open access population dynamics are given by

$$\dot{x} = g(x) - h_{oa}(x), \quad (3.25)$$

with

$$g'(x) = r\left(1 - \frac{2x}{K}\right) + \mu y,$$

$$g''(x) = -\frac{2r}{K} < 0.$$

Proof. Under condition (3.7), the expression on the right-hand side of Eq. (3.25) is negative for all x , as we show in the following. A local extremum (over all x) of net population

growth (the right-hand side (RHS) of (3.25)) is determined by the condition

$$\begin{aligned}
 g'(x) - h'_{oa}(x) &= 0 \\
 r\left(1 - \frac{2x}{K}\right) + \mu y - b a \bar{x}^{b-1} &= 0 \\
 \Leftrightarrow a \bar{x}^b &= \frac{r\bar{x}}{b}\left(1 - \frac{2\bar{x}}{K}\right) + \frac{\mu y \bar{x}}{b}. \tag{3.26}
 \end{aligned}$$

For $\bar{x} = \Theta$, the left-hand side (LHS) of (3.26) is larger than the RHS,

$$a \Theta^b > \frac{r\Theta}{b}\left(1 - \frac{2\Theta}{K}\right) + \frac{\mu y \Theta}{b}$$

which holds by condition (3.7). Around \bar{x} , the LHS of (3.26) is monotonically increasing in \bar{x} , and the RHS is monotonically decreasing in \bar{x} , otherwise \bar{x} would not be a local maximum. Thus, it must be that $\bar{x} < \Theta$.

Using (3.26) in the RHS of (3.1), we obtain

$$\begin{aligned}
 & r x \left(1 - \frac{x}{K}\right) + \mu y x - a x^b \\
 & < r \bar{x} \left(1 - \frac{\bar{x}}{K}\right) + \mu y \bar{x} - a \bar{x}^b \\
 & = r \bar{x} \left(1 - \frac{\bar{x}}{K}\right) + \mu y \bar{x} - \left(\frac{r\bar{x}}{b}\left(1 - \frac{2\bar{x}}{K}\right) + \frac{\mu y \bar{x}}{b}\right) \\
 & = \bar{x} \left(r \left(1 - \frac{\bar{x}}{K}\right) + \mu y - \frac{r}{b}\left(1 - \frac{2\bar{x}}{K}\right) - \frac{\mu y}{b}\right) \\
 & = \bar{x} \left(\bar{x} - \frac{r - r/b + \mu y - \mu y b}{r/K - 2r/Kb}\right) = \bar{x} (\bar{x} - \Theta),
 \end{aligned}$$

For $\bar{x} < \Theta$, the expression on the right hand side is negative, that is, the maximum amount of net growth of the predator stock is zero.

□

3.5.3 Calculation of Rents

With (3.22) in (3.23) ((3.23) in (3.22) respectively) we derive the equilibrium wage and capital rental rate

$$w_{eq} = \left(\omega^{1+\psi\varphi} \left(\frac{h}{q x^\chi e^{\rho t}} \right)^{\zeta(1+\psi)} \left(\frac{\kappa\varphi}{1-\varphi} \right)^{\zeta(1-\varphi)} \right)^{\frac{1}{1+\psi\varphi+\zeta(1-\varphi)}}, \quad (3.27)$$

$$r_{eq} = \left(\kappa^{1+\zeta(1-\varphi)} \left(\frac{h}{q x^\chi e^{\rho t}} \right)^{\psi(1+\zeta)} \left(\frac{\omega(1-\varphi)}{\varphi} \right)^{\psi\varphi} \right)^{\frac{1}{1+\psi\varphi+\zeta(1-\varphi)}}. \quad (3.28)$$

Worker surplus is defined as the area between the equilibrium wage rate and the inverse labor supply curve:

$$\begin{aligned} WS &= w_{eq} l_{eq} - \int_0^{l_{eq}} \omega l^\zeta dl = \frac{\zeta}{1+\zeta} \omega l_{eq}^{1+\zeta} = \frac{\zeta}{1+\zeta} \omega^{-\frac{1}{\zeta}} w_{eq}^{\frac{1+\zeta}{\zeta}} \\ &= \frac{\zeta}{1+\zeta} \left(\omega^{(1+\psi)\varphi} \left(\frac{h}{q x^\chi} \right)^{(1+\zeta)(1+\psi)} \left(\frac{\kappa\varphi}{1-\varphi} \right)^{(1+\zeta)(1-\varphi)} \right)^{\frac{1}{1+\psi\varphi+\zeta(1-\varphi)}} \\ &= \frac{\zeta}{1+\zeta} \omega^\alpha \left(\frac{\kappa\varphi}{1-\varphi} \right)^\beta \left(\frac{h}{q x^\chi} \right)^{1+e} = \varphi \frac{\zeta}{1+\zeta} c \left(\frac{h}{x^\chi} \right)^{1+e} \end{aligned}$$

Analogous, capital owner surplus is defined as the area between the equilibrium capital rental rate and the inverse capital supply curve:

$$\begin{aligned} RS &= \frac{\psi}{1+\psi} \kappa^{-\frac{1}{\psi}} r_{eq}^{\frac{1+\psi}{\psi}} \\ &= \frac{\psi}{1+\psi} \left(\kappa^{(1+\zeta)(1-\varphi)} \left(\frac{h}{q x^\chi} \right)^{(1+\psi)(1+\zeta)} \left(\frac{\omega(1-\varphi)}{\varphi} \right)^{(1+\psi)\varphi} \right)^{\frac{1}{1+\psi\varphi+\zeta(1-\varphi)}} \\ &= \frac{\psi}{1+\psi} \kappa^\beta \left(\frac{\omega(1-\varphi)}{\varphi} \right)^\alpha \left(\frac{h}{q x^\chi} \right)^{1+e} = (1-\varphi) \frac{\psi}{1+\psi} c \left(\frac{h}{x^\chi} \right)^{1+e} \end{aligned}$$

Total factor surplus then is the sum of capital owner surplus and worker surplus:

$$FS = WS + RS = \left(\varphi \frac{\zeta}{1+\zeta} (1-\varphi) \frac{\psi}{1+\psi} \right) c \left(\frac{h}{x^\chi} \right)^{1+e} = \frac{e}{1+e} c \left(\frac{h}{x^\chi} \right)^{1+e} \quad (3.29)$$

This is just the same as the area between open access equilibrium output price p^* and

the unit cost curve:

$$\begin{aligned}
 FS &= p^* h - \int_0^h \frac{c(h, x)}{h} dh \\
 &= p^* h - \frac{1}{1+e} c \left(\frac{h}{x^x} \right)^{1+e} && \stackrel{!}{=} \frac{e}{1+e} c \left(\frac{h}{x^x} \right)^{1+e} \\
 &\Rightarrow p^* h && \stackrel{!}{=} c \left(\frac{h}{x^x} \right)^{1+e} \\
 & && \stackrel{!}{=} c(h, x),
 \end{aligned}$$

which, by the open access zero profit condition, is true.

3.5.4 Empirical Part

3.5.5 Data Summary

Variable	Obs.	Mean	Std. Dev.	Minimum	Maximum	Units
Data on Aggregate Baltic Fisheries (Source: ICES (2011, 2013c))						
H_c	61	0.143	0.089	0.032	0.405	mio t
H_s	61	0.166	0.147	0.001	0.505	mio t
H_h	61	0.282	0.106	0.053	0.441	mio t
x_c	47	0.239	0.173	0.062	0.643	mio t
x_h	39	0.932	0.382	0.419	1.683	mio t
x_s	39	0.965	0.422	0.268	1.931	mio t
Data on Finish fisheries (Source: FGFRI (2014))						
vessels	19	3500.789	284.566	3163	3988	number
$CPUE_c$	18	6.034	2.535	3.331	12.648	t/vessel
$CPUE_h$	18	46.845	5.778	36.723	55.481	t/vessel
$CPUE_s$	18	62.584	10.589	53.462	98.097	t/vessel
h_{all}	34	0.100	0.018	0.060	0.138	mio t
h_c	34	0.002	0.001	0.000	0.005	mio t
h_h	34	0.083	0.014	0.052	0.122	mio t
h_s	34	0.010	0.010	0.000	0.027	mio t
p_c	34	0.942	0.442	0.200	1.649	Euro/kg
p_h	34	0.169	0.033	0.123	0.280	Euro/kg
p_s	34	0.242	0.152	0.061	0.502	Euro/kg

Tab. 3.2: Summary of Utilized Data. This table lists the number of observations (Obs.), the mean, standard deviation (Std. Dev.), and minimum and maximum observed level of required data for the estimation of population dynamics, aggregate open access harvest, and the market equilibrium for Finland.

Table 3.2 summarizes employed data on harvest (H , h), stock size (x), prices (p), and Catch per unit effort (CPUE). ICES (2011, 2013c) provide data on aggregate Baltic harvest levels from 1950 to 2010 and stock estimates from 1974 (1966 for cod) to 2012. FGFRI (2014) provide data on harvest and landed value for all species, from which we derive local prices p . Catch-per-unit effort is calculated as harvest divided by vessels allocated to the fishery. The latter is calculated as the total number of vessels (summarized in the table) multiplied by the value share of each fishery. There is quite some variation in the number of vessels in the dataset. Variations in our measure for CPUE are caused by both, changes in the number of vessels and variations in value share.

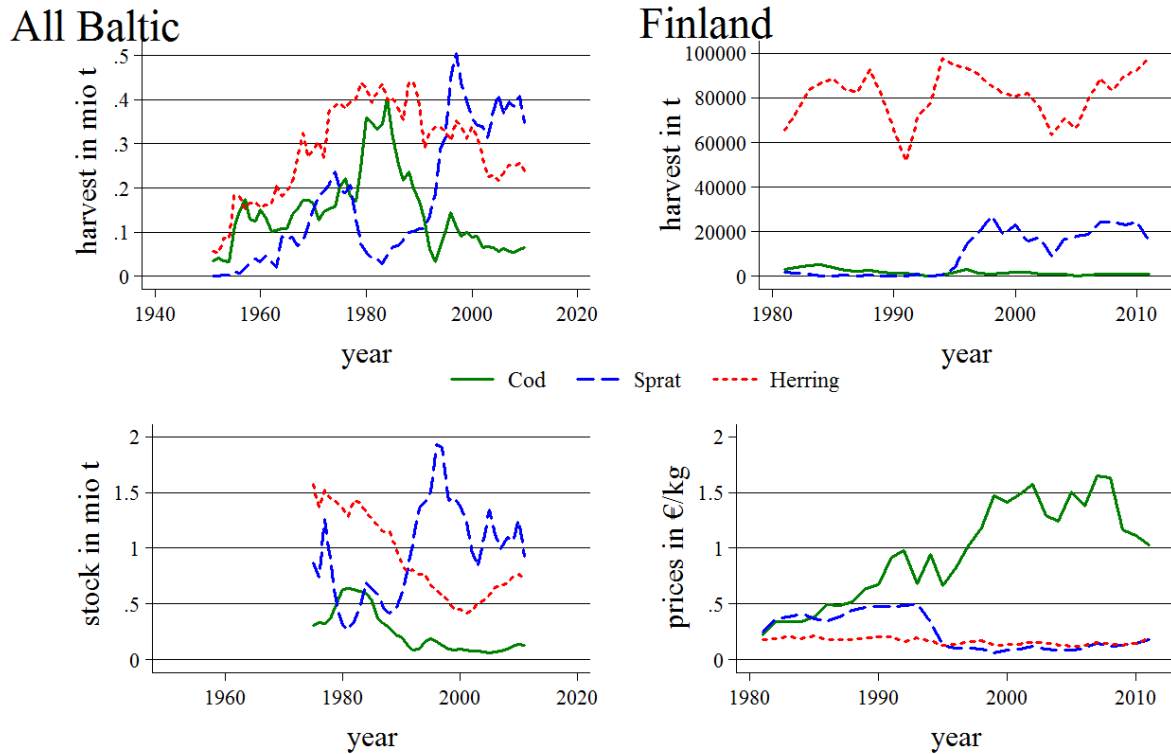


Fig. 3.5: Available Time Series Data on aggregate harvest (top left), Finish harvest (top right), stock levels (bottom left), and Finish price levels (bottom right). Cod is depicted in green, herring in red and sprat in blue color.

Figure 3.5 depicts observed stock, price and aggregate and Finish harvest development over time. Finish harvest levels (top right) do – to some extent – correspond to changes in aggregate harvest levels in the Baltic (top left). Sprat landings jump up in the mid 1990s.¹⁴ Cod landings are low but still decline over time. Only herring landings fluctuate more or less constantly around 80 000 t.

Finnish prices for cod vary significantly, supporting the assumption that output markets are local and demand is not perfectly elastic. Except for a significant drop in sprat prices in the mid 1990s from around 0.5 Euro to 0.15 Euro (the same time Finish and aggregate landings suddenly jumped), prices for the two pelagic species are relatively constant over time compared to the cod price.

¹⁴ This is a development not restricted to Finland but observed in several countries (ICES, 2013d) leading to the peak in overall catches of more than half a million tonnes.

3.5.6 Population Dynamics

Population dynamics (in Eqs. (3.10)) are estimated separately for each fishery, making use of data on aggregate harvest H and stock size x , using non-linear least square estimator with Newey-West errors. A Breusch-Pagan Test for contemporaneous correlation of the errors indicated that the H_0 hypothesis of independence of the three equations cannot be rejected at any reasonable level. Estimated parameters are listed in Table 3.3. We detect a significantly negative ecosystem effect μ_i on the growth function of cod and herring. Estimates for intrinsic growth rates and carrying capacities for all three species are well within a reasonable range.

$y =$	Cod $D_{t \geq 1988}$	Herring $D_{t \geq 1988}$	Sprat $x_{c,t}$
r	0.887*** <i>0.064</i>	0.877*** <i>0.116</i>	0.647*** <i>0.169</i>
K	1.506*** <i>0.173</i>	1.997*** <i>0.085</i>	2.894*** <i>0.744</i>
μ	-0.121* <i>0.062</i>	-0.141** <i>0.057</i>	-0.832** <i>0.355</i>
R^2	0.966	0.966	0.592
N	45	37	37
Breusch-Pagan Test for independence			
$LM =$	6.327		
p-value	0.097		
NLS estimates with robust standard errors.			
Standard errors below estimates. Significance: 1%*** 5% ** 10%*			

Tab. 3.3: Estimates of population dynamics for cod, herring and sprat. Below the list of estimates, we list the result of the Breusch-Pagan test for independence of regressions.

Table 3.4 lists variations of the proposed stock dynamics using different time points for the regime shift as well as other possible interactions. Changes in the choice of regime shift do not affect information criteria and R^2 much for cod and herring. Other species interactions are mostly insignificant.

Stock/Method	Effect y	sign(μ)	p-value(μ)	log(Likel)	AIC	BIC	R^2
Cod/NLS							
	none	n.a.	n.a.	87.067	-170.134	-166.520	0.964
	D_{1988}	-	0.056	88.661	-171.321	-165.901	0.966
	D_{1987}	-	0.017	89.409	-172.818	-167.398	0.967
	D_{1989}	-	0.130	88.188	-170.377	-164.957	0.965
	Zooplankton	+	0.115	69.930	-133.861	-129.110	0.965
	Herring	+	0.025	72.394	-138.788	-133.955	0.967
	Sprat	+	0.911	70.102	-134.204	-129.371	0.959
Herring/NLS							
	none	n.a.	n.a.	47.130	-90.260	-87.038	0.956
	D_{1988}	-	0.019	51.629	-97.258	-92.426	0.966
	D_{1987}	-	0.036	51.329	-96.658	-91.825	0.965
	D_{1989}	-	0.074	49.866	-93.733	-88.900	0.962
	Zooplankton	+	0.010	50.675	-95.351	-90.600	0.967
	Cod	+	0.039	48.957	-91.915	-87.082	0.960
	Sprat	-	0.306	47.670	-89.340	-84.507	0.957
Sprat/NLS							
	none	n.a.	n.a.	1.593	0.815	4.037	0.516
	Zooplankton	+	0.112	3.775	-1.551	3.200	0.584
	Herring	-	0.006	5.980	-5.960	-1.127	0.618
	Cod	-	0.025	4.742	-3.484	1.349	0.592

Tab. 3.4: Model variations for population dynamics. The table lists information criteria (AIC, BIC), R^2 , likelihood, direction and significance of parameters μ for different choices of the interaction effect y for cod, herring, and sprat.

3.5.7 Harvesting: All Baltic Sea

We estimate the logarithmic open access harvest function (as in (3.11)) making use of data on aggregate harvest levels H and stock size x for the three Baltic sea fisheries separately using instrumental variable estimation with robust standard errors. Due to existing endogeneity, stock levels in t are instrumented with their lagged values. Estimates are listed in Table 3.5. We test for the existence of a trend term to control for technological progress as suggested in chapter 2 of the thesis (Fricke and Quaas, 2015a). The estimated trend coefficient c is insignificant at a 5% level for two out of three cases. We therefore exclude it from the final regression.

	Cod	Herring	Sprat
B_i	0.865*** <i>0.07</i>	0.399*** <i>0.09</i>	1.599*** <i>0.21</i>
$\ln A_i$	-0.577*** <i>0.09</i>	-1.02*** <i>0.02</i>	-1.51*** <i>0.09</i>
$\Rightarrow A_i$	0.562***	0.3605***	0.221***
N	42	34	34
$F(1, N - 2)$	171.8	21.912	59.5
$Prob$	0.000	0.000	0.000
Wu-Hausman test of exogeneity of x_{it} :			
$F(1, N - 3)$	17.094	13.730	9.066
$Prob$	0.000	0.000	0.005
Breusch-Pagan Test for independence			
$LM =$	5.307		
$p - value > \chi^2(3) =$	0.151		
Parameter for technological progress (excluded)			
c_i	0.002	-0.027***	0.020*
Using 3SLS estimation with Newey-West standard errors. Instrumented: $x_{i,t-1}$ for x_{it} . Standard errors below estimates. Significance: 1%*** 5% ** 10%*			

Tab. 3.5: Baltic region: Estimated open-access harvest functions for cod, herring, and sprat. Tests for exogeneity of x_{it} , independence and technological progress below the list of estimates.

3.5.8 Harvesting and Markets: Finland

We make use of harvest levels h , price levels p and CPUE data from FGFRI (2014) and combine it with data on stock sizes x from ICES (2013c) to estimate elasticities and other necessary coefficients for the Finish fishing economy. To estimate the model of the open access market equilibrium from Eqs. (3.13) we need to rewrite it in reduced form (Greene, 2003, Ch. 15). Using $p(h_t) = uc(h_t, x_t)$ and solving for h_t we get:

$$h_t = \left(\frac{\bar{p}}{c}\right)^{1/(e+\nu)} x^{\chi \frac{1+e}{e+\nu}} \left(\frac{\epsilon_{d,t}}{\epsilon_{s,t}}\right)^{1/(e+\nu)}.$$

Plugging this back into the demand function, we derive

$$p_t = c \left(\frac{\bar{p}}{c}\right)^{e/(e+\nu)} x^{-\nu \chi \frac{1+e}{e+\nu}} \epsilon_{d,t} \left(\frac{\epsilon_{d,t}}{\epsilon_{s,t}}\right)^{e/(e+\nu)}.$$

Finally, taking logarithms we derive the reduced for equations:

$$\ln p_t = \ln(ca^e) - \nu b \ln x_t + \ln \eta_{p,t} \quad (3.30)$$

$$\ln h_t = \ln a + b \ln x_t + \ln \eta_{h,t} \quad (3.31)$$

and:

$$\ln \text{CPUE}_t = \ln q + \chi \ln x_t + \ln \epsilon_{c,t} \quad (3.32)$$

with

$$a = \left(\frac{\bar{p}}{c}\right)^{\frac{1}{(e+\nu)}}, \quad b = \chi \frac{(e+1)}{(e+\nu)},$$

$$\eta_{p,t} = \epsilon_{d,t} \left(\frac{\epsilon_{d,t}}{\epsilon_{s,t}}\right)^{e/(e+\nu)}, \quad \eta_{h,t} = \left(\frac{\epsilon_{d,t}}{\epsilon_{s,t}}\right)^{1/(e+\nu)}.$$

Note that Eq. (3.31) of the reduced form model is just the open access harvest function (3.5).

The reduced form equilibrium model is estimated separately for each fishery as a system of seemingly unrelated equations using FGNLS estimation and robust standard errors.¹⁵ For the sprat and herring fishery we impose the restriction $\nu_h = \nu_s = 0$ to derive convergence while the cod system is estimated without any constraints.

The actual regression equations (as used in Stata) look like the following.

For Cod:

$$\ln p_t = \frac{e}{e+\nu} \ln \bar{p} + \frac{\nu}{e+\nu} \ln c - \nu \chi \frac{1+e}{e+\nu} \ln x_t + \ln \eta_{p,t}$$

$$\ln h_t = \frac{1}{e+\nu} \ln \bar{p} + \frac{1}{e+\nu} \ln c + \chi \frac{1+e}{e+\nu} \ln x_t + \ln \eta_{h,t}$$

$$\ln \text{CPUE}_t = \ln q + \chi \ln x_t + \ln \epsilon_{c,t}$$

¹⁵ The model could theoretically be estimated using OLS and in a regular SUR setting. However, since we impose cross-equation restrictions on parameters, using an FGNLS model is much more practical. For more details see Stata's *nlsur* command.

For Herring and Sprat:

$$\ln p_t = \bar{p} + \ln \eta_{p,t}$$

$$\ln h_t = \underbrace{\ln a}_{\frac{1}{e} \ln \bar{p} - \frac{1}{e} \ln c} + \chi \underbrace{E}_{\frac{1+e}{e}} \ln x_t + \ln \eta_{h,t}$$

$$\ln \text{CPUE}_t = \ln q + \chi \ln x_t + \ln \epsilon_{c,t}$$

Results from these estimations are listed in the 'Main Results' column in Table 3.6.¹⁶

	Main Results			Unrestricted Estimations	
	Cod	Sprat	Herring	Sprat	Herring
Restrictions:	-	$p = \bar{p}$	$p = \bar{p}$	-	-
e	0.261** <i>0.12</i>	0.8876 <i>1.37</i>	-3.844 <i>5.40</i>	112.979*** <i>2.14</i>	281.088*** <i>8.53</i>
ν	0.314*** <i>0.12</i>	-	-	0.807** <i>0.33</i>	-0.119 <i>0.5</i>
$\ln \bar{p}$	-1.849** <i>0.79</i>	-2.311*** <i>0.06</i>	-1.945*** <i>0.03</i>	-5.534*** <i>1.32</i>	-1.644 <i>1.25</i>
$\ln c$	-0.391 <i>0.64</i>	1.3107 <i>5.50</i>	-11.206 <i>12.81</i>	456.895 <i>.</i>	666.422 <i>.</i>
χ	0.806*** <i>0.07</i>	0.174** <i>0.07</i>	0.265* <i>0.14</i>	0.298* <i>0.16</i>	0.246** <i>0.12</i>
$\ln q$	3.500*** <i>0.17</i>	3.950*** <i>0.09</i>	4.114*** <i>0.03</i>	4.085*** <i>0.03</i>	3.939*** <i>0.08</i>
Leading to:					
a	0.079 <i>0.07</i>	0.017*** <i>0.00</i>	0.090*** <i>0.01</i>	0.0171*** <i>0.00</i>	0.0927 <i>0.01</i>
b	1.769*** <i>0.37</i>	0.370 <i>0.42</i>	0.196 <i>0.13</i>	0.2983* <i>0.1603</i>	0.247 <i>0.125</i>
N	13	13	13	13	13
R_p^2	0.518	0	0	0.078	-0.009
R_h^2	0.61	0.061	0.066	0.065	0.057
R_{CPUE}^2	0.817	0.174	0.194	0.211	0.192

Standard errors below estimates. Significance: 1%*** 5% ** 10%*

Tab. 3.6: Finland: Estimated production function and market equilibrium for cod, herring and sprat. The table lists main regression results used for the simulations (left side) as well as results of the unrestricted regressions ($\nu_s, \nu_h \neq 0$) on the right side.

¹⁶ Estimates of the unrestricted, non-converging systems for sprat and herring are listed in the same table on the right side.

3.5.9 *Rents in the Finish Fishing Industry*

Table 3.7 lists vectors of point estimates (α, β, γ) and corresponding covariance matrices (Cov) of the open access harvest functions, stock growth functions, and market equilibrium for all three species. We draw $N = 10000$ parameter combinations separately from the multinomial normal distributions indicated in Table 3.7.

Figure 3.6 depicts the distribution of the effect of the regime shift on fishermen surplus, Δ_{FS} , for the three fisheries: Cod in the top row, herring in the middle, and sprat in the bottom for a discount rate $\delta = 0.1$.

Population Dynamics										
$\alpha_c =$	r	=	0.887	$Cov_{\alpha_c} =$	0.004	-0.008	0.003			
	K	=	1.506		-0.008	0.030	-0.004			
	μ	=	0.121		0.003	-0.004	0.004			
$\alpha_s =$	r	=	0.647	$Cov_{\alpha_s} =$	0.029	-0.101	0.042			
	K	=	2.894		-0.101	0.553	-0.081			
	μ	=	0.832		0.042	-0.081	0.126			
$\alpha_h =$	r	=	0.877	$Cov_{\alpha_h} =$	0.013	-0.009	0.006			
	K	=	1.997		-0.009	0.007	-0.004			
	μ	=	0.141		0.006	-0.004	0.003			
Finland: Harvesting and Markets										
$\beta_c =$	e	=	0.261	$Cov_{\beta_c} =$	0.014	-0.003	0.021	0.070	-0.001	-0.004
	ν	=	0.314		-0.003	0.014	-0.091	-0.023	0.002	0.006
	$\ln \bar{p}$	=	-1.849		0.021	-0.091	0.617	0.162	-0.017	-0.046
	$\ln c$	=	-0.391		0.070	-0.023	0.162	0.408	-0.022	-0.056
	χ	=	0.806		-0.001	0.002	-0.017	-0.022	0.005	0.012
	$\ln q$	=	3.501		-0.004	0.006	-0.046	-0.056	0.012	0.029
$\beta_s =$	$\ln \bar{p}$	=	-2.311	$Cov_{\beta_s} =$	0.003	0.002	-0.002	-0.004	-0.001	
	$\ln a$	=	-4.080		0.002	0.018	-0.007	-0.188	0.001	
	χ	=	0.174		-0.002	-0.007	0.005	0.081	0.001	
	$(1+e)/e$	=	2.127		-0.004	-0.188	0.081	3.025	-0.023	
	$\ln q$	=	4.114		-0.001	0.001	0.001	-0.023	0.001	
$\beta_h =$	$\ln \bar{p}$	=	-1.945	$Cov_{\beta_h} =$	0.001	0.001	0.001	0.003	0.001	
	$\ln a$	=	-2.409		0.001	0.007	0.007	0.018	0.004	
	χ	=	0.265		0.001	0.007	0.019	-0.009	0.011	
	$(1+e)/e$	=	0.740		0.003	0.018	-0.009	0.133	-0.009	
	$\ln q$	=	3.951		0.001	0.004	0.011	-0.009	0.007	
Baltic Sea: Open Access Harvest										
$\gamma_c =$	$\ln A$	=	0.865	$Cov_{\gamma_c} =$	0.004	0.005				
	B	=	-0.577		0.005	0.007				
$\gamma_s =$	$\ln A$	=	1.599	$Cov_{\gamma_s} =$	0.043	-0.001				
	B	=	-1.512		-0.001	0.008				
$\gamma_h =$	$\ln A$	=	0.399	$Cov_{\gamma_h} =$	0.007	-0.001				
	B	=	-1.020		-0.001	0.001				

Tab. 3.7: Estimates and covariance matrices of population dynamics (top), Finland harvest (middle), and aggregate harvest (bottom). The table lists unconverted estimates on the left and corresponding covariance matrices on the right.

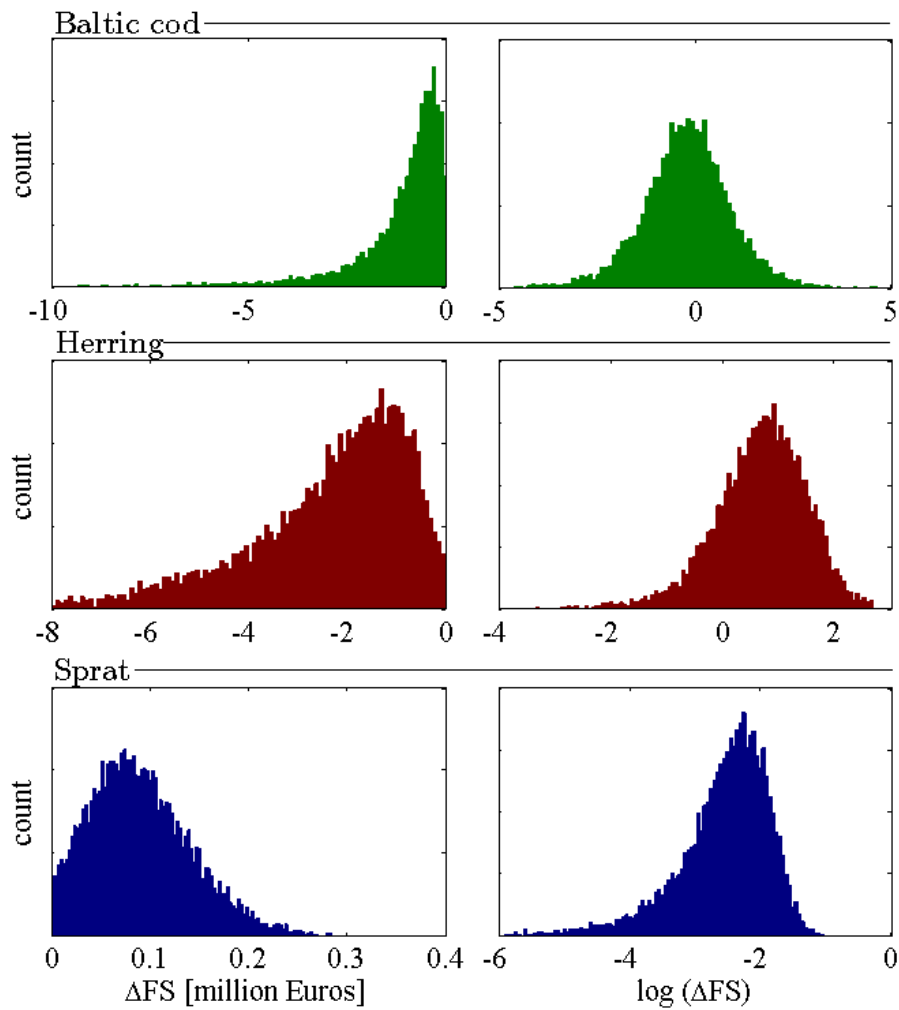


Fig. 3.6: Histogram of the annuities of changes in fishermen surplus for the cod (top row), herring (middle) and sprat (bottom) fisheries using a discount rate $\delta = 0.1$. Panels on the left show the annuities, panels on the right the log annuities.

4. ECONOMIC DRIVERS OF REGIME SHIFTS IN OPTIMALLY MANAGED FISHERIES



Fogo Island, Newfoundland

4.1 *Introduction: Optimal Management and Regime Shifts*

Limited resilience and regime shifts have been discovered in various terrestrial and aquatic ecological systems (Biggs et al., 2012). A system is called multistable when - depending on the initial conditions - it can stabilize in several different equilibria. When shocked, a multistable system may cross a tipping point and move towards a new equilibrium. These abrupt changes from one state to another are commonly called regime shifts. The resilience of a system is usually characterized by its ability to buffer shocks without shifting to a new stable state (Scheffer et al., 2001).

While multistability can result from ecologic dynamics and interactions (such as predator-prey dynamics and/or minimum viable population levels), empirical evidence suggests that (especially unregulated) human interaction often decreases the stability of an ecosystem (Folke et al., 2004). How and why unregulated fishing may lead to regime shifts in marine ecosystems has been discussed extensively in chapter 2 and 3 of this thesis (Fricke and Quaas, 2015a,b). Therefore, the interplay between human actions and ecosystem dynamics is key to understanding the stability of ecosystems.

In resource economics, the possibility of multistability has long been part of theoretical models of open access and optimal management (Levhari et al., 1981; Dasgupta, 1982). One typical approach to model multistability and limited resilience in economic-ecologic systems is to couple initially stable ecological systems with economic dynamics, which can lead to a destabilization of the overall system. Alternatively, intrinsically multistable ecological systems may or may not be stabilized by human interactions and management of the corresponding ecological-economic system (examples for both can be found in Mäler et al. (2003); Horan et al. (2011); Quaas et al. (2013)).

While unregulated bioeconomic systems generally tend to be less stable than regulated ones, 'optimal' management of resources does not necessarily imply a stabilization of the coupled system. It has been shown that both the quality of institutions (Horan et al., 2011), and human preferences for consumption diversity and patience (Quaas et al., 2013) may lead to multistability in optimally managed fisheries.

In this paper I investigate the determinants of resilience and regime shift in an oceanic

economic-ecologic system. In particular I look at the economic drivers (prices and costs) of multistability in optimally managed predator-prey fisheries. The underlying ecological system is an intrinsically stable model of two interacting species which are both harvested independently of each other. Interactions between the two resources are thus restricted to the ecological side (predator-prey dynamics). I will regard these two resources as fish species that are both caught by independent fishing fleets.

The model here is a simplified version of the bioeconomic model developed by Fricke and Quaas (2015a,b) in chapter 2 and 3 of this thesis. There we assumed an underlying harvesting technology under which catch per unit of effort does not decrease linearly with stock size. We also explicitly model input and output markets to investigate producer and consumer surplus generated by the fisheries.

One of the simplifications employed in this paper is the utilization of a Gordon-Schaefer harvesting technology where the stock-output elasticity equals unity. I take input markets into account for constructing the cost function, which is assumed to be quadratic in harvest. Lastly, output demand is assumed to be perfectly elastic. These restrictions facilitate the derivation of analytic results for the optimally managed fishery. However, I will show that even in such a simplified model universal conditions for multistability cannot be derived analytically such that one has to rely on numerical results.

For this purpose I calibrate the model to fit two prominent examples of predator-prey fisheries: the Baltic cod and sprat, and the Newfoundland cod and snow crab fishery. Both ecosystems experienced regime shifts in the early 1990s, which were mainly caused by overfishing along with changes in climate variables (Moellmann et al., 2009; Myers et al., 1996). In both ecosystems the predator stock collapsed while prey abundances increased due to decreasing predatory pressure. The interesting difference between these systems is the economic value of the prey species. In the Baltic sea, sprat is low priced and mainly used as fish fodder, while the Newfoundland snow crab is a high priced gourmet food. In both cases effort is made to rebuild the cod stocks to pre-collapse levels. The results in this paper suggests that these efforts are worthwhile.

I show how changes in economic parameters (price levels and harvesting costs) affect

the location of optima, and the system's resilience. In particular, I look at how these changes can lead to regime shifts in the optimally managed fishery for both ecosystems.

The remainder of the paper is organized as follows: In section 4.2, I present the bioeconomic model and describe the optimization problem analytically. In Section 4.3, I apply the model to the Baltic cod and sprat, and the Newfoundland cod and snow crab fishery. In section 4.4 summarize the results and briefly conclude.

4.2 The Theoretical Model

In the following, I sketch the bioeconomic model, which is a simplified version of the model in (Fricke and Quaas, 2015a,b).¹ The assumed population dynamics for predator (x_c) and prey (x_s) biomass follow a logistic growth function,

$$\begin{aligned}\dot{x}_c &= r_c x_c \left(1 - \frac{x_c}{k_c}\right) - h_c, \\ \dot{x}_s &= r_s x_s \left(1 - \frac{x_s}{k_s}\right) - \mu_s x_s x_c - h_s,\end{aligned}\tag{4.1}$$

where $r_c, r_s > 0$ are the intrinsic growth rates, $k_c, k_s > 0$ the capacity limits, and h_c, h_s the harvest rates. Predator-prey interactions enter the prey dynamics linearly, where μ_s is the predator's success rate when meeting prey at random in a homogeneous environment.² The basic idea behind this interaction is that the predator is an opportunistic feeder with several food sources, such that the prey's biomass does not feed back into the predator's population dynamics.

Note that interactions between fisheries solely exist on the ecological side. On the economic side - costs, harvest, input and output markets - I assume that they are independent. This makes sense if the two fisheries (denoted by the subscript $i = c, s$) are reasonably different from each other, e.g. focusing on different seasons and utilizing different technologies. Therefore, the following parameters allow for heterogeneity between

¹ Here, I only sketch the main characteristics of the model. More details and derivations can be found in Appendix 4.5.1.

² This simplified form of interaction is known from literature on fisheries (Flaaten, 1991; Brown et al., 2005) and grazing systems (Walker et al., 1981).

fisheries.

Harvesting is described by the Gordon-Schaefer production function, $h_i = q_i E_i x_i$, where $q_i > 0$ denotes the so-called ‘catchability’. The fishing effort E_i can be thought of as an intermediate product that is produced by different input factors. I furthermore assume that the production technology is of Cobb-Douglas type with constant returns to scale and that production factors are supplied on local markets, with iso-elastic supply functions.

Fishing enterprises minimize their costs subject to factor supply with the additional restriction that the fishing industry is characterized by strongly decreasing returns to scale, that is the cost function is quadratic in harvest (e.g. Nieminen et al. (2012); Arnason et al. (2004)). The market equilibrium cost function can thus be written as³

$$c_i(h_i, x_i) = c_i \left(\frac{h_i}{x_i} \right)^2, \quad (4.2)$$

with $c_i > 0$. The non-linear cost structure allows for positive factor rents, denoted as fisherman’s surplus, $FS_i = \frac{c_i}{2} \left(\frac{h_i}{x_i} \right)^2$.

Finally I assume output demand for all fish species to be perfectly elastic. Hence, output prices are set to the world market level:

$$p_i(h_i) = \bar{p}_i. \quad (4.3)$$

This is a reasonable assumption for many fisheries such as small pelagics that supply a global market for fish oil, or larger demersal species that accommodate the market for white fish.

4.2.1 The Optimization Problem

The social planner maximizes the present value of profits along with fisherman’s surplus for both fisheries given constant prices (4.3) and the cost function (4.2). The correspond-

³ The mathematical derivation of the cost function and fisherman’s surplus can be found in Appendix 4.5.1.

ing optimization problem reads as follows:

$$\max \int_0^{\infty} e^{-\delta t} \sum_{i=c,s} \left[\bar{p}_i h_i - \frac{c_i}{2} \left(\frac{h_i}{x_i} \right)^2 \right] dt \quad (4.4)$$

$$\text{s.t.} \quad \dot{x}_c = g_c(x_c) - h_c,$$

$$\dot{x}_s = g_s(x_s, x_c) - h_s,$$

$$x_{i,\text{initial}} \text{ given; } x_{i,t}, h_{i,t} \geq 0 \forall t, i \in c, s,$$

yielding in the current value Hamiltonian

$$H^c = \sum_{i=c,s} u_i(h_i, x_i) + \lambda_c(g_c(x_c)) - h_c + \lambda_s(g_s(x_s, x_c)) - h_s, \quad (4.5)$$

where harvest h_c and h_s are the control variables, and λ_c and λ_s denote the shadow price of the corresponding fish stock. From the Hamiltonian one obtains 3x2 first order conditions of the optimal control problem, along with the transversality conditions $\lim_{t \rightarrow \infty} \exp(-\delta t) \lambda_{it} = 0$.⁴ Rearranging the first order conditions for optimal harvest yields

$$\lambda_i = \bar{p}_i - c_i h_i x_i^{-2} \quad \forall i = c, s. \quad (4.6)$$

Hence, the shadow price of a stock at the optimal harvest level equals the marginal utility with respect to harvest. The first order conditions for the optimal motion of fish stocks can be written as

$$\begin{aligned} \delta &= \frac{\dot{\lambda}_c}{\lambda_c} + \left(r_c \left(1 - \frac{2x_c}{k_c} \right) \right) - \frac{\lambda_s}{\lambda_c} x_s \mu_s + \frac{c_c \lambda_c h_c^2 x_c^{-3}}{\lambda_c}, \\ \delta &= \frac{\dot{\lambda}_s}{\lambda_s} + \left(r_s \left(1 - \frac{2x_s}{k_s} \right) - x_c \mu_s \right) + \frac{c_s \lambda_s h_s^2 x_s^{-3}}{\lambda_s}, \end{aligned} \quad (4.7)$$

⁴ Apart from the first order conditions (4.6), (4.7), and (4.8) Arrow's sufficiency condition states that if the maximized Hamiltonian is (strictly) concave with respect to the state variable (x_i), for a given value of the costate variable (λ_i), then the first-order conditions characterize a maximum. See Appendix 4.5.2 for the formal derivation and application to the above optimization problem.

which implies that each stocks own rate of return has to equal the discount rate δ . Note that the conditions (4.6) do not include any interactions between fisheries. In contrast, the two conditions for the optimal motion of fish stocks both depend on the two fish stocks. Lastly, the population dynamics in (4.1) have to hold:

$$\frac{\partial H^c}{\partial \lambda_i} = g_i(x_i, x_j) - h_i = \dot{x}_i. \quad (4.8)$$

Taking the time derivative of (4.6), along with (4.6) and (4.8) in (4.7), allows me to solve for \dot{h} , the optimal harvest dynamics:

$$\begin{aligned} \dot{h}_c &= -\frac{x_c^2}{c_c} \left[\left(\delta - \frac{\partial g_c}{\partial x_c} \right) \lambda_c - \frac{\partial g_s}{\partial x_c} \lambda_s - \frac{\partial u_c}{\partial x_c} - \frac{2c_c h_c}{x_c^3} (g_c - h_c) \right] = \dot{h}_c(x_c, x_s, h_c, \dot{x}_c), \\ \dot{h}_s &= -\frac{x_s^2}{c_s} \left[\left(\delta - \frac{\partial g_s}{\partial x_s} \right) \lambda_s - \frac{\partial u_s}{\partial x_s} - \frac{2c_s h_s}{x_s^3} (g_s - h_s) \right] = \dot{h}_s(x_c, x_s, h_s, \dot{x}_s). \end{aligned} \quad (4.9)$$

These differential equations describe the change in harvest as a function of the current level of stock size and harvest. The optimal dynamics for harvest (4.9) and the population dynamics (4.1) form the four dimensional dynamical system that depends on the two control variables, h_i , and the two state variables, x_i , only:

$$\begin{pmatrix} \dot{x}_c \\ \dot{x}_s \\ \dot{h}_c \\ \dot{h}_s \end{pmatrix} = \begin{pmatrix} \dot{x}_c(x_c, x_s, h_c, h_s) \\ \dot{x}_s(x_c, x_s, h_c, h_s) \\ \dot{h}_c(x_c, x_s, h_c, h_s) \\ \dot{h}_s(x_c, x_s, h_c, h_s) \end{pmatrix}. \quad (4.10)$$

The differential equations for harvest (4.9) emerge from the optimality conditions and can thus be seen as 'endogenous'. In contrast to that, the two differential equations for the stock size (4.1) that are part of the initial optimization problem (4.4) can be viewed as 'exogenous'. The dynamical system (4.10) is in a steady state if harvest, stock, and

shadow prices are constant over time:

$$\dot{x}_i = \dot{\lambda}_i = \dot{h}_i = 0 \text{ for } i = c, s.$$

In the optimal control problem described above, it is optimal to drive the stock and harvest to a certain steady state level. Given this and the endogenous and exogenous parts in the system of differential equations (4.10), a steady state can be at most 'saddle-stable'.⁵

Using the steady state condition above along with (4.6) and (4.8) in (4.7), and solving the resulting two steady state conditions, I obtain convex isoclines for the two fish stocks.⁶ The predator isocline depends on parameters from both the predator and prey fishery:

$$\begin{aligned} x_s &= f_c(x_c, r_c, r_s, k_c, k_s, \mu_s, \bar{p}_c, \bar{p}_s, c_c, c_s, \delta) \\ \text{with } \frac{\partial x_s}{\partial x_c} &< 0 \text{ and } \frac{\partial^2 x_s}{\partial x_c^2} > 0. \end{aligned} \quad (4.11)$$

Since the size of the predator stock directly affects the prey stock via the interaction term μ_s , and the social planner considers this in her optimization problem, the parameters of the prey fishery are included in the predator isocline. The species interaction is however not reciprocal: the prey does not feed back on the predator. Thus, the prey isocline depends on parameters of the prey fishery only:

$$\begin{aligned} x_c &= f_s(x_s, r_s, k_s, \mu_s, \bar{p}_s, c_s, \delta) \\ \text{with } \frac{\partial x_c}{\partial x_s} &< 0 \text{ and } \frac{\partial^2 x_c}{\partial x_s^2} > 0. \end{aligned} \quad (4.12)$$

The isoclines represent the optimal steady state combinations of predator and prey stock for each fishery. The dynamical system (4.10) is in a steady state when the isoclines

⁵ The stability of the dynamical system is derived via the eigenvalues of its Jacobian matrix (see (4.30) in Appendix 4.5.1 for details). In the following, the notation of 'saddle stability' is used to indicate stability properties of steady states. However, when considering a 2-dimensional system of only stock sizes where harvest is an optimal feedback policy, instead of the 4-dimensional system above, this 'saddle stability' translates to 'pure' stability.

⁶ The isoclines, their slope and curvature are explicitly derived in (4.28) and (4.29) in Appendix 4.5.3.

intersect. Both isoclines are decreasing and convex curves with respect to the other stock size. Hence, it is possible that the optimization problem above may result in multiple steady states implying that there is not only one single optimal harvesting strategy for the ecosystem.

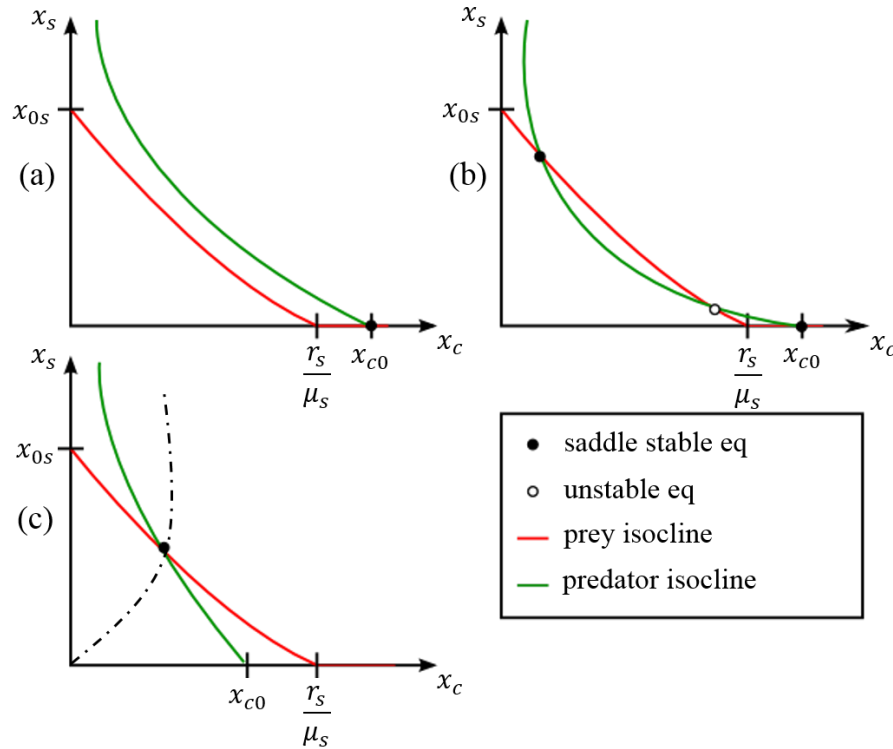


Fig. 4.1: Possible phase diagrams of the optimally managed fishery. The isoclines are depicted as red (prey) and green (predator) curves in the x_s - x_c space. Steady states are illustrated by colored dots as indicated in the legend. The dashed line is the separatrix separating the two basins of attraction of the stable states.

Since both isoclines are convex there may be an arbitrary number of intersection points. Abstracting from more involved cases with up to infinitely many steady states, I only describe cases with up to three intersection points in the following discussion. Possible shapes of the convex isoclines are depicted in the phase diagrams in Figure 4.1. The steady states along with their stability properties are depicted as black/white dots in the figure.⁷ Panel (a) depicts a case where extinction of the prey species is the unique equilibrium in the optimally managed fishery. In panel (b) the slope and curvature of the isoclines is altered such that a second 'coexistence' equilibrium appears at a high level of

⁷ Stability characteristics are derived by evaluating the sign of the eigenvalues of the Jacobian corresponding to the dynamical system (4.10). This is why steady states can be at most saddle stable. See (4.30) in Appendix 4.5.3 for a description.

prey but low level of predator biomass. The two basins of attraction of these stable states are separated by the separatrix that emanates from the unstable node in between. Panel (c) depicts the case where the unique steady state is characterized by the coexistence of the prey and predator species. The intersection point of the prey (predator) isocline with the $x_s(x_c)$ -axis is denoted by x_{0s} (x_{c0}) in the following.

From (4.12) we know that the red prey isocline solely depends on the parameters of the prey fishery. In Figure 4.1 we observe that it intersects the vertical x_s -axis at the single species optimum stock level for prey, x_{0s} , which can be written as:

$$x_{0s} = \frac{(k_s \frac{\bar{p}_s}{c_s} + r_s)(r_s - \delta) + \sqrt{(k_s \frac{\bar{p}_s}{c_s} + r_s)^2 (r_s - \delta)^2 + 4r_s^2 (2k_s \frac{\bar{p}_s}{c_s} + r_s)\delta}}{2r_s (c_s r_s + 2k_s \bar{p}_s)} \quad (4.13)$$

For $r_s > \delta$, the single species prey optimum is always decreasing in the value of the prey species, $\frac{\bar{p}_s}{c_s}$.⁸

The maximum predator stock level for which a coexistence equilibrium is viable is at $x_c = r_s/\mu_s$, that is the intersection point of the prey isocline with the horizontal x_c -axis. For any level of predator biomass that exceeds this critical value, the social planner would fish down the prey to extinction. On the other hand, the green predator isocline (4.11) converges to infinity for $x_c \rightarrow 0$, implying that extinction of the predator is never an optimal management strategy.⁹

In Figure 4.1 we observe that the predator isocline intersects the x_c -axis at the point x_{c0} , which can be written as

$$x_{c0} = \frac{(k_c \frac{\bar{p}_c}{c_c} + r_c)(r_c - \delta) + \frac{c_s}{c_c} k_c r_s \mu_s}{2 \left(r_c^2/k_c + \frac{c_s}{c_c} k_c \mu_s^2 + 2k_c \frac{\bar{p}_c}{c_c} r_c \right)} + \frac{\sqrt{\left((k_c \frac{\bar{p}_c}{c_c} + r_c)(r_c - \delta) + \frac{c_s}{c_c} k_c r_s \mu_s \right)^2 + 4r_c \delta (2k_c \frac{\bar{p}_c}{c_c} r_c + r_c^2 + \frac{c_s}{c_c} k_c^2 \mu_s^2)}}{2 \left(r_c^2/k_c + \frac{c_s}{c_c} k_c \mu_s^2 + 2k_c \frac{\bar{p}_c}{c_c} r_c \right)}. \quad (4.14)$$

⁸ I furthermore focus on effect of changes in this value of a certain species, e.g. the price (4.3) divided by the scaling parameter of the cost function (4.2).

⁹ For $\delta = 0$, the predator isocline intersects with the x_s axis at the point $\frac{r_c^2/k_c + (\frac{\bar{p}_c}{c_c} r_c + \frac{c_s}{c_c} r_s \mu_s)}{(\frac{\bar{p}_s}{c_s} + r_s/k_s)\mu_s \frac{c_s}{c_c}}$. However, the fact that discounting guards the predator stock from becoming extinct is a pure mathematical relic stemming from the fact that the exponents of h_c and x_c in the equilibrium cost function (4.2) are the same.

Note that x_{c0} depends not only on parameters of the prey fishery but also on biological characteristics and harvesting costs (but not the price level) of the prey fishery. In contrast to x_{0c} , this point does thus not represent the single species optimum predator level. It must be noted that the effects of changes in the basic value of prey (\bar{p}_s) or predator (\bar{p}_c) on x_{c0} is ambiguous. Given the characteristics of the above isoclines, the optimal level of prey and prey stock must fall into the interval $x_s^* \in [0, x_{0s})$ and $x_c^* \in (0, x_{c0}]$ respectively.

Comparing panels (a) and (c) in Figure 4.1, it is clear that depending on the intersection of each isocline with the horizontal axis, one can determine whether there exists a steady state in which only the predator survives: for $x_{c0} > r_s/\mu_s$ extinction of the prey species is always an optimum. However, since the level of x_{c0} does not unambiguously react to parameter changes as derived in (4.14), it remains to be confirmed on a case by case basis whether extinction of prey is optimal.

Given these results, we see that conclusions on the existence of multiple steady states and extinction cannot be drawn universally. However, the derived shape of the isoclines implies that multistability is possible in an optimally managed predator-prey fishery, and that a larger optimal predator stock is always attended by a smaller optimal prey stock and vice versa. I derive critical levels for the predator stock that determine whether extinction of prey is an optimal steady state or the social planner always aims for coexistence of both species. The effects of changes in the economic value of each species on isoclines and critical levels are sketched but cannot be universally determined. Therefore I present a numerical analysis on how changes in the relative values of the predator and prey fishery may lead to multiple steady states in the next section. From the derivation and discussion of the predator and prey isoclines it is clear that the number and location of equilibria depend on both ecological and economic parameters. However, here I focus on how changes in economic parameters affect multistability in optimally managed fisheries. Therefore, ecological parameters are taken as given in the following case studies.

4.3 Two Case Studies

The results from the previous section indicated that - depending on the model parameters - there may be a single or several optimal steady states of the ecosystem, with extinction of the prey species possibly being one of them. Key parameters that determine the intrinsic stability of the optimally managed fisheries are hard to determine from a theoretical perspective. Hence, even in a simplified model statements regarding the resilience of optimally managed predator-prey fisheries can only be obtained numerically for different cases. This is exactly what I do in this section.

In the following, two case studies are chosen that represent differences in the relative economic value of predator and prey while keeping constant as many other factors as possible. By restricting the focus on the effects of changes in economic parameters, that is prices \bar{p}_i and costs c_i , the following discussion of both systems allows for a more practical view on optimal fishing and resilience of the ecological-economic systems.

Here I look at the Baltic cod and sprat, and the Newfoundland cod and snow crab fishery. Both ecosystems experienced a regime shift in the late 1980s/early 1990s that led to a decline in the cod stocks and an increase in the respective prey biomass. For the Baltic sea case this regime shift is extensively discussed in chapter 3 of this thesis (Fricke and Quaas, 2015b). For both, Newfoundland cod and Baltic cod effort is made to rebuild the cod stocks to historic levels before the regime shift. The application of the model to the two fisheries therefore additionally informs us whether these strategies appear reasonable for the respective fishing industries as a whole. Note that the aim of this paper is not to explain previous regime shifts (that happened in de facto unregulated regimes) but to investigate the possibility of multistability optimally managed fisheries.

4.3.1 Background

The Baltic Sea commercial fishery is mainly dominated by three species, namely cod, herring, and sprat (STECF, 2013).¹⁰ Suggested interactions between cod and sprat in-

¹⁰ Herring is ignored in this case since biological interactions are not as clear as interactions between cod and sprat.

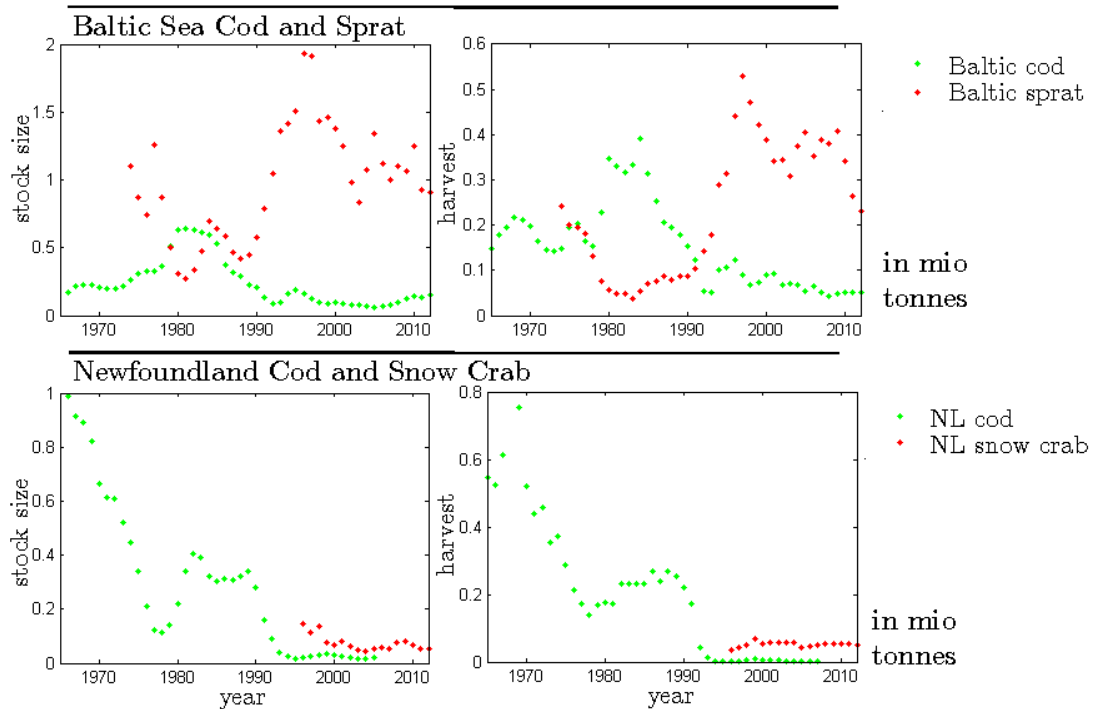


Fig. 4.2: Timeseries of stock and harvest data from ICES (2013a,d); DFO (2014, 2013). The left panels depict the stock development in the Baltic Sea and Newfoundland, the right panels the corresponding harvest development.

clude cod predation on sprat while sprat may prey on cod eggs/larvae and impose food competition for young cod (Lindgren et al., 2009). The top left panel of Figure 4.2 illustrates that since the early 1980s cod stocks (green) plummeted, while sprat biomass (red) increased using data from ICES (2013a,d). A regime shift from a cod towards a sprat dominated state of the Baltic in the late 1980s has been extensively investigated (Moellmann et al., 2009). Following the stock development, cod landings peaked in early 1980s followed by a swift decline in spite of high effort levels (ICES, 2013c). Simultaneously, catches of sprat increased substantially in the 1980s and 1990s. This is shown in the top right panel of Figure 4.2.

In Newfoundland and Labrador the cod fishery has historically been of dominant economic importance until a massive decline in the cod population in the 1980s and the official collapse of the northern cod stock in the 1990s. Ecologists suspect that the marine ecosystem at the Canadian east coast has shifted towards a new regime, where cod stocks remain at a low level while other species, especially cod prey, remain abundant (Bundy and Fanning, 2005; Worm and Myers, 2003; Rice, 2002; Bundy, 2001). Canada imposed

a moratorium for the cod fishery in 1992. It remained closed for more than 20 years, during which invertebrates (northern shrimp, snow crab, American lobster) increased in abundance (Boudreau et al., 2011; Frank et al., 2005; Worm and Myers, 2003). Because harvest rates of these valuable species increased, the total value of Newfoundland landings increased by about 60% in real terms from 1990 to 2002 (Schrank, 2005). As of today, these fisheries are the most valuable in Atlantic Canada, despite the recent decline in abundance of Snow Crab (DFO, 2013). The bottom part of Figure 4.2 illustrates mainly the development of the cod stock (left panel) and harvest (right panel) over time using data from DFO (2014, 2013). For snow crab only few data points on stock and harvest rates are available.

4.3.2 Results

Table 4.1 lists parameters used for the simulation of both ecosystems. Whenever possible, parameters are chosen from previous empirical estimates. Estimates for population dynamics of Baltic cod are taken from Quaas et al. (2012). The intrinsic growth rate of cod r for Newfoundland cod is set to the same level while its carrying capacity k stems from the maximum estimated biomass in 1962 (Haedrich and Hamilton, 2000). For snow crab and sprat no estimates on biological parameters are available, thus parameters are calibrated to fit stock level and growth estimates from DFO (2013) and ICES (2013d).

	Baltic Sea		Newfoundland	
Parameter	Cod	Sprat	Cod	Snow Crab
r	0.7	0.7	0.7	1
k	1.8	3	3	0.4
μ	-	0.5	-	0.8
$\frac{\bar{p}}{c}$	4.8	0.3	3.6	13.5
δ	0.03			

Tab. 4.1: Overview of calibrated parameters. r is the intrinsic growth rate, k the capacity limit, μ the interaction parameter, $\frac{\bar{p}}{c}$ the economic value of a fishery, and δ the discount rate.

Finally, the economic parameters ($\frac{\bar{p}}{c}$) are calibrated under the assumption that the fish-

eries were open-access in the period of record.¹¹ I assume that the social planner optimizes fisheries where the ecological parameters are taken as given. Thus, my main focus here is to explore the effect of changes in the economic parameters \bar{p} and c on the number and location of equilibria in both cases. In the following, I discuss the effect of prey price changes which increase the economic value of the prey fisheries. A short discussion of changes in prey costs can be found in Appendix 4.5.4. Effects of changes in the predator price and cost level are not discussed explicitly since they provide no additional information: A decrease in the value of cod *ceteris paribus* yields very similar results than the increase in the value of sprat.

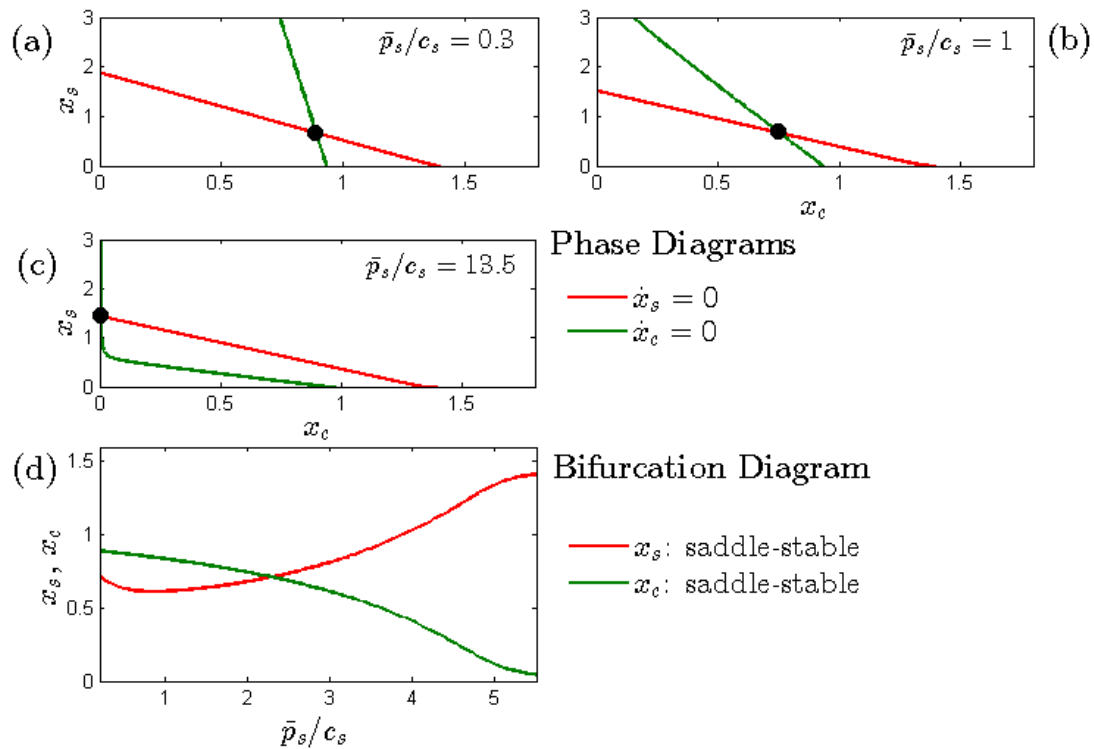


Fig. 4.3: Equilibria and bifurcation diagram for the **Baltic Sea**. Parameters as in Table 4.1 unless indicated otherwise. Panels (a)-(c) depict phase diagrams for different levels of the basic value of sprat. Sprat isoclines are in red, cod isoclines in green. Black dots indicate saddle stable equilibria, white dots indicate unstable nodes. Panel (d) illustrates the development of steady states for a continuously changing basic value of sprat.

¹¹ A more detailed discussion of the calibration process can be found in Appendix 4.5.4.

Baltic Sea

The optimally managed Baltic Sea fishery for different levels of the economic value of prey (sprat) is depicted in Figure 4.3. Panels (a)-(c) illustrate different states of the system for several economic values of the sprat fishery, starting from the calibrated $\frac{\bar{p}_s}{c_s} = 0.3$ and ending at the very high value corresponding to the Newfoundland snow crab fishery ($\frac{\bar{p}_s}{c_s} = 13.5$). The three phase diagrams show how an increase in the economic value of sprat influences the sprat (in red) and cod (in green) isoclines and the resulting equilibrium.¹²

From the fact that x_{c0} does not react to changes in \bar{p}_s (as determined in (4.14)) and that x_{c0} lies below $\frac{r_s}{\mu_s}$, one can deduct that for the Baltic sea system coexistence of both species must be always one possible optimal steady state. This is observable in panel (a)-(c) of Figure 4.3: there is only one saddle-stable steady state characterized by the coexistence of cod and sprat, although the cod stock level is very low in panel (c).¹³

The single species optimal level of sprat x_{0s} decreases with an increasing value of the sprat fishery since leaving fish in the water becomes less profitable (as determined in (4.13)). However, this effect is dominated by the change in the shape of the cod isocline. Its slope increases and curvature decreases in \bar{p}_s . An increase in the value of sprat thus leads to an increase in the optimal level of sprat and decrease in the optimal level of cod biomass.

The bifurcation diagram in panel (d) illustrates the changes in optimal cod and sprat steady state biomass for a continuously increasing value of the sprat fishery. With its increasing economic value, sprat becomes more and more dominant in the ecosystem. However, this change is continuous, and lacking sudden shifts from one to another steady state. The optimally managed Baltic sea fishery is thus quite resilient with respect to changes in prices and costs.

Given the originally calibrated values of both fisheries from Table 4.1 corresponding

¹² In this numerical exercise, \bar{p}_s is increased and $c_s = 1$ held constant in this figure as the system proves to be much more variable with respect to price changes compared to changes in the cost parameter. A corresponding figure for change in costs c_s instead of prices is depicted in Figure 4.6 in Appendix 4.5.4. The same is true when looking at changes in predator value levels: the system is more resilient with respect to changes in c_c than to changes in p_c (unreported result).

¹³ For the single derived steady state two eigenvalues of the Jacobian (4.30) are negative, two positive. The optimality can be confirmed by using Arrow's optimality condition in Appendix 4.5.2: $\Delta_1 < 0$, $\Delta_2 > 0$ (unreported results).

to panel (a) in Figure 4.3, it appears that current efforts to rebuild the cod stock are indeed the optimal management strategy for the Baltic sea.

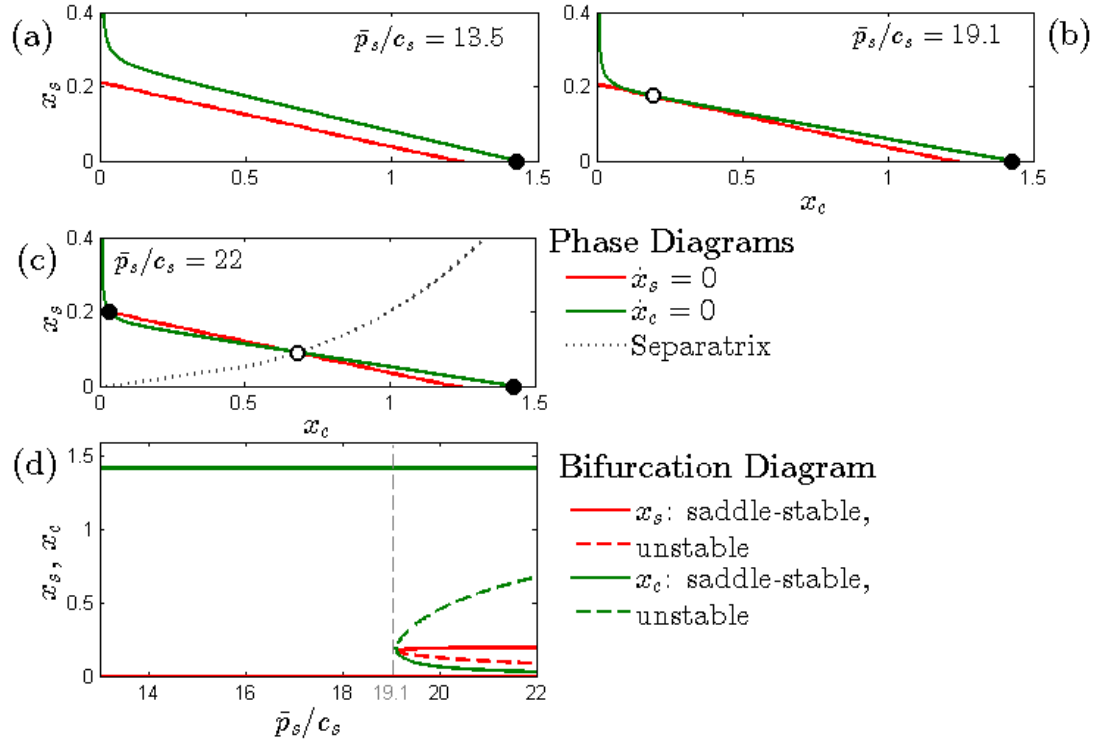


Fig. 4.4: Equilibria and bifurcation diagram for **Newfoundland**. Parameters as in Table 4.1 unless indicated otherwise. Panels (a)-(c) depict phase diagrams for different levels of the basic value of snow crab. Snow crab isoclines are in red, cod isoclines in green. Black dots indicate saddle stable equilibria, white dots indicate unstable nodes. Panel (d) illustrates the development of steady states for a continuously changing basic value of snow crab. Saddle stability is indicated by continuous lines, unstable nodes by dashed lines.

Newfoundland

Optimal steady states in the Newfoundland fishery for varying levels of the economic value of prey (snow crab) are depicted in Figure 4.4. Again, panels (a)-(c) show the isoclines for cod and snow crab in the x_s - x_c plane.¹⁴ We observe that $x_{c0} > \frac{r_s}{\mu_s}$ in case of the Newfoundland cod and snow crab fishery, thus, extinction of snow crab is always one optimal (saddle-stable) steady state in this ecosystem.

¹⁴ Here again, \bar{p}_s is increased and $c_s = 1$ held constant for the same reasons than before. A corresponding figure for change in costs c_s instead of prices is depicted in Figure 4.7 in Appendix 4.5.4. The critical price level of cod corresponding to panel (b) is $\bar{p}_c = 2.1$.

An increase in the value of snow crab leads to a decrease in its single species optimum, x_{0s} . Again, the effect of changes in p_s/c_s on the shape of the cod isocline dominates the situation.

Panel (b) depicts the system given the 'critical' economic value $\bar{p}_s/c_s = 19.1$ for which the cod and snow crab isocline are tangent to each other at a second (unstable) state of the system. Panel (c) shows that when increasing the value of snow crab further, the cod isocline turns downwards such that two new steady states (one saddle stable and one unstable) appear, while the original 'extinction' steady state remains in place.¹⁵

The emerging stable state is a coexistence optimum at a very low level of cod corresponding to a high level of snow crab. The state space is divided by the separatrix that runs through the unstable node. It separates the state space into two basins of attraction. Depending on the initial location in the phase diagram, it is optimal for the social planner to aim at one or the other optimal steady state. A shock on the stock size of one or the other species could thus have very different implications for the optimal management.

The bifurcation diagram in panel (d) illustrates the emergence and location of saddle-stable and unstable steady states for a continuously increasing value of snow crab in the Newfoundland setting. At the critical value of snow crab two additional steady states emerge. One of them is unstable (dashed curve), one of them saddle stable (continuous curve). The optimally managed Newfoundland fishery system is thus less resilient for high values of the prey species snow crab. However, given the originally calibrated value of snow crab ($\bar{p}_s/c_s = 13.5$), the single optimal steady state is characterized by the extinction of snow crab. Hence, also for the Newfoundland fishery current efforts to rebuild the cod stock up to its historic size is consistent with the model's suggested optimal management strategy.

Comparing the two case studies from Figures 4.3 and 4.4, we find that while the relative economic value of both species affects the location of the optimal steady states, an effect on the resilience or multistability cannot be predicted with certainty. In particular,

¹⁵ In case of the extinction steady state, two eigenvalues of the Jacobian (4.30) are negative, two equal zero. In case of the coexistence steady state in panel(c), two eigenvalues are negative, two positive. The optimality of both is confirmed by using Arrow's optimality condition in Appendix 4.5.2: $\Delta_1 < 0$, $\Delta_2 > 0$ (unreported results).

the behavior of the isoclines at very low levels of prey biomass (the position of x_{c0} relative to $\frac{r_s}{\mu_s}$) seems to determine whether the system is inclined to bifurcate or not. When the system is inclined to bifurcate (as is the case for Newfoundland), a higher economic value of the prey species compared to the predator appears to facilitate multistability.

4.4 *Conclusion*

In this paper I analyzed how changes in market values of interacting species affect the character and the resilience of an optimally managed fishery. I thereby contribute further to the discussion of why optimal managed fisheries may lead to regime shifts, which has been attributed to the quality of institutions (Horan et al., 2011), preferences for consumption diversity, and the discount rate (Quaas et al., 2013).

In the theoretical part I derived the dynamic system of an optimally harvested predator-prey fishery making use of a simplified version of the model in Fricke and Quaas (2015a,b) in previous chapters of this thesis. This allowed me to explore the location and number of possible steady states for some specific situations. I determined critical levels for the predator stock that indicate whether extinction of prey is optimal or the social planner always aims for coexistence of both species. The shape of the derived system's isoclines imply that multistability is possible. Still, the structure of the model is too complex to formally investigate the effect of the economic values of each species on the emergence of multiple steady states.

Therefore, I relied on two case studies to illustrate how changes in the relative values of the predator and prey fishery may lead to multiple steady states depending on the characteristics of the fishery. The two case studies chosen are the Baltic Sea cod and sprat, and the Newfoundland cod and snow crab fishery. The predator belongs to the same species in both cases while the prey fisheries differ greatly in biological and economic characteristics. While the biological difference are obvious - sprat being a small pelagic species while snow crab is a large invertebrate - the interesting economic difference between these fisheries is their different economic value. In the Baltic sea, sprat is low priced and mainly used as fish fodder, while in Newfoundland snow crab is a high priced

gourmet food.

The economic and ecologic differences lead to very different implications for the fisheries, that may appear counter-intuitive. Given the current economic value of the fisheries, it would be optimal to aim at a coexistence state of Baltic cod and (low valued) sprat, where both species are harvested on a medium level. In contrast, the optimal harvested Newfoundland fishery would lead to a collapse of (high priced) snow crab and to a high level of cod stocks.

Thus, optimal extinction of a species does not seem to be driven by its low economic value but by the ecological side of the model. Stronger predator-prey interactions and/or smaller carrying capacities may thus foster optimal extinction in optimally managed fisheries.

The results also imply that an increase in the economic value of the prey relative to its predator may lead to multistability and thus a decrease in the resilience of the system depending on the ecological conditions. The two case studies revealed that the optimally managed Baltic sea fishery is much more resilient than the Newfoundland fishery. For an increasing value of the prey species, the optimal state of the Baltic sea ecosystems shifts smoothly from cod towards sprat domination, while for Newfoundland bifurcation and sudden regime shifts occur after a critical level is reached. Thus, in a system that is inclined to bifurcate, an increasing economic value of the prey species compared to the predator seems to decrease the resilience by increasing the number of optimal steady states.

This study can only be another step to understanding the economic drivers of regime shifts in optimally managed fisheries. While I chose a simplified model here to show some analytical results, it would be quite interesting to discuss the effects of local factor and/or output markets on the resilience by loosening the restrictions on prices and costs. Furthermore, I focused on more qualitative results and did not discuss welfare effects of different management strategies, but it would be useful to apply (a possibly less restricted version of) the model to a specific ecosystem and derive implications for fisherman's surplus and profits in order to give concrete policy advice. Lastly, it would be an interesting

extension to explore the effects of variation in ecological parameters.

4.5 Appendix

4.5.1 The Theoretical Model

In the following I provide the description of the theoretical model. For the sake of convenience I omit the subscript i from all equations in this section. However, the reader is advised to remember that each fishery is characterized by its own factor markets and technology.

Harvesting is described by the Gordon-Schaefer production function

$$h = q E x, \quad (4.15)$$

means of i.e. labor l and capital k using Cobb-Douglas technology with constant returns to scale:

$$E = l^\varphi k^{1-\varphi} \quad (4.16)$$

with $\varphi \in (0, 1)$. The supply functions of both inputs are assumed to be iso-elastic. Both production factors cannot be transferred between fisheries of different species, which makes sense if the fisheries are very different and/or the fishing seasons vary. Supply of both input factors is thus defined as:

$$w(l) = \omega l^\zeta, \quad (4.17)$$

$$r(k) = \kappa k^\psi, \quad (4.18)$$

where ζ (ψ) denote the inverse supply elasticity of labor (capital) and w (r) is the wage rate (capital rental rate). When supply of labor is perfectly elastic the wage rate equals the "global" wage rate ω (κ for capital, respectively).

Fishermen minimize their costs to determine their optimal harvest quantity in each period. They have to take local factor markets into account when they decide on their

harvest strategy. Solving the representative firm's cost minimization problem

$$\begin{aligned} \min_{l,k} \quad & wl + rk \\ \text{s.t.} \quad & \text{Eqs (4.15), (4.16)} \end{aligned}$$

leads to the factor demand functions

$$l = \frac{h}{qx} \left(\frac{\varphi}{1-\varphi} \frac{r}{w} \right)^{1-\varphi}, \quad (4.19)$$

$$k = \frac{h}{qx} \left(\frac{1-\varphi}{\varphi} \frac{w}{r} \right)^{\varphi}, \quad (4.20)$$

as well as the cost function that is linear in harvest,

$$\tilde{c}(h, w, r; x) = \frac{w^{\varphi} r^{1-\varphi}}{\varphi^{\varphi} (1-\varphi)^{1-\varphi}} \frac{h}{qx}. \quad (4.21)$$

In labor and capital market equilibrium, the equilibrium wage and capital rental rate is (using (4.19) in (4.17), (4.20) in (4.18) respectively):

$$w = \omega l^{\zeta} = \omega \left(\frac{h}{qx} \right)^{\zeta} \left(\frac{\varphi}{1-\varphi} \frac{r}{w} \right)^{\zeta(1-\varphi)}, \quad (4.22)$$

$$r = \kappa k^{\psi} = \kappa \left(\frac{h}{qx} \right)^{\psi} \left(\frac{1-\varphi}{\varphi} \frac{w}{r} \right)^{\psi\varphi}. \quad (4.23)$$

Using (4.22) and (4.23) in (4.21), the market equilibrium cost function becomes

$$c(h, x) = c \left(\frac{h}{x} \right)^{e+1},$$

with

$$c = q^{-(e+1)} \left(\frac{\omega}{\varphi} \right)^{\frac{\varphi(1+\psi)}{1+\psi\varphi+\zeta(1-\varphi)}} \left(\frac{\kappa}{1-\varphi} \right)^{\frac{(1-\varphi)(1+\zeta)}{1+\psi\varphi+\zeta(1-\varphi)}} > 0$$

and

$$e = \zeta \frac{\varphi(1+\psi)}{1+\zeta(1-\varphi)+\psi\varphi} + \psi \frac{(1-\varphi)(1+\zeta)}{1+\zeta(1-\varphi)+\psi\varphi} > 0.$$

Assuming that firm's minimize their costs, and assuming that the cost function is quadratic in harvest (implying $e_i = 1$) following Nieminen et al. (2012), the market equilibrium cost function can be written as¹⁶

$$c_i(h_i, x_i) = c_i \left(\frac{h_i}{x_i} \right)^2. \quad (4.24)$$

Rents

Worker surplus is defined as the area between the equilibrium wage rate and the inverse labor supply curve:

$$\begin{aligned} WS &= w_{eq} l_{eq} - \int_0^{l_{eq}} \omega l^\zeta dl = \frac{\zeta}{1+\zeta} \omega l_{eq}^{1+\zeta} = \frac{\zeta}{1+\zeta} \omega^{-\frac{1}{\zeta}} w_{eq}^{\frac{1+\zeta}{\zeta}} \\ &= \frac{\zeta}{1+\zeta} \left(\omega^{(1+\psi)\varphi} \left(\frac{h}{qx} \right)^{(1+\zeta)(1+\psi)} \left(\frac{\kappa\varphi}{1-\varphi} \right)^{(1+\zeta)(1-\varphi)} \right)^{\frac{1}{1+\psi\varphi+\zeta(1-\varphi)}} \\ &= \frac{\zeta}{1+\zeta} \omega^\alpha \left(\frac{\kappa\varphi}{1-\varphi} \right)^\beta \left(\frac{h}{qx} \right)^{1+e} = \varphi \frac{\zeta}{1+\zeta} c \left(\frac{h}{x} \right)^{1+e} \end{aligned}$$

Analogous, capital owner surplus is defined as the area between the equilibrium capital rental rate and the inverse capital supply curve:

$$\begin{aligned} RS &= \frac{\psi}{1+\psi} \kappa^{-\frac{1}{\psi}} r_{eq}^{\frac{1+\psi}{\psi}} \\ &= \frac{\psi}{1+\psi} \left(\kappa^{(1+\zeta)(1-\varphi)} \left(\frac{h}{qx} \right)^{(1+\psi)(1+\zeta)} \left(\frac{\omega(1-\varphi)}{\varphi} \right)^{(1+\psi)\varphi} \right)^{\frac{1}{1+\psi\varphi+\zeta(1-\varphi)}} \\ &= \frac{\psi}{1+\psi} \kappa^\beta \left(\frac{\omega(1-\varphi)}{\varphi} \right)^\alpha \left(\frac{h}{qx} \right)^{1+e} = (1-\varphi) \frac{\psi}{1+\psi} c \left(\frac{h}{x} \right)^{1+e} \end{aligned}$$

Total fisherman surplus then is the sum of capital owner surplus and worker surplus:

$$FS = WS + RS = \left(\varphi \frac{\zeta}{1+\zeta} (1-\varphi) \frac{\psi}{1+\psi} \right) c \left(\frac{h}{x} \right)^{1+e} = \frac{e}{1+e} c \left(\frac{h}{x} \right)^{1+e} \quad (4.25)$$

In the main text the restriction $e = 1$ is employed in the equation above.

¹⁶ A quadratic cost function simplifies the derivation of analytic results greatly. However, in principal the restriction of a quadratic cost function is not necessary.

4.5.2 Second Order Optimality Condition: Arrow

The first order conditions (4.6), (4.7), and (4.8) are necessary conditions for an optimum. Since the Hamiltonian is not concave in with respect to the state (x_i) and control (h_i) variable Arrow's theorem requires following type of concavity as a sufficient condition for optimality:

The Hamiltonian is maximized with respect to the control variables, for a given value of state and costate variable (λ_i). The optimum values of the control variable is substituted into the Hamiltonian to derive the maximized Hamiltonian (MH). Arrow states that if MH is (strictly) concave with respect to the state variable, for the given values of the costate variable, then the first-order conditions characterize an optimum.

Optimal harvest $h_i^*(x_i, \lambda_i)$ can be directly derived from (4.6):

$$h_i^*(x_i, \lambda_i) = \frac{\bar{p}_i - \lambda_i}{c_i} x_i^2 \quad (4.26)$$

It thus increases in stock size and decreases in the shadow price of the stock.

The maximized Hamiltonian using (4.26), and given the level of λ_c , and λ_s is

$$MH^c(x_c, x_s) = \sum_{i=c,s} \bar{p}_i \left(\frac{\bar{p}_i - \lambda_i}{c_i} x_i^2 \right) - \frac{c_i}{2} \left(\frac{\bar{p}_i - \lambda_i}{c_i} x_i^2 \right)^2 x_i^{-2} + \lambda_i (g_i(x_i, x_j) - \frac{\bar{p}_i - \lambda_i}{c_i} x_i^2).$$

The Hessian of MH^c can be written as:

$$\text{Hessian}_{MH^c} = \begin{pmatrix} \frac{\partial^2 MH^c}{\partial x_c^2} & \frac{\partial^2 MH^c}{\partial x_c \partial x_s} \\ \frac{\partial^2 MH^c}{\partial x_c \partial x_s} & \frac{\partial^2 MH^c}{\partial x_s^2} \end{pmatrix} = \begin{pmatrix} \frac{k_c(\bar{p}_c - \lambda_c)^2 - 2c_c r_c \lambda_c}{c_c k_c} & -\lambda_s \mu_s \\ -\lambda_s \mu_s & \frac{k_s(\bar{p}_s - \lambda_s)^2 - 2c_s r_s \lambda_s}{c_s k_s} \end{pmatrix}$$

By Young's Theorem the maximized Hamiltonian is concave at the point x^* only if the Hessian is negative semidefinite at that point. The principal minors are

$$\Delta_1 = \frac{\partial^2 MH^c}{\partial x_c^2} = \frac{k_c(\bar{p}_c - \lambda_c)^2 - 2c_c r_c \lambda_c}{c_c k_c}$$

$$\Delta_2 = \frac{\partial^2 MH^c}{\partial x_c^2} \frac{\partial^2 MH^c}{\partial x_s^2} - \left(\frac{\partial^2 MH^c}{\partial x_c \partial x_s} \right)^2 = \frac{k_c(\bar{p}_c - \lambda_c)^2 - 2c_c r_c \lambda_c}{c_c k_c} \frac{k_s(\bar{p}_s - \lambda_s)^2 - 2c_s r_s \lambda_s}{c_s k_s} - \lambda_s^2 \mu_s^2$$

The Hessian is negative semi-definite if $\Delta_1 < 0$, and $\Delta_2 > 0$. This needs to be evaluated at each steady state to determine optimality.

4.5.3 The Steady State Conditions

Using the steady state condition, $\dot{x}_i = \dot{\lambda}_i = \dot{h}_i = 0$, along with (4.8) and (4.6) in (4.7), the two optimal steady state conditions are

for predator:

$$0 = \left(\frac{\partial g_c}{\partial x_c} - \delta \right) \frac{\partial u_c}{\partial h_c} \Big|_{h_c=g_c(x_c)} + \frac{\partial g_s}{\partial x_c} \frac{\partial u_s}{\partial h_s} \Big|_{h_s=g_s(x_s)} + \frac{\partial u_c}{\partial x_c} \Big|_{h_s=g_s(x_s)},$$

and for prey:

$$0 = \left(\frac{\partial g_s}{\partial x_s} - \delta \right) \frac{\partial u_s}{\partial h_s} \Big|_{h_s=g_s(x_s, x_c)} + \frac{\partial u_s}{\partial x_s} \Big|_{h_s=g_s(x_s, x_c)}. \quad (4.27a)$$

Or in their extensive form,

$$\begin{aligned} 0 = & \left(r_c \left(1 - \frac{2x_c}{k_c} \right) - \delta \right) \left[\bar{p}_c - c_c x_c^{-2} \left(r_c x_c \left(1 - \frac{x_c}{k_c} \right) \right) \right] \\ & + c_c x_c^{-3} \left(r_c x_c \left(1 - \frac{x_c}{k_c} \right) \right)^2 \\ & - x_s \mu_s \left[\bar{p}_s - c_s x_s^{-2} \left(r_s x_s \left(1 - \frac{x_s}{k_s} \right) - \mu_s x_s x_c \right) \right] \end{aligned} \quad (4.27b)$$

and ,

$$\begin{aligned} 0 = & \left(\left(r_s \left(1 - \frac{2x_s}{k_s} \right) - \mu_s x_c \right) - \delta \right) \left[\bar{p}_s - c_s x_s^{-2} \left(r_s x_s \left(1 - \frac{x_s}{k_s} \right) - \mu_s x_s x_c \right) \right] \\ & + c_s x_s^{-3} \left(r_s x_s \left(1 - \frac{x_s}{k_s} \right) - \mu_s x_s x_c \right)^2. \end{aligned} \quad (4.27c)$$

Solving (4.27b) for x_s and plugging it into (4.27c), it is possible to derive one single steady state condition solely dependent on x_s .

Rewriting (4.27b) ((4.27c) respectively) in terms of x_s (x_c respectively) one derives

the isoclines for the predator fishery as,

$$x_s = \frac{\frac{r_c}{k_c} \left(r_c \left(1 - \frac{x_c}{k_c} \right) - \delta \right) + \frac{\bar{p}_c}{c_c} \left(r_c \left(1 - \frac{2x_c}{k_c} \right) - \delta \right) + \frac{r_c \delta}{x_c} + \frac{c_s}{c_c} \mu_s (r_s - \mu_s x_c)}{\mu_s \left(\frac{r_s}{k_s} + \frac{\bar{p}_s}{c_s} \right) \frac{c_s}{c_c}}$$

$$\text{with } \frac{\partial x_s}{\partial x_c} = - \frac{2 \frac{\bar{p}_c}{c_c} r_c / k_c + (r_c / k_c)^2 + r_c \delta / x_c^2 + c_s / c_c \mu_s^2}{(\bar{p}_s + c_s r_s / k_s) \mu_s / c_c} < 0 \quad (4.28)$$

$$\text{and } \frac{\partial^2 x_s}{\partial x_c^2} = \frac{2 r_c c_c \delta}{\mu_s x_c^3 (c_s r_s / k_s + \bar{p}_s)} > 0.$$

and the prey fishery as,

$$x_c = \frac{(\delta + r_s \frac{x_s}{k_s} + \frac{\bar{p}_s}{c_s} x_s) \left(r_s \left(1 - \frac{x_s}{k_s} \right) \right) + \frac{\bar{p}_s}{c_s} x_s \left(r_s \frac{x_s}{k_s} + \delta \right)}{(\delta + r_s \frac{x_s}{k_s} + \frac{\bar{p}_s}{c_s} x_s) \mu_s},$$

$$\text{with } \frac{\partial x_c}{\partial x_s} = - \frac{r_s \left(\delta + 2 \frac{\bar{p}_s}{c_s} x_s \right)^2 - 2 r_s \left(\frac{\bar{p}_s}{c_s} \right)^2 x_s^2 + r_s^3 (x_s / k_s)^2 + \delta^2 k_s \frac{\bar{p}_s}{c_s} + r_s^2 x_s / k_s (2 c_s \delta + 3 \frac{\bar{p}_s}{c_s} x_s)}{\mu_s (\delta k_s + r_s x_s + k_s \frac{\bar{p}_s}{c_s} x_s)^2} < 0 \quad (4.29)$$

$$\text{and } \frac{\partial^2 x_c}{\partial x_s^2} = \frac{2 \delta^2 \left(\frac{\bar{p}_s}{c_s} \right)^2}{\mu_s (\delta + r_s x_s / k_s + \frac{\bar{p}_s}{c_s} x_s)^3} > 0.$$

The stability of a steady state is determined by linearizing the dynamic system described in (4.10), resulting in the following system:

$$\begin{pmatrix} \dot{x}_c \\ \dot{x}_s \\ \dot{h}_c \\ \dot{h}_s \end{pmatrix} = \underbrace{\begin{pmatrix} \frac{\partial g_c}{\partial x_c} & 0 & -1 & 0 \\ \frac{\partial g_s}{\partial x_c} & \frac{\partial g_s}{\partial x_s} & 0 & -1 \\ \frac{\partial \dot{h}_c}{\partial x_c} & \frac{\partial \dot{h}_c}{\partial x_s} & \frac{\partial \dot{h}_c}{\partial h_c} & \frac{\partial \dot{h}_c}{\partial h_s} \\ \frac{\partial \dot{h}_s}{\partial x_c} & \frac{\partial \dot{h}_s}{\partial x_s} & \frac{\partial \dot{h}_s}{\partial h_c} & \frac{\partial \dot{h}_s}{\partial h_s} \end{pmatrix}}_{\equiv J} \begin{pmatrix} dx_c \\ dx_s \\ dh_c \\ dh_s \end{pmatrix}. \quad (4.30)$$

The four eigenvalues (*EV*) of the Jacobian matrix J in the steady states determine the stability of the respective state. Typically, an equilibrium of an optimal control problem can be at most saddle-stable. That is, at least one eigenvalue will be positive.

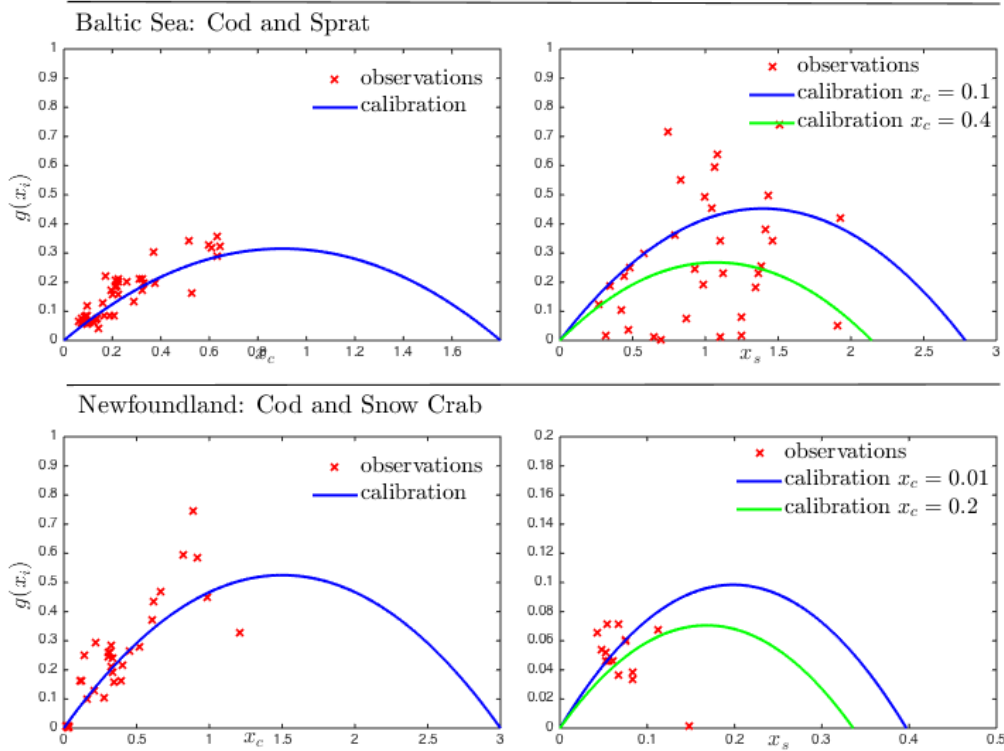


Fig. 4.5: Calibrated Population Dynamics using parameters from Table 4.1. The top panels depict the growth function of Baltic cod and Baltic sprat for different levels of cod biomass. The bottom panels depict the same for Newfoundland cod and snow crab.

4.5.4 Parametrization and Numerical Simulation

Figure 4.5 illustrates the calibration of the Baltic Sea and the Newfoundland predator-prey fisheries. The parameters for Baltic cod population dynamics are taken from Quaas et al. (2012), $r_c = 0.7$ and $k_c = 1.8$ mio tonnes. Being the same species (*Gadus morhua*), the intrinsic growth rate of Newfoundland cod is set to the same level $r_c = 0.7$. Haedrich and Hamilton (2000) provide time series of Newfoundland cod estimates. The maximum estimated stock size in 1962 is taken as carrying capacity, $k_c = 3$ mio tonnes.

Parameters for Baltic sprat and snow crab are calibrated using expert opinion along with visual judgment with respect to stock and growth estimates and presumed population dynamics (4.1).

Parameters for the economic part of the model ($\frac{p}{c}$) are derived by assuming open access conditions in all four fisheries over the observation period. Rearranging the zero-profit condition $c(x, h) = p h$ for $\frac{p}{c}$ one derives $\bar{\frac{p}{c}} = \frac{h}{x^2}$, that can be used to determine the

economic parameters.

Following the criterion for *de facto* open access from Quaas et al. (2012), Baltic cod and sprat can be considered open access until 2012.¹⁷

For Newfoundland a total allowable catch (TAC) management for cod was implemented in the mid 1970s but was never binding until the moratorium in 1992. For snow crab the open access assumption is not perfectly convincing. However, assuming that the management would lie somewhere in between open access and optimal management, and using the derived optimal harvest condition (4.26), it is obvious that the estimated open access parameter $\frac{p_s}{c_s}$ must be somehow an upper bound. Figure 4.4 shows that for lower initial $\frac{p_s}{c_s}$, the phase diagram and bifurcation analysis would qualitatively remain the same.

Bifurcation: Other parameters

Figure 4.6 and Figure 4.7 depict again changes in the value of the prey species for the Baltic and the Newfoundland ecosystem. In these figures, however, instead of increasing prices cost are decreased accordingly. Obviously, both ecosystems are much more resilient with respect to changes in cost parameters than with respect to changes in prices. Since in the proposed model the cost function strongly depends on the stock size, the stock effect may dominate the effect of changing c_i .

¹⁷ The criterion is: A fishery is considered *de facto* open-access when in at least three consecutive years the catch was less than 90% of the total allowable catch (TAC) and no additional management measures are in place. This is true for all considered Baltic fisheries (ICES, 2013a,d).

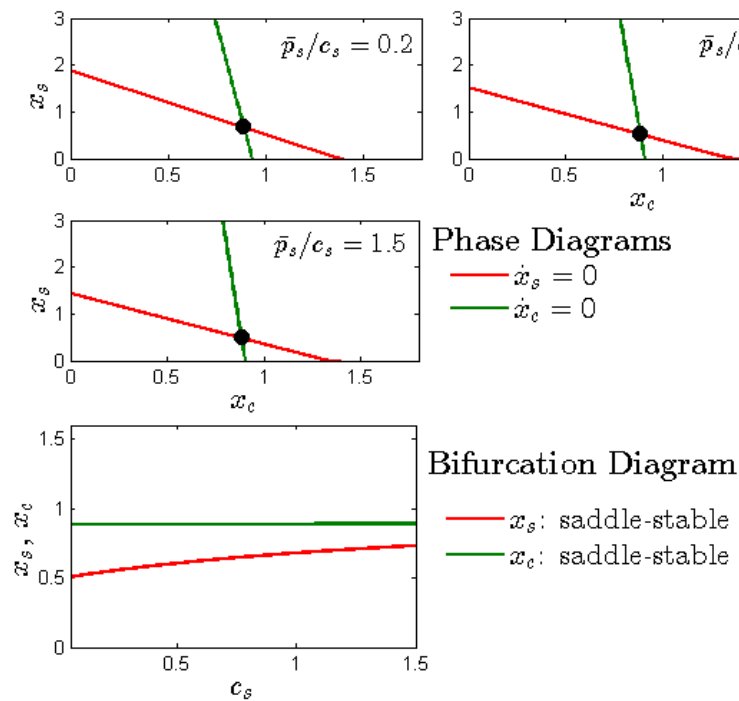


Fig. 4.6: Equilibria and bifurcation diagram for the **Baltic Sea** depicting changes in c_s . Parameters as in Table 4.1 unless indicated otherwise. Panels (a)-(c) depict phase diagrams for different levels of the basic value of sprat. Sprat isoclines are in red, cod isoclines in green. Black dots indicate saddle stable equilibria, white dots indicate unstable nodes. Panel (d) illustrates the development of steady states for a continuously changing c_s .

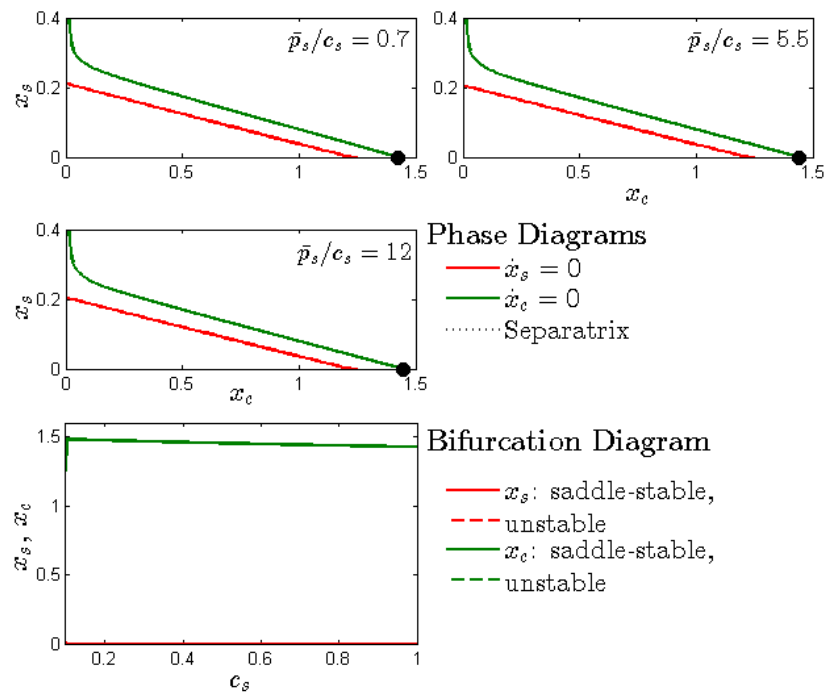


Fig. 4.7: Equilibria and bifurcation diagram for the **Newfoundland** depicting changes in c_s . Parameters as in Table 4.1 unless indicated otherwise. Panels (a)-(c) depict phase diagrams for different levels of the basic value of snow crab. Snow crab isoclines are in red, cod isoclines in green. Black dots indicate saddle stable equilibria, white dots indicate unstable nodes. Panel (d) illustrates the development of steady states for a continuously changing c_s .

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Eidesstattliche Erklärung

Ich erkläre hiermit, an Eides Statt, dass ich meine Doktorarbeit 'The Economics of Regime Shifts in Marine Ecosystems' selbständig und ohne fremde Hilfe angefertigt habe und dass ich alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen meiner Arbeit, besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert habe.

Oxford, April 2015

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