Research article

Ecological-economic sustainability of the Baltic cod fisheries under ocean warming and acidification

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ABSTRACT

Human-induced climate change such as ocean warming and acidification, threatens marine ecosystems and associated fisheries. In the Western Baltic cod stock socio-ecological links are particularly important, with many relying on cod for their livelihoods. A series of recent experiments revealed that cod populations are negatively affected by climate change, but an ecological-economic assessment of the combined effects, and advice on optimal adaptive management are still missing. For Western Baltic cod, the increase in larval mortality due to ocean acidification has experimentally been quantified. Time-series analysis allows calculating the temperature effect on recruitment. Here, we include both processes in a stock-recruitment relationship, which is part of an ecological-economic optimization model. The goal was to quantify the effects of climate change on the triple bottom line (ecological, economic, social) of the Western Baltic cod fishery. Ocean warming has an overall negative effect on cod recruitment in the Baltic. Optimal management would react by lowering fishing mortality with increasing temperature, to create a buffer against climate change impacts. The negative effects cannot be fully compensated, but even at 3 °C warming above the 2014 level, a reduced but viable fishery would be possible. However, when accounting for combined effects of ocean warming <u>and</u> acidification, even optimal fisheries management cannot adapt to changes beyond a warming of $+1.5°$ above the current level. Our results highlight the need for multi-factorial climate change research, in order to provide the best available, most realistic, and precautionary advice for conservation of exploited species as well as their connected socio-economic systems.

1. Introduction

Marine fisheries play a central role for world food supply. Fish provides at least 15% of per capita animal protein intake for 4.5 billion people (Béné et al., 2015). Worldwide approximately 500 million people are directly dependent on fisheries for their livelihoods (FAO, 2014). Ocean warming (OW) has been identified as a potential major stressor to marine fisheries, threatening the sustainable use of these renewable resources and their associated socio-economic systems. OW will increasingly affect species distribution (Perry et al., 2005; Last et al., 2011) as well as impact vital rates, e.g. growth and mortality rates (Björnsson et al., 2007). Accordingly, the Paris Agreement has set

the target to keep "… *a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels* … " (United Nations, 2015). However, for the recent 3 decades, Baltic Sea surface temperature warming trends have been determined between 0.4 and 0.7 °C per decade (Lehmann et al., 2011, BACC II, 2015). Thus, the 2 °C threshold will already be crossed in the mid of this century.

In addition to OW, in recent years, the effects of dissolution of CO_2 in upper ocean waters, named ocean acidification (OA), has been identified as potential additional stressor for marine fish stocks. The effects of increasing OA are system- and species specific: Experimental work shows e.g. effects on behavior (e.g. Simpson et al., 2011) and vital rates (e.g. Stiasny et al., 2016; Baumann et al., 2012). Evidence for

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commercially exploited fish species is still scarce, but also suggests non-uniform reactions (as for OW) of different species or stocks (Frommel et al. 2012, 2014; Maneja et al., 2012; Stiasny et al., 2016).

In the North-Atlantic region, cod has for centuries been a major natural resource, and has even been described as a "fish that changed the world" (Kurlansky, 1998). The impact of temperature variations on recruitment success and hence stock dynamics of North-Atlantic cod stocks has long been recognized (e.g. Planque and Frédou, 1999). While some cod stocks might react positively on OW, most stocks in the eastern North-Atlantic are negatively affected by temperature increase, as recruitment success is lowered (Drinkwater, 2005). The effect of OA has been studied in laboratory experiments on Norwegian Coastal cod (Frommel et al., 2012) and Western Baltic cod (Stiasny et al., 2016), which showed increased larval mortality under increased OA, which might have severe consequences for population dynamics (Voss et al., 2015). The importance of the combined effect of these two potential stressors related to climate change has recently been highlighted by a number of international scientific communities (Pörtner et al., 2014; ICES, 2016; ICSU, 2017). However, investigations for economically important fisheries remain scarce (AMAP, 2018). Western Baltic cod has a century-old history of exploitation, which is strongly linked to the socio-economic system in its' area of distribution (Fig. 1). Still today, many rural villages have fishing as their main economic activity (Delaney, 2007). Besides traditional small-scale fisheries, increasing levels of recreational fishing for cod (ICES, 2017a) and associated tourism play a major role to sustain peoples' livelihoods. Furthermore, cod plays a central role in the western Baltic food web where it is the most important demersal fish top predator (Harvey et al., 2003). Therefore, it is of critical importance to understand the potential interactive effects of climate change (ocean warming <u>and</u> acidification, OAW) on Western Baltic cod stock dynamics along with adjusted local management that allow long-term sustainable future exploitation.

Here, we first quantify the temperature effect on recruitment using spatially and temporally resolved temperature time-series and we up-scale effects of acidification on recruitment success from laboratory experiments to the population scale (Stiasny et al., 2016). In a second step, we determine the risk of stock collapse under climate change for different levels of fishing effort. Finally, we investigate how to best adapt western Baltic cod fisheries management to changing environmental conditions using an ecological-economic optimization model. The model is run either only accounting for OW effect or including the combined OAW effects. It quantifies climate change effects in terms of ecological (stock size), economic (catches, profits), and social (fishing mortality as proxy for employment) terms.

2. Materials and methods

2.1. Population dynamics under OAW

To investigate climate change effects on the triple bottom line of Baltic cod fishery management, a quantification of changes in population dynamics is needed. Changes in ocean pH and temperature might have both, density-dependant as well as density-independent effects on a variety of processes, e.g. growth, maturation, survival, recruitment. We take a first step, investigating how the combined effect of OAW changes the stock-recruitment relationship, and hence stock dynamics. Even more precisely, we focus on changes in the density-independent processes alone, as quantifiable data for density-dependant effects are still missing (Hjermann et al., 2007; Röckmann et al., 2007).

Usually, a Ricker model is used to best describe the stock-recruitment relationship in cod (Ricker, 1954). In the Ricker stock-recruitment model, a special parameter "alpha" quantifies the density-independent mortality. We include climate change effects on stock dynamics by modifying this parameter with the additional factor e^{-a}. In a baseline scenario without climate change, the parameter a is set to zero and hence $e^{-a} = 1$ (meaning no influence of climate change on stock dynamics). Under the influence of OAW, e^{-a} takes a value between 0 and 1, describing the fraction of recruits surviving climate induced additional mortality.

The baseline scenario is parameterized with data from the Baltic Fisheries Assessment Working Group for the years 1970–2013 (ICES, 2014). Quantification of ocean acidification on Western Baltic cod recruitment are based on experimental work, while temperature effects were analysed by time-series analyses (see below).

We explicitly consider uncertainty of climate change by varying the degree of future temperature increase between 0 and 3 °C in our model runs. This approach avoids any potential issues of inconsistency between historic observations and climate scenario data. The additional effect of ocean acidification is included as on/off factor, reflecting increased larval mortality rates due to acidification under end-of-the century conditions.

2.2. Ocean acidification effects

Stiasny et al. (2016) performed the first set of experiments, which allowed quantifying the direct effect of ocean acidification of cod larval mortality. They reared offspring from the Western Baltic cod stock under two ocean acidification scenarios. A control group kept under current CO_2 conditions of 400–500 µatm was contrasted to a second group, which was exposed to ca. 1100 µatm CO_2. Such acidification levels might be reached in the Baltic Sea by the end of the century. In their experiments, increased ocean acidification resulted in a doubling of the larval mortality rates (see Stiasny et al. (2016) for full detail on experiment and population recruitment implications).

2.3. Ocean warming effects

We used a multiple regression analysis to evaluate the temperature effect on the stock-recruitment relationship in Western Baltic cod. The temperature data was acquired from the Helmholtz Centre for Ocean Research Kiel (GEOMAR) for each of the ICES sub-divisions 21 to 24 within the Baltic Sea, which reflects the distribution and spawning area of the stock. The horizontally resolved temperature fields were taken
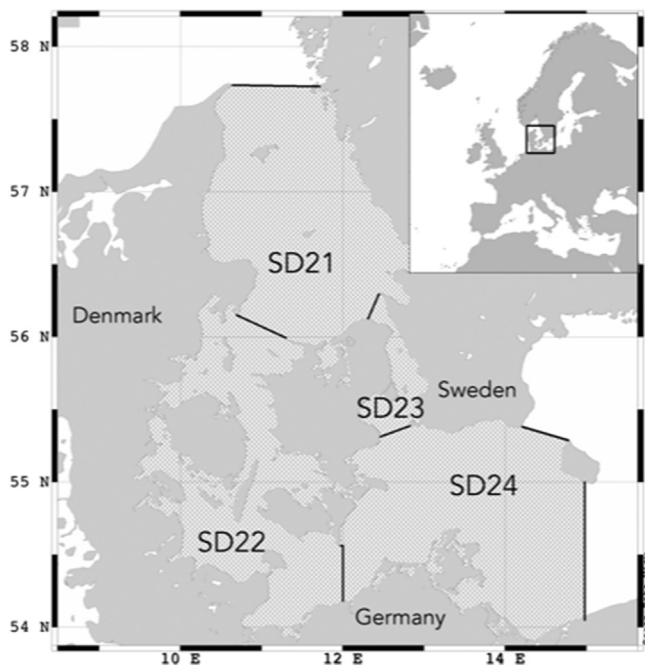

Fig. 1. Map of the western Baltic Sea, indicating the ICES sub-divisions 21–24. The shaded area represents the major distribution and reproduction area of the western Baltic cod stock.

from the hydrodynamic Kiel Baltic Sea Ice-Ocean Model (BSIOM) in its most current version (Lehmann et al., 2014). The spatial resolution of the model is at present 2.5 km, and in the vertical 60 levels are specified, which means the upper 100 m is resolved into levels of 3 m thickness. The model domain comprises the Baltic Sea, Kattegat and Skagerrak. Full details on model forcing, e.g. atmospheric forcing, surface heat and momentum fluxes, river runoff, etc, are provided by e.g. Rudolph and Lehmann (2006). The hindcast period used in this study covers 37 years between 1979 and 2015. For this period we used monthly means per sub-division and depth layer in our analysis as follows:

Using x_{1t} for the number of recruits, x_{0t} for the spawning stock biomass, and T_{rlmt} for the temperature in ICES area r, depth layer l, month m in year t, and ε_t to denote an iid error term, we estimate the following model by means of OLS.

$$\log(x_{1t}/x_{0t}) = \varphi_0 - \varphi_1 x_{0t} + \varphi_T T_{rlmt} + \varepsilon_t \tag{1}$$

For each ICES Sub-Division (SD) 21–24 we repeated the estimate for all depth layers l and all months. Including a time trend in (1) did not result in a robust significantly negative estimate and did not substantially change the explanatory power of the model. We thus did not include a time trend in the final model.

For each ICES SD there is a clear peak for the temperature in a particular layer and month combination that has the strongest explanatory power (Table 1).

In a next step, we construct a weighted average of temperatures over ICES Sub-Divisions. Considering the temperature time series $\hat{T}_{rlmt}$ in the layer and month that maximizes the R^2 for each of the ICES rectangles 21–24, we construct a weighted average of temperatures as:

$$\bar{T}_t = \sum_{r=21}^{24} w_r \hat{T}_{rlmt}. \tag{2}$$

The weights are determined by maximizing the statistical explanatory power of the final temperature-dependent stock-recruitment model. In the final model, for all other combinations of Area/Layer/Month the weights are set to zero.

Using this index $\bar{T}_t$ instead of T_{rlmt} in the regression model (1), leads to a value $R^2 = 0.50$. A Durbin Watson test for this model did not indicate serial autocorrelation ($dw = 2.15$, $p = 0.948$). The final estimates for the coefficients of a Ricker-type stock-recruitment model are given in Table 2.

2.4. Risk of stock collapse

For both scenarios (ocean warming versus warming and acidification) we calculate the risk of stock collapse as a function of temperature increase and fishing mortality. We estimate the spawning stock biomass in comparison to the virgin (un-fished) biomass at the 2015 temperature level. A value of e.g. 0.1 indicates a stock decline to 10% of the un-fished biomass at current temperature conditions.

2.5. Ecological-economic optimization model

In order to address the triple bottom line of Western Baltic cod

Table 1
Statistical results for the temperature index on ICES Sub-Division basis. Depth-layer and month combination yielding highest coefficients of determination, p-value, and weighting factor in the final model.

ICES area	Layer	Month	R^2	p-value	Weighting factor
SD 21	57	March	0.35	< 0.01	0.53
SD 22	18	November	0.35	< 0.01	0.20
SD 23	12	November	0.34	< 0.01	0.22
SD 24	21	November	0.25	< 0.05	0.05

Table 2
Estimates for coefficients of a Ricker-type stock-recruitment model as given in Eq. (1).

Parameter	Estimate	Lower Bound	Upper Bound	Unit
φ_0	7.12	4.59	9.66	
φ_1	0.036	0.020	0.053	(1/1000 tons)
φ_T	−0.81	−1.16	−0.47	(1/°C)

fisheries management, we need to apply a multi-disciplinary ecological-economic model. We used an age-structured optimization model as developed by Tahvonen et al. (2018) to (i) reflect the ecological peculiarities of the stock, and (ii) determine optimal management and adaptation strategies, which include ecological as well as economic considerations. Ecological input data is taken from official stock assessment (ICES, 2014). The economic model component reflects the Western Baltic trawl fishery for cod, with stock-dependent harvesting costs, and a non-linear demand function. All parameters were specifically estimated for the Western Baltic cod fishery.

2.6. Economic parameters

To estimate the parameter values for the utility and cost functions, we construct the time series of efficient biomasses B_t using estimated age class-specific stock numbers, weights, and fishing mortalities from ICES (2014) stock assessment. Further, we utilize the fact that the Baltic cod fishery has been de-facto open access in the past (Kronbak, 2005; Quaas et al., 2012). Under open access, harvest is determined by the condition that the market price P_t is equal to the marginal harvesting cost, that is $P_t = c B_t^{-\chi}$. Using price data from German fishery statistics for the years 1988–2013 (BLE, 1989–2015), allowing for a time trend ($t = 2013$– year of observation) to capture effects of inflation on prices and exogenous technical progress in fishing technology, and including the efficient stock biomass for Eastern Baltic cod to take alternative fishing opportunities into account, as well as a dummy variable D_R for years before reunification (before 1990), we estimate

$$\ln P_t = c_0 + c_t t + c_R D_R - \chi_{EBC} \ln B_t^{EBC} - \chi \ln B_t + \varepsilon_t, \tag{4}$$

where ε_t is an IID error term. Applying OLS, we obtain the estimates $c_0 = 3.26$ with 95% confidence interval [1.70, 4.83], $c_t = 0.0053$ with 95% confidence interval [-0.006, 0.017], $c_R = 0.25$ with 95% confidence interval [-0.10, 0.62], $\chi_{EBC} = 0.42$ with 95% confidence interval [0.15, 0.69], and $\chi = 0.23$ with 95% confidence interval [0.018, 0.45], with $R^2 = 0.45$.

We specify the marginal utility function as an iso-elastic inverse demand function $U'(H_t) = \bar{P} H_t^{-\nu}$. Here, H_t is the overall catch quantities of Western Baltic cod (ICES, 2014), and $\bar{P}$, and ν are parameters to be estimated. Using this specification in the open-access condition $U'(H_t) = c B_t^{-\chi}$, we use data on catch quantities and efficient biomass to estimate

$$\ln(H_t) = a_1 + a_2 t + a_3 \ln(B_t) + \varepsilon_t \tag{5}$$

where ε_t is error term, and again a time trend is included. Applying OLS, we obtain the estimates $a_1 = -0.014$ with 95% confidence interval [-0.81, 0.78], $a_2 = 0.72$ with 95% confidence interval [0.53, 0.92], and $a_3 = 0.0006$ with 95% confidence interval [-0.008, 0.009], with $R^2 = 0.81$. In the computations, we use $\nu = \chi/a_4 = 0.23/0.74 = 0.32$, $\bar{P}/c = \exp(\nu a_1) = 0.996$. From the estimate of c_0, and using the average efficient biomass for Baltic cod, we obtain $c = \exp(c_0 - \chi_{EBC} \ln(123)) = 3.45$, and thus $\bar{P} = c \exp(\nu a_1) = 3.45 \cdot 0.996 = 3.44$. For the demand function, we thus use $P(H_t) = 3.44 \cdot H_t^{-0.32}$ euros per kg of fish, with H_t measured in 1000 tons.

2.7. Sensitivity analysis

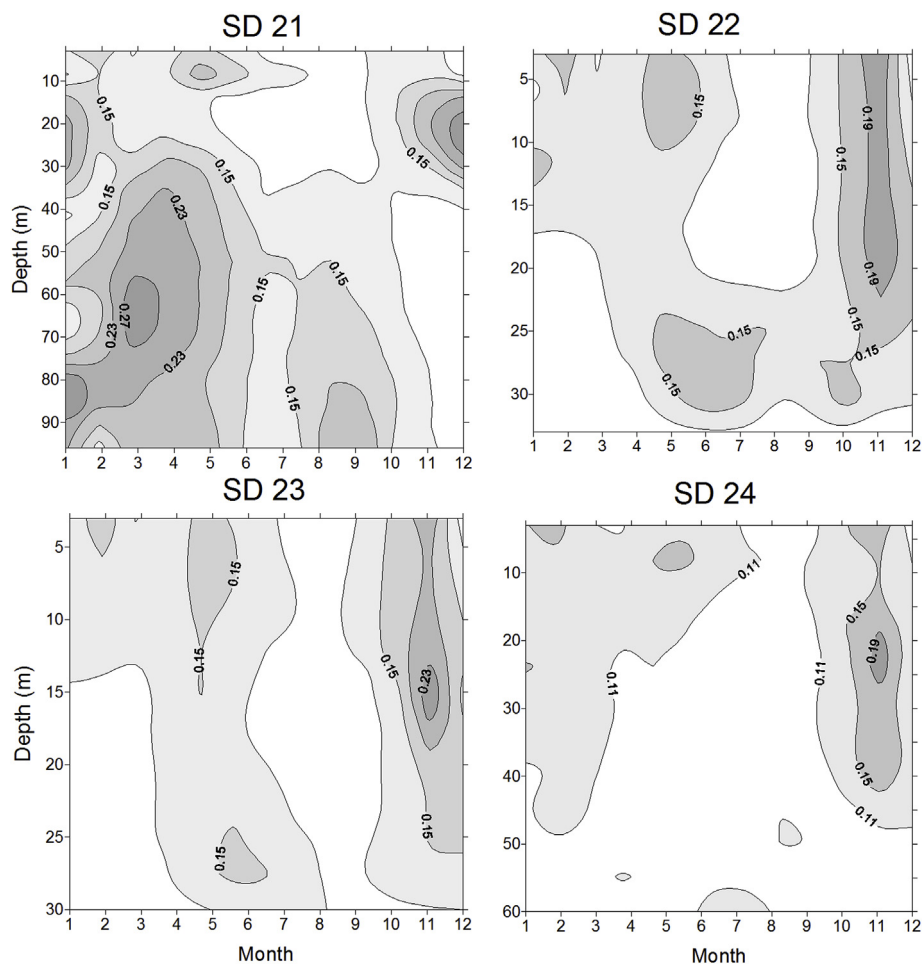To quantify the uncertainty of model results that stems from

Fig. 2. Temperature effects on western Baltic cod recruitment. Depicted are coefficients of determination of temperature-dependent stock-recruitment functions (Eq. (1)) in four ICES sub-divisions (SD) in the western Baltic. Data are depth-resolved and were collected on monthly basis.

parameter uncertainty, we do a Monte-Carlo sensitivity analysis taking into account uncertainty in all empirically estimated model parameters, keeping the temperature fixed at the 2014 level. We draw a random sample of 10,000 parameter sets, from multivariate normal distributions for the coefficients estimated in equations (1), (4) and (5), using the point estimates as means and the covariance matrices from the estimations. We compute the resulting parameters of the recruitment model and the economic model for each set in the resulting sample and repeat the optimization. The standard deviations of the results are used to compute the confidence intervals of the model output.

3. Results

In a first step, a multiple regression analysis using spatially and temporally resolved temperature fields revealed the major temperature effects on cod recruitment in the different ICES Sub-Divisions (SD). Fig. 2 depicts the coefficients of determination of temperature-dependent stock-recruitment functions according to equation (1). In November, high values are found from surface waters down to 15–20 m depth (SD 22–24). Additionally, in SD 22 high coefficients of determination are observed in the summer months, at depths of 25–30 m. Subdivision 21 is under a comparatively stronger influence of the North Sea (Rosenberg et al., 1996) as SDs 22–24 (Fig. 1). Within this transition zone, strongest coefficients of determination are observed early in the year (March) at 60–70 m depth. Timing and vertical position of the maxima suggest an important influence of temperature on the adult spawning fish (March and summer months) as well as the juvenile stages, after their transition to a benthic habitat (November).

As described above, a temperature-dependent stock-recruitment model was derived, for which the explanatory power of the stock-recruitment function was maximized.

This temperature-dependent stock-recruitment model was then used in the assessment of the risk of stock collapse, and the bio-economic optimization model to determine optimal management and socio-economic outcomes.

3.1. Risk of stock collapse under climate change

The impacts of different global climate stressors on local resources are often considered independently. Furthermore, there is synergy between climate change at a global scale and local stressors, which might be managed more easily. Understanding these synergies might provide management guidance in order to define a safe operating space, e.g. for coastal fisheries (Scheffer et al., 2015). In the western Baltic cod stock the risk of stock collapse (or the risk of staying depleted) will generally increase with ongoing climate change (Fig. 3). However, when applying only low levels of fishing mortality, the stock is relatively insensitive to the single pressure of ocean warming (Fig. 3a), and the risk of stock collapse only slightly increases with increasing temperature. On the other hand, intense fishing (F ≈ 1; as has been observed for many years from mid 1990s-early 2000s in this stock; ICES, 2017b) will drastically raise the probability of a collapse.

Assessing the combined effect of ocean warming and acidification (Fig. 3b) suggests that the western Baltic cod stock is at high risk, even when fishing mortality could be reduced to the current target reference point of $F_{MSY} = 0.26$ (ICES, 2017b). Therefore, a further adaptation of
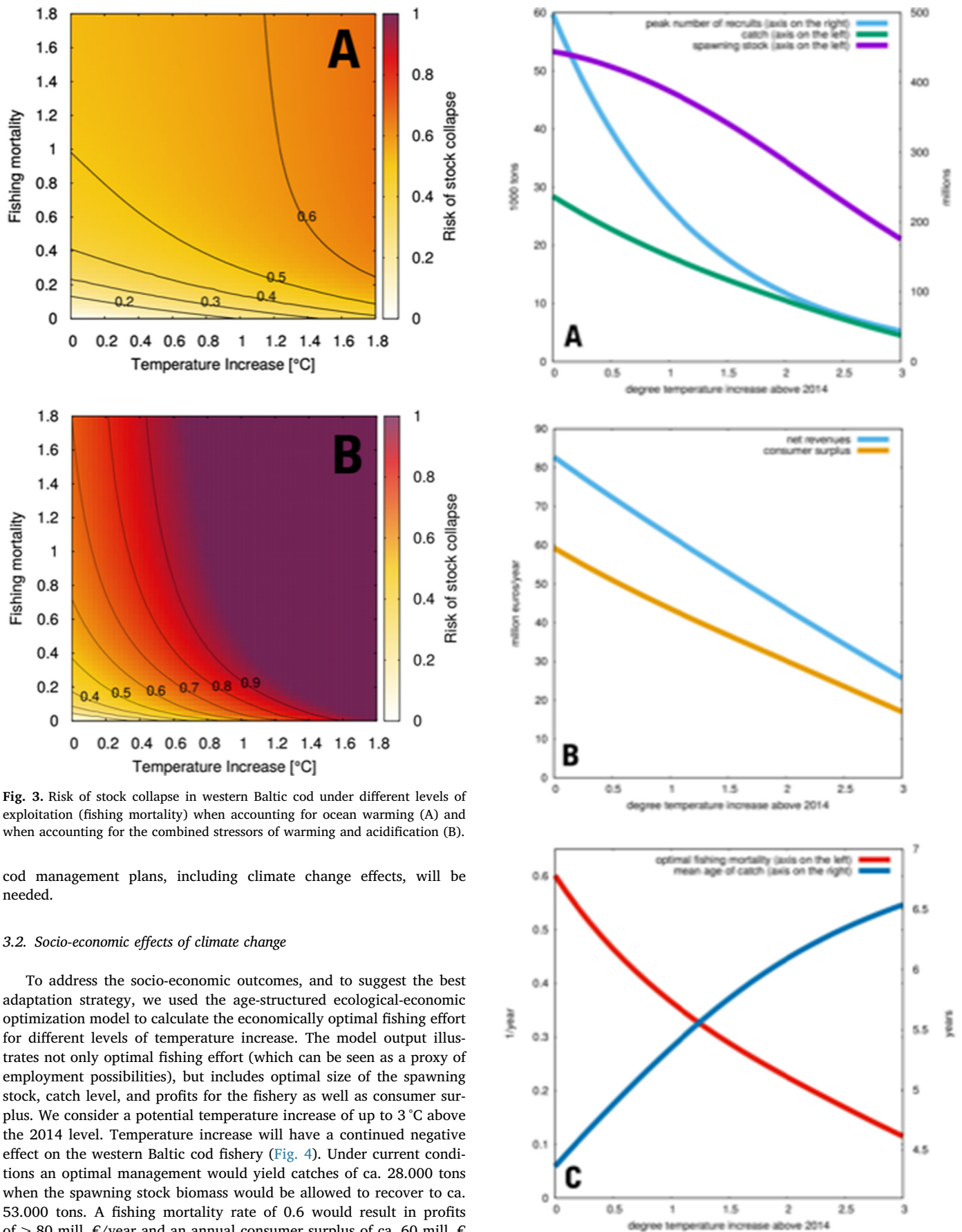
Fig. 3. Risk of stock collapse in western Baltic cod under different levels of exploitation (fishing mortality) when accounting for ocean warming (A) and when accounting for the combined stressors of warming and acidification (B).

cod management plans, including climate change effects, will be needed.

3.2. Socio-economic effects of climate change

To address the socio-economic outcomes, and to suggest the best adaptation strategy, we used the age-structured ecological-economic optimization model to calculate the economically optimal fishing effort for different levels of temperature increase. The model output illustrates not only optimal fishing effort (which can be seen as a proxy of employment possibilities), but includes optimal size of the spawning stock, catch level, and profits for the fishery as well as consumer surplus. We consider a potential temperature increase of up to 3 °C above the 2014 level. Temperature increase will have a continued negative effect on the western Baltic cod fishery (Fig. 4). Under current conditions an optimal management would yield catches of ca. 28.000 tons when the spawning stock biomass would be allowed to recover to ca. 53.000 tons. A fishing mortality rate of 0.6 would result in profits of > 80 mill. €/year and an annual consumer surplus of ca. 60 mill. € compared to todays values.

This is much more than has been achieved in recent years (ICES,

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Fig. 4. Temperature effects on recruitment, catch, and spawning stock biomass (A), fishery profits and consumer surplus (B), as well as fishing mortality and mean age of catch under optimal management (C) for the western Baltic cod (*Gadus morhua*) fishery.

2017a) when the spawning stock was estimated to have a size of only 12.900 tons, with commercial catches of 6.200 tons generated by a fishing mortality of 0.93 (year 2017).

Under ocean warming, the optimal size of the SSB decreases in a slightly concave way, down to ca. 22.000 tons at 3 °C temperature increase. Catches, profits, consumer surplus, and optimal fishing mortality, all decrease in a slightly convex fashion. At 3 °C temperature increase, only a restricted, but still viable, fishery is present. Optimal fisheries management counteracts the steep decrease in recruitment numbers due to adverse environmental conditions by stronger protecting the spawning stock, and by increasing mesh size, i.e. directing fishing effort to older age-classes. Under these management actions, the stock as well as the fishery would still be in a better condition than today (2017 situation).

The sensitivity analysis (Fig. 5) reveals a broad range of possible outcomes. Spawning stock biomass and economic surplus may vary over orders of magnitude. This emphasizes that our modeling approach cannot be taken as a numerical prediction of future states of the fishery; rather it illustrates the relative importance of factors under different climate change scenarios. The results highlight the need for increasing compensatory ("adaptive") management actions for the fisheries if the negative effects of ocean warming become more adverse.

Finally, we investigated optimal management and socio-economic outcomes for the combined effect of two stressors, ocean warming and acidification. Estimates of mortality increase due to ocean acidification are based on experiments, in which the survival of western Baltic cod larvae was quantified in direct response to increased pCO_2 levels. End-of-century levels of ocean acidification ($\sim 1100\,\mu$atm according to the IPCC RCP 8.5) resulted in a doubling of daily mortality rates compared to present-day CO_2 concentrations during the first 25 days post hatching, a critical phase for population recruitment. Applying the effects of both stressors in the recruitment function results in severe outcomes for the fishery. All variables show a much steeper decline (Fig. 6): catches of < 1.000 tons are reached already at a temperature increase of 0.85 °C. Even under economically optimal management the stock might collapse to < 1.000 tons SSB at 1.7 °C temperature increase. If the experimentally derived impact of ocean acidification holds true, a further temperature increase of +2 °C might not be sustained by this fishery. The strong negative impacts of climate change, and therefore the strong need for adaptive management actions is emphasized when comparing the outcome of the sensitivity analysis for the model with two stressors (Fig. 7) to the model assuming only ocean warming (Fig. 5). The distributions for spawning stock biomass as well as net economic benefits are shifted towards the left, i.e. to lower values: Even taking uncertainty of predictions into account, there is a high probability that climate change will have severe negative impacts on western Baltic cod.

4. Discussion

Global climate change poses multiple pressures on the marine environment. Recent studies start to address interactive effects of two of the most important pressures, ocean warming and acidification on a variety of organisms and ecosystems (Boyd, 2011; Fernandes et al., 2017; Hoegh-Guldberg et al., 2017). However, more elusive is how the management of exploited fish populations should and can adapt under these future scenarios. Using the example of a well-studied fish stock, the western Baltic cod stock, we considered the combined effect of two stressors. In line with our initial hypothesis, the combined action result in a large difference in the assessment of climate change outcomes.
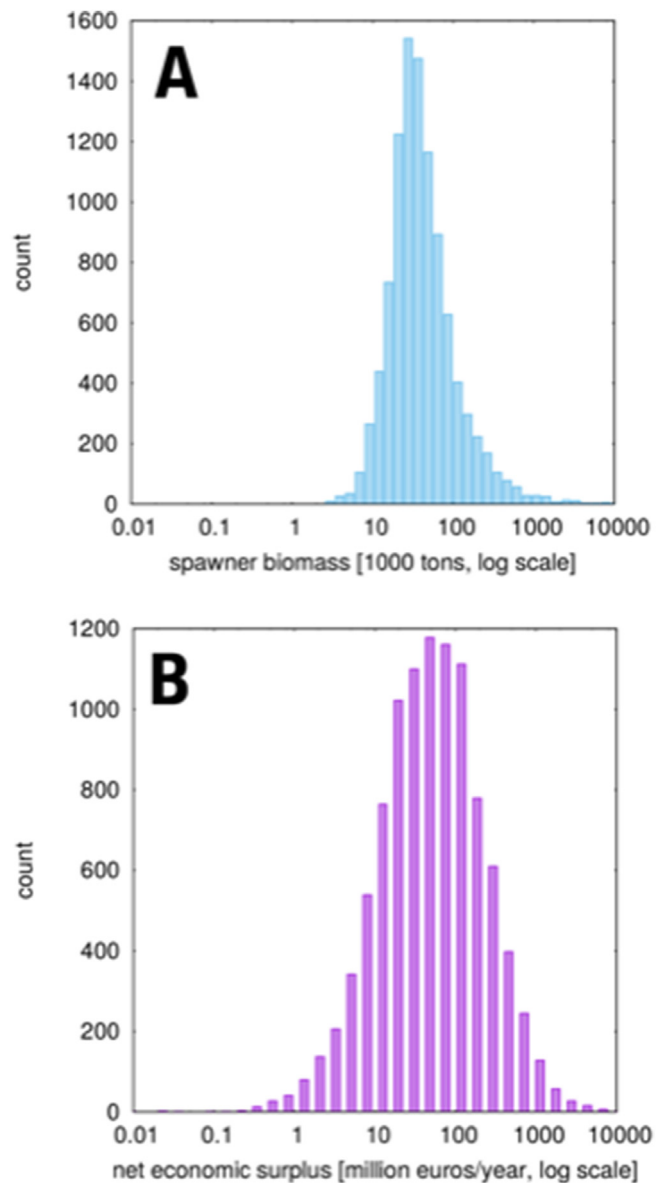
Fig. 5. Results of the sensitivity analysis applying 2014 temperature levels ignoring ocean acidification: spawning stock biomass (A) and net economic surplus, i.e. the sum of net revenues and consumer surplus (B).

While improved management might be able to successfully cope with either ocean warming or ocean acidification as single stressors, the combined effect of OAW renders the ecological-economic future of western Baltic cod very uncertain.

The consideration of ocean acidification without including ocean warming effects (not included in this study), might not be expected to be the most realistic scenario. Yet, climate scientists increasingly discuss the risks, potential benefits, and feasibility of climate engineering by means of solar radiation management (Crutzen, 2006; Sillmann et al., 2015). Geoengineering measures to curb solar radiation will, if at all, reduce the temperature increase by modifying the atmosphere's radiation balance without affecting CO_2 and thus ocean acidification levels (Klepper and Rickels, 2014).

The importance of decreasing pH levels for fish stock dynamics is still under debate. Adult fish have a high capacity to osmoregulate and therefore appear to be tolerant even to extreme values of ocean acidification (Ishimatsu et al., 2008). However, early life stages prior to gill formation have a very limited capacity for pH regulation (Falk-Petersen, 2005) and are therefore more likely to be impacted. In this
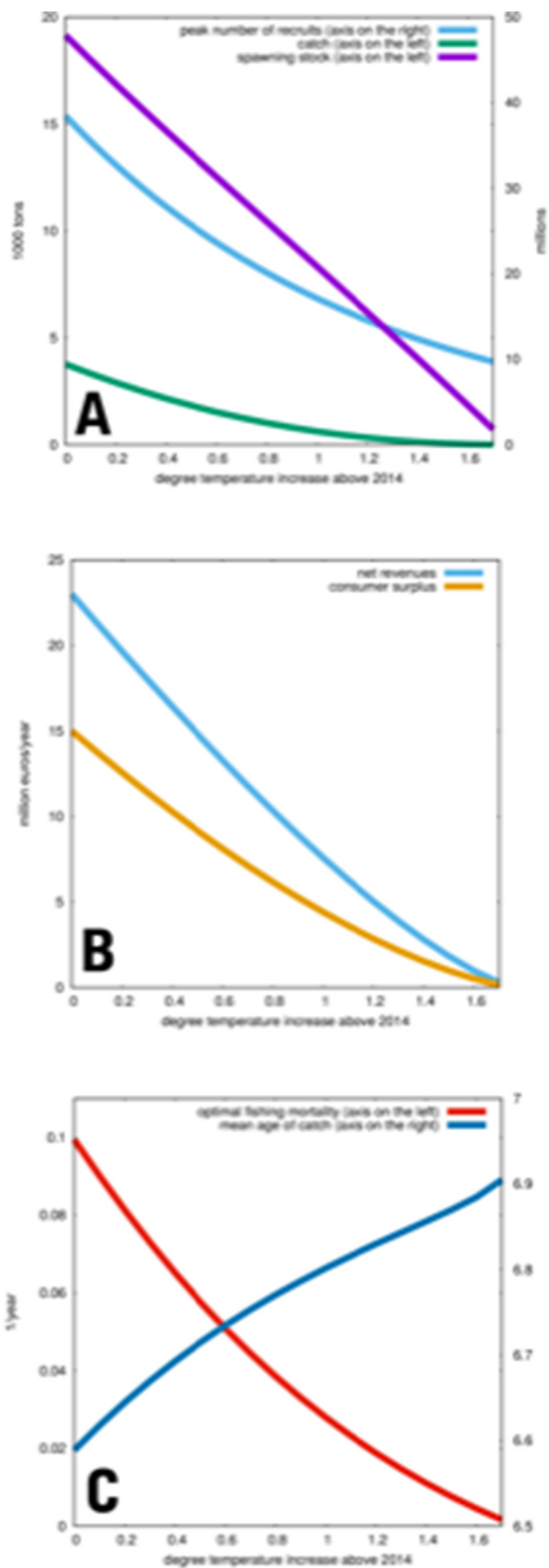
Fig. 6. The combined effect of temperature increase and ocean acidification on recruitment, spawning stock biomass and catch (A), fishery profits and consumer surplus (B), as well as fishing mortality and mean age of catch of the western Baltic cod fishery under optimal management (C).
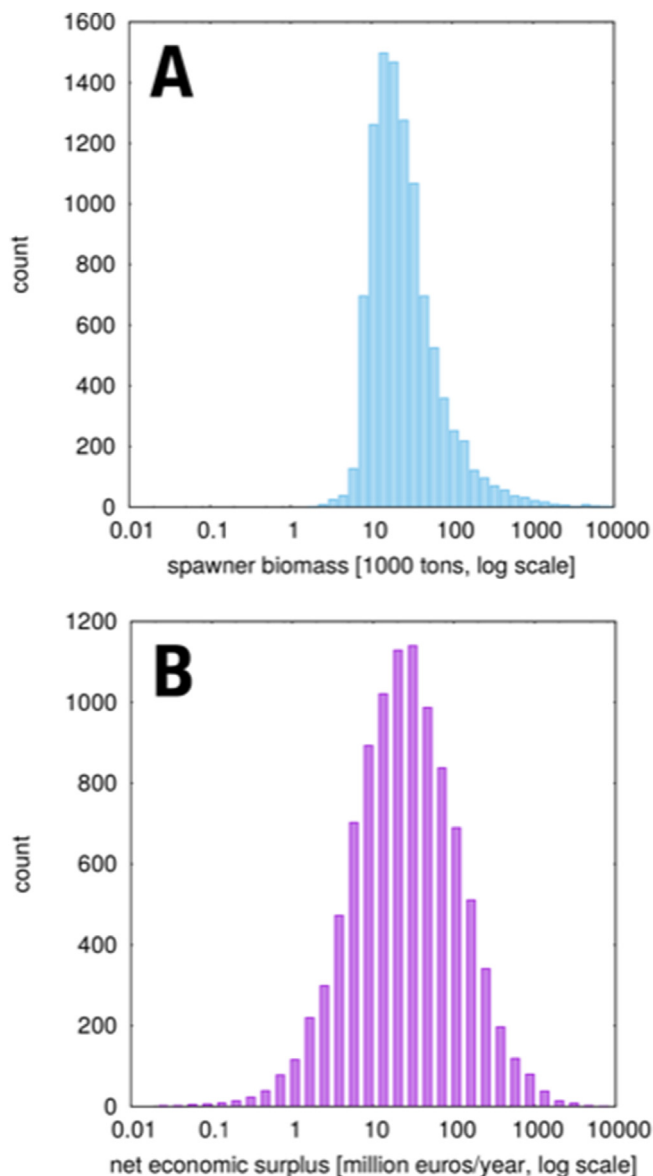

Fig. 7. Results of the sensitivity analysis applying 2014 temperature levels, and including ocean acidification: spawning stock biomass (A) and net economic surplus, i.e. the sum of net revenues and consumer surplus (B).

study, we used experimental data on changes in OA induced mortality rates, which showed consistent results in two cod populations, even when varying critical experimental parameters like stocking densitiy, and food concentration. Other studies found a broad range of potential impacts, e.g. on sensory abilities and behavior (Dixson et al., 2012; Munday et al., 2010), or damage induced to organ structure (Frommel et al., 2012, 2014) of larval fish. Others found effects on hatching success (Chambers et al., 2013), and survival of very early larval stages (Baumann et al., 2012; Bromhead et al., 2015).

However, there is also a large number of studies on other populations or life stages showing no impact of OA on egg or larval survival under acidification levels addressed in this study (Frommel et al., 2012; Maneja et al., 2012; Bromhead et al., 2015). Furthermore, there is potential for acclimation, trans-generational plasticity and adaptation, so that the future scenarios used here (no adaptation), might be over-pessimistic.

Temperature, on the other hand, is widely acknowledged as environmental factor potentially impacting vital rates of fish such as growth, or mortality (Pauly, 1980; Köster et al., 2003). Different cod

stocks worldwide have been shown to react in a non-uniform way: some stocks react positively to temperature increase, while others display a negative impact on stock dynamics (Drinkwater, 2005). Effects can either be direct physiologically or second order effects through changes in prey fields or habitat. For Baltic cod early life stages partly detailed process understanding has been gained (e.g. Köster et al., 2001; Kraus et al., 2002), suggesting a negative impact of temperature increase on population dynamics (Voss et al., 2012; Lindegren et al., 2010). E.g. Baltic cod larvae seem to suffer from temperature increase due to a reduced window of survival at the onset of external feeding (Voss et al., 2012). Furthermore, it should be noted that increasing temperature is associated with worsening oxygen conditions and increasing areas of hypoxia and anoxia directly impacting on available habitat sizes (e.g. Bendtsen and Hansen, 2012; Casini et al., 2016).

Therefore, it might be warranted to outline potential future scenarios, using the most up-to-date scientific results – even when clear process-based understanding of ocean acidification impacts is missing. Uncertainty in outcomes is still high, but stakeholders need to be sensitized for the need of better and more adaptive management. This is especially true as other, additional stressors (e.g. oxygen conditions), which might increase the pressure on western Baltic cod, have not been taken into account in this analysis. The same applies for the impacts of changing socio-economic variables: Quaas et al. (2016) have shown for the six economically most important North-Atlantic cod and tuna stocks that changes in fishing technology as well as increasing demand might be equally important in determining fishing activity and ultimately stock dynamics under environmental change.

The general conditions for the Western Baltic cod fishery (e.g. total allowable catch) are set at the European level. However, local management can influence the distribution of catch shares to individual users in the region. Furthermore, regulation of the increasing recreational fishing pressure (ICES, 2017a) can be shaped locally. Over the last years, local initiatives have formed, which promote direct marketing of fish to the end-user in order to secure better prices for the fisher and higher quality for the consumer. Unfortunately, such measures might not be sufficient to safeguard the fishery in the long run, if the cod stock continues to be under multiple pressure, resulting in further declining stock sizes.

A critically reduced cod 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. After the collapse of the cod fishery in Newfoundland 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) try to promote knowledge exchange with stakeholders, and discuss their views on future objectives under climate change.

Our results should not be taken at face value, as precise forecast of the effects of climate change on the size of western Baltic cod stock. Rather, as a sensitivity analysis, they show how fishing pressure and global change interact to produce potential future scenarios. Our results highlight the need to better understand climate change effects on fish stocks, ideally by up-scaling experimentation to stock dynamics in the wild.

If numerically true, our results show that reaching the ambitious goal of limiting climate warming to a maximum of 2 °C on global scale (Paris accord) is not sufficient to sustain a viable cod fisheries. On a regional scale, i.e. within the Baltic Sea, this target temperature will already be reached in the middle of the century (Lehmann et al., 2011).

5. Conclusion

Our results show that in addition to limiting warming to the 2 °C goal, the economic viability of the cod fishery will depend on a significantly improved local fisheries management. It will be central to any mitigation strategy that fisheries management becomes more effective, and that fish stocks are harvested precautionary. This includes the need for a further reduction in fishing mortality, which needs to be co-ordinated among the different user-groups. i.e. recreational and commercial fisheries. The reformed EU Common Fisheries Policy (EU, 2013) seems to be a step in the right direction, but in the case of western Baltic cod, still a lot remains to be achieved.

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