Fisheries management and tipping points: Seeking optimal management of Eastern Baltic cod under conditions of uncertainty about the future productivity regime

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Abstract
Historical patterns of the Eastern Baltic cod stock recruitment show a shift from a regime with high reproductive potential before the early 1980s to a regime with low reproductive potential since then. This shift can be attributed to increasingly unfavorable environmental conditions for cod reproduction at that time: critical salinity and oxygen levels, needed for successful egg and larval development, deteriorated. Yet, significant inflows of salt- and oxygen-rich water from the North Sea or improved eutrophication management might trigger a shift back to a more productive regime. Coupling a statistical recruitment model to a state-of-the-art, age-structured bio-economic model of the Eastern Baltic cod fishery, we study how optimal management depends on the uncertainty about the future productivity regime. We extend the predominantly theoretical literature on optimal management of a natural resource with a potential regime shift by analyzing an empirical model of age-structured population dynamics and by allowing for the possibility of a back-shift from a “bad” into a “good” regime. We find that with a higher probability of a shift back to the...
more productive regime the optimal management of the fishery becomes more conservative in the short run. We conclude that these benefits for the fishery warrant strong action reducing eutrophication to increase the probability of a regime shift back to high reproductive potential of the Eastern Baltic cod fishery.

**KEYWORDS**

Baltic cod, bio-economic model, eutrophication, profits, regime shift, tipping point

**Recommendations for Resource Managers**

1. Optimal fishing quotas strongly depend on the productivity regime, which, for Baltic cod, shifted to low recruitment productivity in the late 20th century.
2. For Baltic cod, whereas the current low productivity regime requires restrictive quotas, optimal catches would be much higher if the ecosystem would shift back into a regime of more productive recruitment.
3. Uncertainty about the future regime and the chance for a shift back to the more productive regime imply that the optimal management of the fishery becomes (even) more conservative in the short run.
4. Benefits for the fishery warrant strong action reducing eutrophication to increase the probability of a regime shift back to high reproductive potential of the Baltic cod fishery.

**1 | INTRODUCTION**

Regime shifts and tipping points are ubiquitous in marine ecosystems over the whole North Atlantic Ocean and adjacent seas (Conversi et al., 2015; Möllmann & Diekmann, 2012). A general characteristic of these ecosystem regime changes are dramatic collapses in important fisheries resources such as cod (*Gadus morhua*) caused by unsustainable fishing pressure (Blenckner et al., 2015; Frank et al., 2016), but also environmental pressures. The historical cod collapses had important ecological consequences (Casini et al., 2008; Frank et al., 2005), and socioeconomic implications (Blenckner et al., 2015; Lade et al., 2015; Tahvonen et al., 2018).

Resource economists have developed theoretical approaches to study how management should optimally take into account the possibility of a regime shift. Reed (1988) has shown that an exogenously fixed probability for a regime shift that would lead to a collapse of the resource tends to increase optimal harvesting. The economic reason is that it is less rewarding to invest
into an asset that may collapse and cease to yield returns on the investment. By contrast, tipping points that depend on stock size can induce a more conservative optimal management (Crépin et al., 2012; de Zeeuw & Zemel, 2012; de Zeeuw, 2014; Polasky et al., 2011). The reason is that more conservative management protects against the risk of a resource collapse, according to Ehrlich and Becker’s (1972) notion of self-protection.

The Baltic Sea is a prime example of an aquatic ecosystem under multiple stressors such as climate change, fishing, eutrophication and invasive species. Of all the potential threats, eutrophication is one of the most important drivers affecting the Baltic Sea ecosystems and its ecosystem services, including fisheries, as it causes hypoxia, blooms of blue green algae and shifts in plankton communities with large ecological and economic consequences (e.g., HELCOM, 2006).

A combination of stressors caused regime shifts in multiple subsystems (Diekmann & Möllmann, 2010, Lindegren et al., 2010, 2012, Möllmann et al., 2009), signified by trophic cascading (Casini et al., 2008, Möllmann et al., 2008). Regime shifts and trophic cascades caused large-scale changes in food web structure in terms of interactions and their strength, in total altering food web function (Conversi et al., 2015, Möllmann et al., 2015).

Eastern Baltic cod was heavily involved in the regime shift of the central Baltic Sea, as described above. For many decades, it had been the main fisheries resource species in the Baltic Sea (ICES, 2019a). This important living marine resource is in danger of collapse. Abrupt declines in Spawning Stock Biomass (SSB) have been observed in the period of the late 1980s and early 1990s. This decrease in stock size was paralleled by abrupt changes in recruitment, that is, year-class strength and stock productivity, leading to a cod spawning stock size of only about 15% of its size in the beginning of the 1980s. Consequently, severe, negative socio-economic outcomes like reduced fleet profitability and associated reductions in fleet capacity were recorded (Scientific Technical and Economic Committee for Fisheries [STECF], 2019).

As for Baltic cod, regime shifts usually result in degraded, unfavorable ecosystem states, and avoidance of a shift (Scheffer et al., 2012), or restoration and recovery to the original ecosystem state, is often the prime management goal (Selkoe et al., 2015).

In the Eastern Baltic Sea, eutrophication management might be key when trying to restore the original ecosystem state: The topography of the Baltic is a sequence of deep basins, separated by shallow sills. There are generally high gradients in both abiotic and biotic variables, due to the strong vertical stratification and the limited exchange with the North Sea. Oxygen renewal in the deep basins depends on irregular inflows of saline, oxygen-rich North Sea water masses, so-called Baltic inflows (Matthäus & Lass, 1995). These have a pronounced impact on oxygen levels especially in the deep basins of the Baltic Sea (Saraiva et al., 2019). Many ecosystem dynamics critically depend on sufficient oxygen levels in the intermediate and bottom waters of the Baltic. For example, cod stock dynamics are strongly influenced by oxygen-dependent egg survival (Plikshs et al., 1993; Voss et al., 2011). Due to its brackish water nature, cod eggs do not float at the surface, but are found in depths below 60 m, where salinities are sufficient to allow for neutral egg buoyancy and fertilization. At this depth, oxygen levels decrease over time due to aerobic degradation processes, and are only replenished by major Baltic inflows. Furthermore, oxygen depletion shortens benthic food supply for juvenile and adult cod (Carstensen et al., 2014), and directly effects cod growth via reduced metabolism (Plambeck et al., 2013) and reduced food intake (Teschner et al., 2010). Oxygen consumption after a major Baltic inflow is considerably faster, if eutrophication is high, thereby establishing a strong link between cod stock dynamics and eutrophication levels. Therefore, stringent
eutrophication management might offer a chance of restoring original conditions, to allow for a potential shift back to the original, high cod stock productivity state.

However, anticipating regime shifts is difficult since these abrupt changes usually come as surprises (Doak et al., 2008) and are a challenge for society as they are hardly predictable (Möllmann et al., 2015).

In this paper we build on, and extend, the previous resource economic literature on managing a resource with a potential regime shift (e.g., Crépin et al., 2012; de Zeeuw, 2014; de Zeeuw & Zemel, 2012; Polasky et al., 2011; Quaas, van Soest, et al., 2013) in three respects. First, we consider an empirically meaningful and quantified model of resource use, for the recent post-regime shift case of the Baltic cod fishery. Second, we consider the case of a potential regime shift back towards a more productive recruitment, which means that the fishery has economic value both before and (even more so) after a possible back-shift of the regime. In addition, whereas the previous literature considers single state (biomass) models, we study a full-fledged age-structured population model.

Our paper also contributes to the broader literature on optimal management of natural resources under uncertainty (Costello et al., 1998, 2001, Parma, 1990, Sethi et al., 2005). This literature considers stochastic shocks on resource stocks that are largely reversible. For the Baltic cod fishery, Kapaun and Quaas (2013) and Tahvonen et al. (2018) show that this type of uncertainty has only small effects on optimal harvesting. Here, by contrast, we focus on tipping points and uncertainty about a potential regime shift in resource productivity. As the climate economics literature suggests, this type of uncertainty may have (even) more pronounced effects on optimal management than regular random shocks (Cai et al., 2016, Lemoine & Traeger, 2016). Indeed, we also find rather strong effects of anticipated optimal tipping points on optimal harvesting.

We start our investigations in a system that has already experienced a tipping point (Figure 1), including the shift from a high productivity regime of a key fishery resource to a low production regime. Afterwards, we investigate what optimal management would look like, if we included the possibility of a potential regime shift back to the original, pre-regime shift, high productivity regime (Figure 1). We hypothesize that fisheries management would need to be

![Figure 1](https://example.com/figure1.png)

**Figure 1** Uncertain futures of Baltic cod: Historical and recent (red line) as well as potential future states (dashed blue lines) of cod stock productivity. How to include the bold dashed lines in fishery management is studied in this paper.
more precautionary, as anticipated profits after a backshift outweigh losses in the current, low productivity regime.

2 | MATERIAL AND METHODS

For Eastern Baltic cod, technical issues, for example, age-reading problems and unresolved ecological changes, disabled analytical stock assessments for several years from 2014 onwards (Eero et al., 2015; Köster et al., 2020). Therefore, we used data from the official ICES stock assessment in 2013 for this analysis (ICES, 2013). We first estimated stock-recruitment models for the pre-regime shift period and the post-regime shift period, indicating different stock productivities. Second, we applied these models to study implications for optimal management. We considered the probability of having a back-shift of the regime, which means, a back to pre-regime shift with conditions of high productivity.

2.1 | Estimating the stock-recruitment model

We follow Skonhoft et al. (2012) and consider a Beverton and Holt (1957) model to describe the number $R_{t+2}$ of recruits to the fish population if the current spawning stock biomass is $x_{0t}$. The ICES stock assessment reports the number of 2-year old recruits. We assume that the number of 2-year old recruits is a Beverton–Holt function of the spawning stock biomass $x_{0t}$ 2 years before:

$$R_{t+2} = \frac{x_{0t}}{z_t(a x_{0t} + b)} \iff \frac{1}{R_{t+2}} = z_t \left( a + \frac{b}{x_{0t}} \right)$$  (1)

with two parameters $a,b > 0$ that capture reproduction, density-dependent mortality/survival of eggs and larvae, and density-independent natural mortality/survival to age 2. The model is formulated such that $1/a$ is the supremum, that is, least upper bound, of recruitment, which is asymptotically approached for spawning stock biomass $x_{0t}$ approaching infinity. The other parameter, $1/b$ is the reproductive rate at very small spawning stock, that is, the maximum slope of the stock-recruitment function. Recruitment is assumed to be affected by environmental conditions and by random environmental fluctuations. Specifically, we assume that the variable $z_t$ is an independently and identically log-normally distributed series of random shocks with unit mean, and that the parameter $a$ depends on environmental conditions. We assume that $a$ depends linearly on the cod reproductive volume $RV_t$ and an indicator $\ell_\tau$ for a regime shift. Using $\tau$ to denote the year of the regime shift, we set $\ell_\tau = 0$ for all $t < \tau$ and $\ell_\tau = 1$ for all $t \geq \tau$. Data on size of the $RV_t$ were taken from the Working Group on Integrated Assessments of the Baltic (WGIAB; ICES, 2018). Applying logs to (1) and estimating

$$\ln \left( \frac{1}{R_{t+2}} \right) = \ln \left( a_0 (1 - \ell_\tau) + a_1 \ell_\tau + a_2 RV_t + \frac{b}{X_{0t}} \right) + \varepsilon_t$$  (2)

by nonlinear least squares, we obtain the parameter estimates presented in Table 1 conditional on the time of regime shift $\tau$. We vary $\tau$ and, for the final model, use the value of $\tau$ that maximizes the $R^2$ of the model.
2.2 | Ecological-economic optimization model

We consider an ecological-economic optimization model of the Baltic cod fishery, building on Quaas, Requate, et al. (2013), Tahvonen et al. (2018), and Stoeven et al. (2021). The vector \( x_t = (x_{2t}, \ldots, x_{nt}) \) captures the number of fish in age class \( s \) in year \( t \), starting with the age at recruitment \( s = 2 \) and ending at the oldest age class that contains fish of age \( n \) and older.

Using \( \alpha_s \) to denote age-specific survival rates, the fish population is described by the population model with nonlinear recruitment (1) and

\[
x_{2t} = R_t = \frac{x_{0,t-2}}{(a_0(1 - \lambda_{1,t-2}) + a_1\lambda_{1,t-2} + a_2\lambda_{2,t-2})x_{0,t-2} + b},
\]

\[
x_{s+1,t+1} = \alpha_s \left(x_{st} - q_s \frac{H_t}{B_t} x_{st}\right) \text{ for all } s = 2, \ldots, n - 1,
\]

\[
x_{nt+1} = \alpha_{n-1} \left(x_{n-1,t} - q_{n-1} \frac{H_t}{B_t} x_{n-1,t}\right) + \alpha_n \left(x_{nt} - q_n \frac{H_t}{B_t} x_{nt}\right).
\]

For the parameters of the fish population model, especially age-specific survival rates \( \alpha_s \), maturities, and weights \( w_s \), we directly use the estimates reported in the ICES (2013) stock assessment.

The harvesting model deserves attention. We use \( q_s \) to denote catchability at age \( s \). The fraction of fish harvested from age class \( s \) is assumed to equal \( q_s \) times the total catch \( H_t \) relative to efficient biomass \( B_t \), that is, the sum of biomasses in the age classes weighted by age-specific catchabilities (Tahvonen et al., 2018),

\[
B_t = \sum_{s=2}^{n} q_s w_s x_{st}.
\]

In terms of fisheries economics, we consider economic welfare, that is, the sum of consumer surplus and producer surplus (or, profit) from the fishery (Quaas et al., 2018) as

\[
U(H_t, B_t) = \int_0^{H_t} P(h)h - p_i H_t + p_i H_t - c B_t^{-\gamma} H_t,
\]

where the first two terms are consumer surplus and the second two profits. Expenditures of households, \( p_i H_t \), equal revenues of fishing industry and thus cancel in economic welfare. In

| TABLE 1 | Estimated coefficients for stock-recruitment model |
|---------|-------------------|----|-----|-----|
| Estimate | SE | \( t \) Stat | \( p \) Value |
| \( a_0 \) | 309.19 | 74.924 | 4.1267 | 0.00023452 |
| \( a_1 \) | 1.6249 | 0.39165 | 4.1488 | 0.00022014 |
| \( a_2 \) | 4.9679 | 0.59832 | 8.3031 | 1.3684e−09 |
| \( b \) | −0.0018433 | 0.00098961 | −1.8626 | 0.071434 |

Note: Number of observations: 37, error degrees of freedom: 33, root mean squared error: 0.266, \( R^2 \): 0.835, adjusted \( R^2 \): 0.82, \( F \)-statistic versus zero model: 423, \( p \) value = 7.72e−28.
(7), $c > 0$ is a cost parameter, and $\chi > 0$ is the stock elasticity of harvesting costs. The assumption is that unit harvesting cost decrease if the stock becomes more abundant, but less than proportionally if $\chi < 1$.

We consider an iso-elastic specification of the inverse demand function, $P(h) = d h^{1-\nu}$, where $d > 0$ and $\nu > 0$ is the elasticity of inverse demand, which specifies how sensitive the price reacts to the quantity of fish available for consumption.

For estimating economic parameters, we follow Tahvonen et al. (2018). We assume that the model was adequate to describe the fishery in a setting of regulated open access, that is, where mesh size regulations have been restricting fishing activity, but total allowable catches have largely not been binding. This assumption is in line with the literature which has documented that the Eastern Baltic cod fishery has operated with restricted open access in the past, mainly due to overly generous total allowable catches (Kronbak, 2005; Quaas et al., 2012). Under this assumption, marginal harvesting costs should equal the fish price, $p_t = cB_t^{-\chi}$, and total catch is determined by the condition that inverse demand equals marginal harvesting costs, $aH_t = cB_t^{-\chi}$. We use time series data on $p_t$ from German fishery statistics provided by Bundesanstalt für Landwirtschaft und Ernährung, BLE (Federal Office for Agriculture and Food) and on $H_t$ and $B_t$ from ICES data to estimate values for the parameters $d$, $\nu$, $c$, and $\chi$. The resulting estimates from Tahvonen et al. (2018) are summarized in Table 2 and are largely in line with previous results from Kronbak (2005), Nielsen (2006), and Quaas et al. (2018). They show in particular that the price of cod is sensitive to the quantity available in the market, which may be due to preferences for local consumption in some Baltic countries.

We consider optimal management, that is, management that maximizes the present value of welfare (see Equation 7) discounted at a constant market interest rate $r$, which we assume to be 5% per year in the application.

In our analysis we include the possibility of a regime shift. We start with the assumption that recruitment is as in the current regime, that is, set $1_{\tau t} = 1$ for the base year 2013. For the future we assume a constant annual probability of a shift back into the high recruitment regime, as it prevailed until 1982. This turns the problem to maximize the present value of welfare in the stochastic problem to maximize the present value of expected welfare. This makes the optimization problem much more difficult, as potential future reactions to a regime shift that might occur must be taken into account. Formally, optimal harvesting becomes a function of the current state of the fishery (a mapping of the $\mathbb{R}^n \to \mathbb{R}$, with $n$ being the number of age classes) rather than simply a function of time (a mapping of the $\mathbb{R} \to \mathbb{R}$), as it would be in the absence of stochasticity.

We use stochastic programming to solve the stochastic optimization problem, following Tahvonen et al. (2018). The approach is to transform the problem into a nonlinear programming problem: Stochasticity can be described by a tree that contains $Q \equiv \frac{1}{2} T(T + 1)$ possible outcomes. Here, an outcome is a history, seen from $T$, that says for which periods in time the fishery has been in which of the two recruitment regimes. All outcomes where the regime shifts at some time $t$ or later share the same history up to $t$. Differences arise only after the time of the regime shift, and thus after a regime shift at $t$ there will be $T - t$ periods of unique history.

| Parameter | $d$ | $\nu$ | $c$ | $\chi$ |
|-----------|-----|-------|-----|-------|
| Estimate  | 27.434 | 0.654 | 6.604 | 0.426 |

TABLE 2 Estimated values for parameters of demand and cost functions (Tahvonen et al., 2018)
Overall, the number of outcomes is given by $Q = \sum_{t=0}^{T}(T - t) = \frac{1}{2}T(T + 1)$. All variables considered – stock numbers at age, harvest, and mesh size—are separately defined for each outcome $i$ which occurs with probability $\pi_i$. Formally, the optimization problem reads

$$\max_{\{H_i; i=0,\ldots, T, i=1,\ldots, Q\}} J = \sum_{i=1}^{Q} \sum_{t=0}^{T} \left( \frac{1}{1 + r} \right)^t U(H_i^t, B_i^t)$$

subject to the dynamics of the age-structured fish population with a potential regime shift in recruitment. For the numerical optimization, we need to specify a finite time horizon, which should be long enough that the fishery could approach a steady state, and allows us to reliably interpret optimization results for the next ten to 20 years. Here we use $T = 71$ years, such that $Q = 2556$. We thus optimize over $Q \times (S + 2) = 25,560$ variables. This is a tractable problem for state-of-the-art solvers for numerical optimization problems. We apply Knitro with AMPL, a state-of-the-art solver for high-dimensional nonlinear continuous optimization problems (Byrd et al., 1999, 2006).

3 \hspace{1em} RESULTS

3.1 \hspace{1em} Optimal management under Post-Regime-Shift conditions

The statistical analysis quantified two distinct stock productivity regimes: a pre-regime shift period, with high stock productivity, which switched to lower stock productivity as early as 1982 (post-regime shift period). The post-regime shift period is characterized by substantially lower recruitment success at the same level of spawning stock biomass (Figure 2 and Table 1).

The reduced stock productivity from 1982 onwards, in combination with high fishing pressure (ICES, 2013), resulted in a sharp decrease of spawning stock biomass (SSB) from more than 600,000 tons to less than 100,000 tons (Figure 3). In the following years, the stock

FIGURE 2 Stock-recruitment relationships of Central Baltic cod for two periods: (i) high productivity, pre-regime shift conditions, years 1970–1982 (Green dots and line), and (ii) lower productivity, post-regime shift period regime, years 1983–2011 (orange dots and line)
somewhat stabilized to a relatively low level around 100,000 tons. It became clear that fisheries management and applied regulations did not succeed in efficiently rebuilding the stock (ICES, 2019a). Using our ecological-economic model, we find that optimal management, as adapted to low productivity, post-regime shift conditions, should restrict fishing to $F$ values of about 0.2, to rebuild the stock biomass to higher levels (Figure 3). More specifically, after initial high growth rates, the spawning stock biomass increase would then slowly level off, and reach a steady state after about 20 years. Steady state SSB is estimated to be about 410,000 tons, with annual catches of 89,000 tons and an estimated fishing mortality $F = 0.19$. It becomes obvious that, even without a potential back-shift to high stock productivity, substantially higher stocks, catches and profits could be achieved. However, even optimal management would not restore the pre-regime shift conditions of the early 1980s.

3.2 | Model experiment: Potential shift to high productivity again

Regional management actions like strong eutrophication management might support a recovery back to a higher cod stock productivity state, if the abiotic state of the Baltic has been returned to similar conditions as observed in the pre regime-shift period (Möllmann et al., 2009). Despite the costs of such a management (e.g., to upstream farmers), it is a declared political goal to reduce eutrophication of the Baltic Sea (HELCOM, 2007). Therefore, we now investigate how optimal management will change if we allow for the possibility of a shift back to the high productivity regime. Allowing for the possibility of a back-shift opens up a wide field of potential stock- and catch-trajectories (Figures 4 and 5). At each point in time (yearly steps in our model), the system might switch, and change to the higher productivity regime, and hence to higher stock size and catches. If the probability of a back-shift is zero, the trajectory follows the optimal solution for the post regime shift setting, as described above. With a positive probability of a back-shift, the trajectories will, at some point in time, depart from this baseline, moving towards higher future stock size and catches. An immediate back-shift to higher
productivity (top lines in Figures 4 and 5) would result in almost doubled catches as well as stock size after only 9 years.

As it is not possible to predict a regime-shift (Doak et al., 2008), nor a potential back-shift, the future trajectory, of course, remains unknown. Given some probability of a back-shift (even if it is very low) will, however, change optimal, forward-looking management outcomes right away. With increasing probability of a regime shift back to high productivity conditions, optimal $F$ decreases, that is, fisheries management becomes more restrictive (Figure 6a). The functional relationship depends on the time-horizon under question, and the effect is most pronounced in the first year. For positive back-shift probabilities >14%, the short-term management becomes even more conservative (lower $F$) than medium to long-term mean values. When no back-shift is possible, mean optimal fishing mortality decreases from 0.265 to 0.242.

**FIGURE 4** Trajectories of spawning stock biomass development, allowing for a potential back-shift to high productivity at different points in time. The bold line and dots show the expected development for a 10% probability of backshift.

**FIGURE 5** Trajectories of catch development, allowing for a potential back-shift to high productivity at different points in time. The bold line and dots show the expected development for a 10% probability of backshift.
FIGURE 6  Optimal fishing mortality ($F$) for different probabilities of a back-shift to higher stock productivity, and for different time horizons considered. (a) shows result for the baseline parameterization with an interest rate $r = 5\%/\text{year}$, (b) and (c) show the sensitivity of results to changes in the interest rate to $r = 15\%/\text{year}$ and $r = 0$, respectively.
and finally 0.236 when only the next year, 10 years, or 40 years into the future are considered (Figure 6a).

Whereas Figure 6a shows results for our baseline parameterization with an interest rate of 5% per year. The two other panels in Figure 6 shows the sensitivity of these results to alternative specifications of the interest rate. Figure 6b shows that an increase of the interest rate to 15% per year substantially increases the optimal fishing mortality. Also, the optimal fishing mortality is less sensitive to the probability of a regime shift, and the initial fishing mortality is higher than the average fishing mortality over the next 10 years even for a 25%/year probability of regime shift.

These effects are reversed when decreasing the interest rate to zero. Then, optimal fishing mortality is substantially smaller than in the baseline parameterization, and also the initial fishing mortality is below the average over the next 10 years already for a 10%/year probability of a regime shift.

For the baseline parameterization, annual economic welfare might exceed 400 million €, if a back-shift is possible, and a longer planning phase is considered (Figure 7, blue line). The larger share of the economic welfare relates to consumer surplus, but still ca. 25% relate to profits by the fishery. For very short planning horizons, that is, when only looking at the next year, optimal management in light of a potential regime shift comes at the cost of slightly reduced mean annual economic welfare of up to 10 million €, depending on the probability of back-shift (Figure 7).

4 | DISCUSSION

The management of aquatic systems is challenged by global (e.g., climate change) as well as region-specific threats. In our case, regional management might address eutrophication levels as one of the important drivers in the Baltic Sea. Our case study revealed that accounting for potential future regime shifts will impact optimal fisheries management decisions maximizing the expected present value of economic surplus. The key result is that, as the probability of

![Figure 7](image-url)  
**Figure 7** Annual economic welfare (consumer surplus and fishery profits) under optimal management for different probabilities of a back-shift to higher stock productivity, and for different time horizons considered. Bold line: annual economic welfare; thin line: consumer surplus; shaded area: fishery profit
moving back to a high productivity regime increases, the optimal fishing mortality rate declines. The reason is that the fishery manager should optimally conserve the resource in anticipation of higher future productivity.

This result is consistent with previous theoretical analyses of managing resources with stochastic and uncertain productivity: Assuming long-term trends in environmental conditions, Parma (1990) finds that escapement is raised, when favorable conditions are expected, and also Costello et al. (2001) find that a shift toward improved environmental conditions, which increases growth of the stock, increases optimal current escapement, that is, it decreases optimal current harvest. Whereas this literature has predominantly focused on developing the theory in simple biomass models, the main contribution of this paper is to consider an empirically meaningful and quantified age-structured model of resource use, for the recent post-regime shift case of the Baltic cod fishery.

The main policy conclusion from this analysis is that optimal fishing mortality should be reduced in light of the possibility that improved eutrophication management could shift the Baltic ecosystem back to a more productive regime. As our analysis rests on several simplifying assumptions, this conclusion should be taken more as a strategic than tactical advice. In particular, we have not taken into account costs and ecosystem effects of eutrophication beyond the cod fishery. A more encompassing assessment of eutrophication management could be done, for example, by applying a stochastic eco-viability approach (Doyen et al., 2017).

The conceptual ecological underpinning of regime states in marine ecosystems (Conversi et al., 2015; Fisher et al., 2015) was recently reviewed in Möllmann et al. (2015), and addresses implications for management of marine resources—especially ecosystem-based management of fisheries (King et al., 2015; Levin & Möllmann, 2015), ecosystem services (Rocha et al., 2015), and early warning indicators (Dakos et al., 2015). The theoretical underpinning and the state-of-the-art of the latter has recently been reviewed by Scheffer et al. (2015). Further landmark literature on principles for management of marine ecosystems that have shown tipping points, including current options and future perspectives, have been provided by the US Ocean Tipping Points project (www.oceantippingpoints.org). In this study, we showed that the shift in cod recruitment preceded the Baltic-wide regime shift (Möllmann et al., 2009), but is well in line with large-scale distributional changes in the cod egg distribution (Karaseva, 2018), as well as the food web shift observed in the Gotland Basin by Uusitalo et al. (2018).

Systems that have experienced regime shifts often show hysteresis effects, that is, reduction of external drivers need to have substantial stronger driver forcing to recover to the original state (Scheffer et al., 2001). Although the existence of alternative states is contentious (Cardinale & Svedäng, 2011, Möllmann et al., 2015), it is assumed that food webs that have experienced regime shifts have reorganized into novel states (e.g., in terms of species composition, population size and species interaction strength). Furthermore, and in addition to food web changes, altered environmental and anthropogenic conditions may limit their recovery potential (Lotze et al., 2011). A recent example from the Baltic Sea is the apparent recovery of Eastern Baltic cod predicted by linear, steady-state models (Eero et al., 2012), but challenged by food web models incorporating threshold dynamics (Blenckner et al., 2015). Food webs may hence develop novel properties due to novel climates and multiple anthropogenic impacts leading to uncertain future ecosystem states and pathways (see also Figure 1).

Any critically reduced fish stock might not be able to maintain its central position in the food-web. Novel food-webs might emerge, with so far unknown specifications. While such changes are commonly seen to be negative, they might also include new fishing opportunities, as shown here as a hypothetical scenario. An example from the real world is the collapse of the
cod fishery in Newfoundland, after which a new and profitable fishery on shrimps emerged (Hamilton et al., 2003). In this respect, a number of scientific projects (e.g., EU-project PANDORA, https://www.pandora-fisheries-project.eu) attempt to promote knowledge exchange with stakeholders, and discuss their views on future objectives under conditions of climate change.

We believe that meaningful approaches to fisheries management require model systems that link ecology and economy (Kellner et al., 2011; Lindegren et al., 2009), and include the stochastic nature of stock dynamics. Here, we applied stochastic programming. The stochastic programming technique has been introduced to fisheries resource economics by Tahvonen et al. (2018) who argued that stochastic programming has an advantage compared to stochastic dynamic programming as it is less exposed to the curse of dimensionality. This is even more evident for the problem considered here. A stochastic dynamic programming problem with $n = 8$ state variables is numerically very hard to solve, and would require long computing time on super computers. This has been exemplified by recent applications of stochastic dynamic programming to integrated assessment models in climate economics that have several state variables (Lemoine & Traeger, 2016). Cai et al. (2016), for example, consider a model with ten state variables. Each run of their dynamic program required three hours on more than ten thousand cores on a supercomputer to find an approximate optimal solution. The stochastic programming approach taken here allows problems to be solved with a similar number of state variables in just a few seconds on a single core of a standard laptop computer.

However, our model framework has room for improvements, in particular regarding density-dependent growth (Casini et al., 2011, Gårdmark et al., 2013), consideration of other forms of environmental variability, and potentially altered biological variables like fecundity and natural mortality. Accordingly, the most recent assessment of the Baltic cod (ICES, 2019b) paints a pessimistic picture. The stock dynamics seem to have changed again as compared to the post-regime shift conditions of the 2000s, which we used in this analysis. Natural mortality increased, individual growth rates decreased, leading to a further decline of stock productivity. Whether these are signs of another regime shift, or just changes in the stock dynamics of cod, can not be answered yet.

The general finding of this study, pointing to a more conservative fisheries management, if a potential back-shift to better conditions is (at all) possible, might therefore be more relevant than ever.

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AUTHOR CONTRIBUTIONS

Rudi Voss: conceptualization (equal); data curation (lead); methodology (equal); writing—original draft (lead); writing—review and editing (lead). Martin Quaas: conceptualization
DATA AVAILABILITY STATEMENT
The data that support the findings of this study are openly available from ICES (2013, 2018) and from German fishery statistics provided by Bundesanstalt für Landwirtschaft und Ernährung, BLE (Federal Office for Agriculture and Food) at https://www.ble.de/DE/Themen/Fischerei/Fischwirtschaft/fischwirtschaft_node.html. The data processing and analysis is explained in Section 2.

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