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Original Article

Waiting for a flourishing Baltic cod (*Gadus morhua*) fishery that never comes: old truths and new perspectives

Henrik Svedäng[1]* and Sara Hornborg[2]

[1]*Swedish University of Agricultural Sciences, Department of Aquatic Resources, Institute of Marine Research, Turistgatan 5, SE-453 30 Lysekil, Sweden*
[2]*SP Technical Research Institute of Sweden, SP Food and Bioscience, Sustainable Food Production, PO Box 5401, SE- 402 29 Gothenburg, Sweden*

**Corresponding author: tel: + 46 10 4784063; fax: + 46 52313977; e-mail: henrik.svedang@slu.se*

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Contrary to the declared recovery of the stock, the density-dependent growth of Eastern Baltic cod (*Gadus morhua*, Gadidae), probably related to increased gear selectivity, may have disrupted the size structure and substantially lowered the productivity of the stock. This naturally affects the profitability and future development of industry as well as ecosystem objectives in relation to policies such as the Marine Strategy Framework Directive. As a result, current management frameworks need to be reconsidered with a clear priority on setting objectives related to both socio-economic and ecosystem considerations. We explore various management options, using bioeconomic modelling to visualize potential trade-offs, and form an integrated decision support to inform managers regarding potential yield in biomass, revenue at both the fleet and individual levels, and environmental impact of fishing. We also investigate the consequences of preventing density-dependence by lowering selectivity, L_c, while optimizing for economic revenue and minimizing ecosystem impacts. Our findings indicate that new strategies need to be adopted by reducing L_c as well as fishing mortality, F, to restore individual growth and, hence, stock productivity. We also note that these more risk-averting strategies are positively linked to better profitability at both the individual and fleet levels as well as with enhanced ecosystem functioning and lower ecological stress.

Keywords: Baltic cod (*Gadus morhua*), bioeconomic modelling, density-dependent growth, ecological indicators, fishing effort, selectivity.

Introduction

After several decades of excess fishing mortality (Zeller *et al.*, 2011), the stock of Eastern Baltic cod (*Gadus morhua*) has recently been heralded as recovered: recruitment has improved considerably and, since 2009, fishing mortality has been reduced to sustainable exploitation levels according to the maximum sustainable yield (MSY) framework put in place (Cardinale and Svedäng, 2011; Eero *et al.*, 2012a; ICES, 2013). These seemingly positive signs have resulted in the certification of fisheries targeting Eastern Baltic cod by the Marine Stewardship Council (MSC, 2014).

However, shortly after management objectives were met in 2009 (Eero *et al.*, 2012a), growth (measured as weight-at-age) was observed to have declined in recent years (ICES, 2013). This decline was believed to be linked to insufficient feeding opportunities, and proposed explanations of the development include inter- and intraspecific competition (Casini *et al.*, 2009; Lindegren *et al.*, 2009; Eero *et al.*, 2012b). Furthermore, it was recently found that the growth potential (measured as the mean maximum length of a year class or population, L_∞, which is a parameter of the von Bertalanffy growth equation) has declined steeply over the last 15 years (Svedäng and Hornborg, 2014). This decline in growth was also found to be linked to a continuous increase in the number of small fish since the turn of the century and to a rapid decline in the abundance of fish >45 cm since 2010. As length at first catch, L_c (measured as the 50% point of the selectivity ogive), nominally increased from 32 cm in 1995 to 44–45 cm in 2010 (Feekings *et al.*, 2013), i.e. from a standard diamond mesh size of 120 mm in 1995 to a "Bacoma" square mesh size of 120 mm in extended exit windows, this development is thought to be linked to increased trawl selectivity inducing density-dependent growth by crowding.

Loss of cod productivity has already resulted in impaired ecosystem functioning (Casini *et al.*, 2009) and non-viable fishing opportunities, quota uptake being only 40% in the Danish and Swedish fisheries as of 2013 (ICES, 2013), suggesting considerable fleet overcapacity relative to available cod and poor fishing industry profitability. The problems now facing Baltic cod fisheries concern not only poor catchability, resulting in poor fuel economy compared with other cod fisheries (Ziegler *et al.*, 2013; Ziegler and Hornborg, 2014), but also the reliance on undernourished specimens 38–40 cm long (Eero *et al.*, 2012b). The latter exacerbates the fishery's poor economics stemming from low prices as it reduces the fillet yield and increases the handling time in the processing industry (Svedäng and Hornborg, 2014). Altogether, the reduced productivity of the stock and lesser abundance of large cod pose serious threats to the trophic stability of the ecosystem, renowned for regime shifts (Österblom *et al.*, 2007; Casini *et al.*, 2009), and to the cod fishing industry (Svedäng and Hornborg, 2014).

Conclusively, the present situation involves a highly skewed size structure of the Eastern Baltic cod population due to growth overfishing and, in particular, to loss of growth potential. Future management strategies should bear in mind that historical data indicate a sizable medieval fishery of fish 50–80 cm long (Orton *et al.*, 2011), i.e. substantially bigger fish in an ecosystem less productive than today's (Elmgren, 1989). Questions arising from these observations concern, for example, how baselines may have changed between generations, affecting what goals should be aimed for, and what alternative paths could better lead us towards sustainable resource use, including fuel use efficiency, without adversely affecting ecosystem structure and function.

Trends in Baltic cod population productivity

The Baltic Sea as a fishing ground is a brackish ecosystem where the oxygen conditions in the saltier and heavier bottom water layer depend on infrequent inflows of salt water and affect fish production (Bagge *et al.*, 1994; Köster *et al.*, 2005). Until the Second World War, cod fishing in the Baltic Sea was mainly small scale and limited to coastal regions (Eero *et al.*, 2008). Motorized trawling did not commence until around the 1920s, which is also when a movement farther offshore began (Eero *et al.*, 2007). The fishery then intensified, landings increasing from 20–40 000 tonnes in the 1930s to at least 70–100 000 tonnes in the 1940–1944 period (Meyer, 1952). After large inflows of oxygenated water in the late 1970s, cod stock recruitment and productivity dramatically increased and the fishery soared in the 1980s (Köster *et al.*, 2005; ICES, 2013). Thereafter, the stock declined due to high fishing pressure and deteriorating spawning conditions in two of three spawning areas, namely, the Gotland and Gdańsk basins (Vallin *et al.*, 1999; Lindegren *et al.*, 2014), altering the population structure of Eastern Baltic cod with implications for total stock productivity. As a result, the recent recovery is almost exclusively limited to the third basin, the Bornholm Basin, and the nursery areas are today restricted to the southern Baltic Sea in subdivisions (SDs; SDs set by ICES, www.ices.dk) 25 and 26 as well as the southernmost part of SD 27 (Eero *et al.*, 2012b; ICES, 2013). For these reasons, the present carrying capacity of the stock is probably much lower than it was in the 1980s (Cardinale and Svedäng, 2011). Nevertheless, these permanent constraints on future harvest levels and spawning-stock biomass development have not been addressed either in the assessment or in the recovery plans (e.g. ICES, 2013).

Harvesting strategies for Baltic cod

Whereas the amount of fishing effort has been paid less attention by actors engaged in managing the Eastern Baltic cod stock, i.e. the EU Commission and Council and related regional political organs such as Baltfish (2013) and the Baltic Sea RAC, improving the size selectivity of the cod fishery has been an ongoing concern, and the Baltic Sea is likely the area where the most fishing gear selectivity studies have been conducted (Madsen, 2007).

In terms of yield, changes in selectivity are generally less rewarding than are changes in effort, the latter usually being set too high, particularly relative to the maximum economic yield (MEY; Beverton and Holt, 1957; Quinn and Deriso, 1999). Increased selectivity might, in fact, lead to lower growth potential by increasing the number of fish in non-fishable size groups, as predicted by Beverton and Holt (1957) and now found in the Eastern Baltic cod fishery (Svedäng and Hornborg, 2014). Induced density-dependent growth will counteract any gains from increased selectivity, leading to a situation in which L_c is eventually above the mean maximum size of the population (L_∞), i.e. leaving fewer and fewer fish to catch. It has also been argued that selective fishing in general (with regard to both species and size) may not benefit total yield (Garcia *et al.*, 2012), and that stronger effort restrictions are instead required. Improving selectivity is still the focus of the newly reformed Common Fisheries Policy (CFP) of the EU (EU, 2013).

When evaluating management options for Eastern Baltic cod, it should be acknowledged that strong policy drivers, such as the Marine Strategy Framework Directive (MSFD), currently favour the integration of environmental and fishery management in the EU (Jennings and Le Quesne, 2012). For example, the newly reformed CFP addresses long-term environmental, social, and economic sustainability in its objectives (EU, 2013). This calls for a broader perspective on fisheries than simply maximizing sustainable yields by implementing F_{MSY}. In the end, the actual environmental performance will depend, among other things, on management actions that may affect the size structure of the stock (Svedäng and Hornborg, 2014), fuel intensity (with associated greenhouse gas emissions), and the area of trawl-swept seabed area per quota (Hornborg *et al.*, 2012). In addition, the economic outcome should be analysed in terms of profitability and stability at the fleet level as well as at the individual fishing enterprise level (e.g. Sterner and Svedäng, 2005). Therefore, in developing a management strategy for Eastern Baltic cod, trade-offs between different management objectives should be clarified in an integrated manner to allow transparent priority setting for management actions.

Study aim

We explore the recent development of the Eastern Baltic cod fishing by tracking of economic and stock indicators between 1991 and 2012. In search for alternative management options, we thereafter model the effects of selectivity, L_c, and fishing mortality, F, on four plausible management objectives: (i) maximizing sustainable yield; (ii) maximizing economic yield; (iii) preventing density-dependence by fishing at low L_c while maximizing economic yield; and (iv) maximizing individual economic yield. The environmental consequences of these management options are also evaluated using a suite of indicators related to the integration of fisheries and environmental policy.

Material and methods

The effects of L_c and F are explored under low, medium, and high stock productive states, determined largely by differences in growth potential, L_∞ (Beverton, 1992).

In analysing the partly conflicting objectives of maximizing sustainable yield in biomass and revenue and minimizing environmental stress, a suite of economic and ecological indicators has been considered. In economic terms, we have chosen to study the cost of fishing, including size-differentiated market prices, while estimating revenues at both the fleet and individual fishing enterprise levels. As for ecological indicators, we explore the effects of fuel use with associated CO_2 emissions (characterizing "low-impact fishing" in the CFP; EU, 2013), trawl-swept-area (related to descriptor 6 in the MSFD; EC, 2008), and development of the cod population size structure as gauged by the large fish indicator (LFI) (related to descriptor 4 in the MSFD; EC, 2008).

Economic data

To model economic performance under different selectivity and effort regulations, the Swedish Agency for Marine and Water Management (SwAM) was asked to provide information concerning a subset of the Swedish demersal trawling fleet, whose landings of cod caught in SD 25–29 exceeded 50% of the value of their annual landings from 2008 to 2011. We used this subset of fishing vessels as a template for the entire Baltic cod fishery. It should be noted that the Swedish cod fishery accounts for only 20% of Eastern Baltic cod landings (using all gear types), whereas demersal trawling, all nations combined, represents 88% of landings (ICES, 2013). For the purposes of this study, we assume that the chosen subset of Swedish demersal trawlers can serve as a proxy for the Eastern Baltic cod fishery in terms of cost and fishing efficiency, although we are aware that different economic circumstances can be expected in other nations' fisheries and in different passive fishing fleet segments.

This sample fleet contributed nearly 60 and 75% of the Swedish Eastern Baltic cod landings in 2008 and 2011, respectively (Table 1). The vessel segment of medium-sized trawlers had the largest share of cod landings during this period, whereas the proportion landed by the largest trawlers has even declined. In the management scenarios, we therefore chose to estimate cost by including only small- and medium-sized trawlers in the 2010–2011 period. Noteworthy, the largest vessels were less fuel efficient per landing than the vessels in the two smaller segments (litre oil per kg landed cod); this may exaggerate the cost efficiency of the fleet used in the modelling work. The cost calculations are based on classified declarations by skippers, administered by SwAM, and include expenditures for fuels, salaries, maintenance, and repairs using a discount rate of 5%. A grand mean in SEK per F was estimated of the two annual mean values for the fleet segments VL1218 and VL1824 (Table 1). Fishing per one unit of fishing mortality, $F = 1.0$, is estimated to cost SEK 652 068 000 (USD 1 ≈ SEK 8.0) and to consume 65 860 000 kWh.

Besides socio-economic indicators, SwAM also provided prices per kg of landed cod obtained for different weight classes (2004–2013; Supplementary data—Details of economic data). Information from logbooks covering years 2005–2012 on cod landings, bycatch, and effort in days or kWh for the same vessels is used to explore fishing cost. The development of filleting yield and processing/handling time (2004–2011) is based on data from the processing industry [see Svedäng and Hornborg (2014)].

Modelling yield at varying selectivity and fishing mortality levels

The modelling part of the study is written in r-script (http://cran.r-project.org/). For modelling reasons, knife-edge selectivity is assumed, meaning that all members of a cohort reach fishable size at a common age, t_c, and length, L_c (Quinn and Deriso, 1999). Selectivity is defined as L_c and the exploitation rate as $E = F/Z$, where Z is the total mortality. Lifetime percentage yield, y, is the

Table 1. Economic and emission data for three segments of the Swedish demersal trawling fleet with a declared annual catch value of >50% in SD 25–29 in the Eastern Baltic Sea (Figure 1).

	No. of vessels	Sum of kWh	Fuel consumption (l)	Cost (SEK)	Cod landings (kg)	All landings (kg)	Partial F_{46} (SURBA based)	Fuel use (l (kg cod) $^{-1}$)	Carbon emission (kg CO_2 (kg cod) $^{-1}$)	Cost/F_SURBA SEK F^{-1}
2008										
VL1218	14	3775	457 586	15 756 179	988 289	1 019 225	0.01657	0.46	1.18	951 056 394
VL1824	19	7713	1 455 525	45 728 109	2 388 728	2 426 662	0.04004	0.61	1.55	1 141 972 818
VL24XX	12	7937	1 106 447	64 584 739	1 847 100	1 880 293	0.03096	0.60	1.52	2 085 829 178
2009										
VL1218	15	3733	569 489	16 917 517	1 241 169	1 258 707	0.01355	0.46	1.17	1 248 088 497
VL1824	17	7147	1 412 917	42 712 447	2 748 914	2 788 768	0.03002	0.51	1.31	1 422 763 757
VL24XX	10	6685	1 915 537	50 079 827	1 983 090	2 003 206	0.02166	0.97	2.45	2 312 383 674
2010										
VL1218	10	2608	420 204	10 359 229	1 191 999	1 211 555	0.02105	0.35	0.90	492 048 601
VL1824	14	5702	1 454 425	43 273 152	3 661 436	3 699 605	0.06467	0.40	1.01	669 150 029
VL24XX	7	4306	1 400 344	38 866 668	1 682 962	1 696 683	0.02972	0.83	2.11	1 307 552 964
2011										
VL1218	11	3249	605 596	17 906 553	1 529 272	1 547 147	0.02608	0.40	1.01	686 576 278
VL1824	17	7040	2 140 816	58 251 162	4 491 262	4 516 434	0.07660	0.48	1.21	760 497 419
VL24XX	6	3043	1 679 307	34 465 807	1 496 540	1 500 590	0.02552	1.12	2.85	1 350 397 789

The three fleet segments consist of vessels in size classes based on overall length: 12–18 m (VL1218), 18–24 m (VL1824), and >24 m (VL24XX). Grand mean for fleet segments VL1218 and VL1824 in 2010–2011: 652 068 082.

SURBA, survey-based assessment (Needle, 2012).

Table 2. Life history data used in modelling.

	L_∞ = 50 cm	L_∞ = 90 cm	L_∞ = 120 cm
M	0.49	0.3	0.18
K	0.5	0.3	0.15
W_∞ in g	1300	7582	17 971
L_{opt} (optimal length at MSY) in cm	37.7	67.5	85.7
Y_w/R at global MSY as a fraction of the possible cohort weight	0.108	0.105	0.081
Y_w/R at global MSY in g	141	800	1456
Mean length in exploited phase at $L_c = 30$ cm and $F = 0.3$ in cm	37.6	50.0	51.4
Mean weight in exploited phase in g	585	1627	1913

For all three growth potentials (L_∞), t_0 was kept constant at −0.2.

fraction of the maximum possible weight a cohort would reach if no mortality occurred after the reference age, t_0. The percentage yield, y, is calculated for combinations of L_c and E at a mortality/growth ratio of $m = M/K$, where M is the natural mortality and K is the growth factor in the von Bertalanffy growth equation (Beverton and Holt, 1964):

$$y = E \times \sum_{n=0}^{3} \Omega_n (1 - c)n + \frac{m}{[1 + n(1 - E)/m]} \tag{1}$$

where $n = 0$, $\Omega_n = +1, -3, +3$, and -1 for $n = 0, 1, 2$, and 3, respectively, and $c = L_c/L_\infty$. Because K is inversely related to L_∞ in the Eastern Baltic cod, as in other fish stocks (Beverton, 1992), K is set at 0.5, 0.3, and 0.15 for L_∞ at 50, 90, and 120 cm, respectively (Table 2). By using these combinations of K and L_∞ as well as the observed experienced mean water temperature for Eastern Baltic cod (Righton *et al.*, 2010), M is estimated to be 0.49, 0.3, and 0.18, accordingly (Pauly, 1980; http://cran.r-project.org/web/packages/fishmethods/). In calculating yield-per-recruit, Y_w/R, the following equation (Quinn and Deriso, 1999), is used to return to the original scaling:

$$\frac{Y_w}{R} = y e^{M(t_r - t_0)} W_\infty \tag{2}$$

where Y_w/R is the yield in weight, t_r is the age at recruitment to a fishable size, t_0 is set at −0.2, and W_∞ is the mean asymptotic weight. W_∞ is calculated using the following weight–length relationship:

$$W_\infty = \frac{aL_\infty^b}{10} \tag{3}$$

where $a = 0.104$ and $b = 3$ (Cardinale and Hjelm, 2012). The mean length of year class i at year j is estimated using the following equation:

$$L_{ij} = L_\infty(1 - e^{(-K \times (t - t_0))}) \tag{4}$$

As the mean total fishable biomass per recruit of a cohort, B''/R, is proportional to the catch-per-unit- effort [cpue; Beverton and Holt, 1957; see also Svedäng (2014)], the following relationship is used:

$$\frac{B''}{R} = \frac{(Y_w/R)}{F} \tag{5}$$

Total yield is estimated using the estimated average recruitment of 2-year-old cod in the Eastern Baltic cod stock between 2004 and 2013, i.e. 158 564 000 recruits.

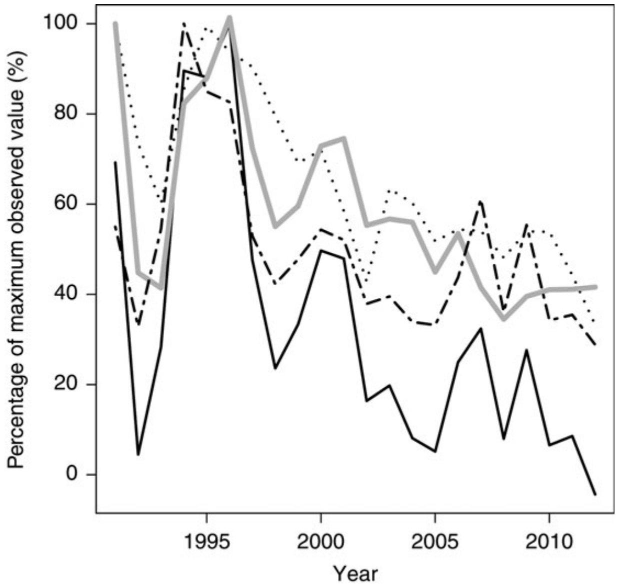

Figure 1. Modelled historical development (1991–2012) of the entire Baltic cod fishing, including total landings (grey line), LPUE (dotted-dashed line), profit at the fleet level (solid line), and LFI (dotted line) shown as percentages of the maximum value recorded in the time-series. Note that the maximum levels do not necessarily imply the most profitable or ecologically sound fishing effort. Revenues, cost (per F), and fishing efficiency are based on information from the Swedish demersal trawling fleet given by SwAM, 2010–2011 (Table 2); estimates of F are based on ICES (2013) estimates up to 2006, and thereafter on SURBA estimates (Svedäng and Hornborg, 2014).

Modelling effects of selectivity and exploitation rate on economic returns under various ecological settings

Gross revenue in year i, GR_i, for the entire Eastern Baltic cod fishery is modelled at different values of L_c and F using information from the Swedish Baltic cod fishery provided by SwAM on market prices, P_i, in SEK per mass unit per weight class, derived cost, Q, in SEK per unit of F (Table 1 and Supplementary Table 1), and Y_w/R at varying recruitment levels, R_i, using the following relationship:

$$GR_i = P_i C_t - Q_i F \tag{6}$$

where $C_t = Y_w \times R_i$ is the total catch at a given R_i, L_c, and F. The partial F_S for this fishery is estimated as F_S = landings in the specific fishery/total Eastern Baltic cod landings × F, where F was previously calculated using the estimated mean Z for fish >37 cm for this stock in

2010–2011 (Svedäng and Hornborg, 2014) and keeping natural mortality, M, constant at 0.3. Q_i (SEK/F) is estimated as:

$$Q_i = \frac{Q_S}{F_S} \tag{7}$$

i.e. the cost in the Swedish trawl fishery divided by F_S for this fishery.

Evaluation of management policies

Different management policies are extrapolated from a reference situation (for economic data, we average over 2010 and 2011) to enable quantitative and qualitative discussion of future development related to the mixed objectives of maximizing sustainable yield, maximum economic yield, and minimizing fishery-induced environmental impact. The effects of the dynamic nature of growth, population size, and predation rate are discussed by comparing three distinct productive states characterized by low (50 cm), medium (90 cm), and high (120 cm) individual growth potential, L_∞ (cf. Svedäng and Hornborg, 2014).

We considered the following four management options:

(i) maximizing sustainable yield (global MSY), under the constraint that F is set at 1.5, as the differences in yield at this harvest rate and higher ones are considered minuscule;

(ii) maximum economic yield (MEY), by obtaining the optimal combination of L_c and F;

(iii) preventing density-dependence while aiming for the optimal economic combination of $L_c = 30$ cm and F; and

(iv) maximizing individual economic yield by minimizing fishing effort, i.e. the economic yield at $L_c = 30$ cm and $F = 0.1$.

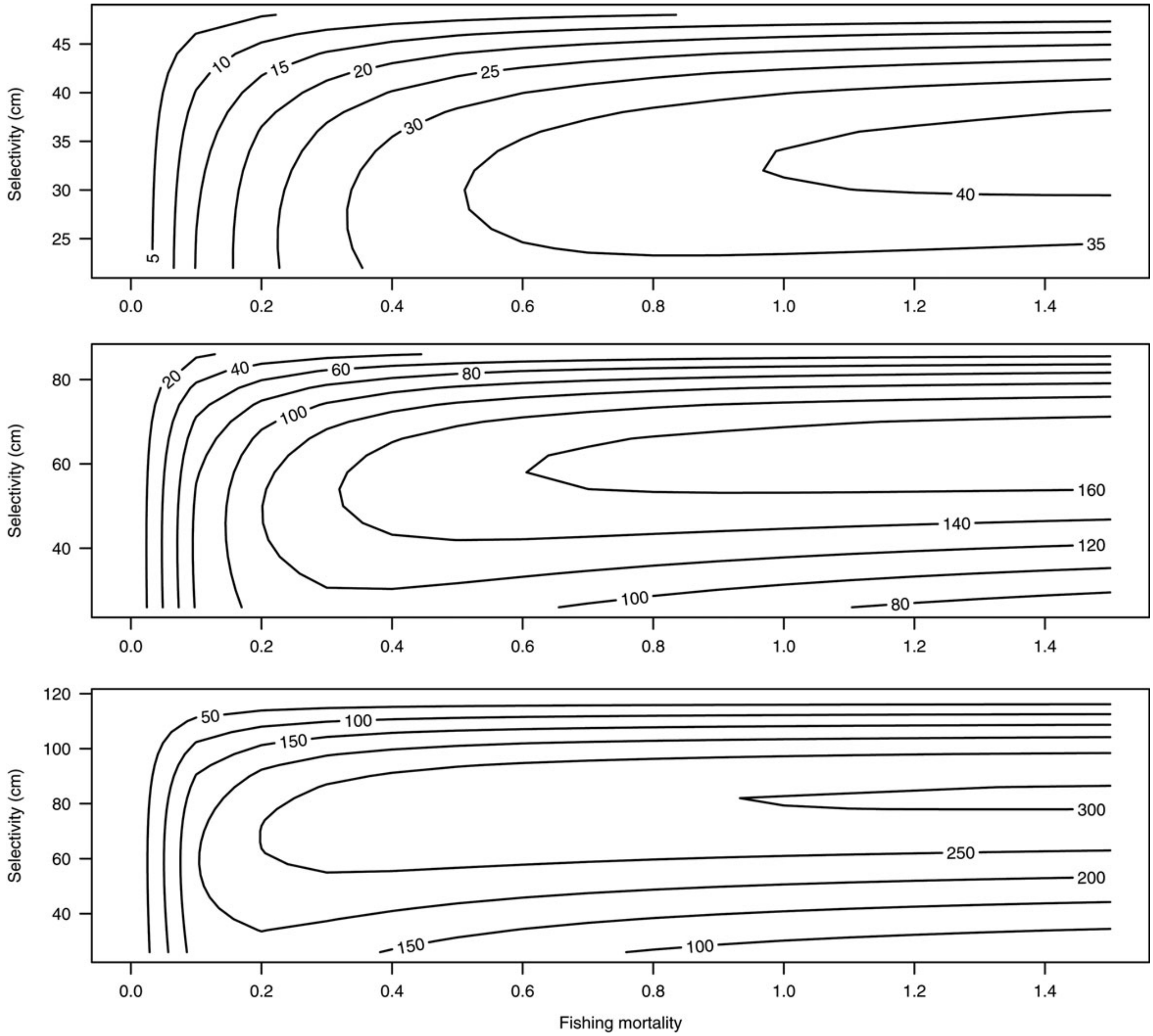

Figure 2. Total yield in thousands of tonnes as a function of fishing mortality, F, and selectivity, L_c, at different growth potentials: upper panel, $L_\infty = 50$; middle panel, $L_\infty = 90$; and lower panel, $L_\infty = 120$.

Trade-offs between management objectives are evaluated as changes in total fishing revenues, landing quantity, and impacts on ecosystem indicators, such as the LFI (adapted for a single species) and trawl-swept seabed area, related to the ecosystem quality objectives for Good Environmental Status set forth in the EU MSFD (EC, 2008). In addition, fuel use and greenhouse gas emissions per kWh are estimated using the relationships between kWh, *F*, and fuel use (Table 1) and between CO_2 emissions and fuel type combusted (www.spbi.se).

The size structure of the Eastern Baltic cod stock is retrieved from the ICES DATRAS database (www.ices.dk; 1991–2013) and used to estimate single-species LFI. LFI is one of the descriptors in the MSFD and may be seen as an indicator of ecosystem structure and productivity (e.g. large fish have higher fecundity and feed differently). As the size of cod is an important implication of our different models, this is a useful indicator to both illustrate this ecosystem effect, as well as it is a step towards integrating MSFD requirements in fishing policy. We argue that a threshold set at 40 cm would better represent proportional changes in larger fish biomass due to variations in growth and/or mortality rates than would a threshold set at 30 cm, the LFI threshold recommended for the Baltic by ICES (2011), as the latter merely reflects recruitment variation in the cod stock (results not shown). In this study, LFI is estimated as a single-species indicator, based on survey estimates of the ratio between the weight of the catch above a certain length threshold (i.e. all cod above 40 cm in this case) and the total weight of the cod catch.

For greenhouse gas emissions, we assume the use of class MK1 diesel, and use emission data from the Swedish Petroleum and Biofuel Institute (www.spbi.se). The results of semi-structured interviews with 12 active Eastern Baltic cod trawl skippers were used to obtain estimates of fuel use per trawl hour for different vessels. These results are used to verify our model of fuel use (litres per kWh) derived from fuel consumption data provided by SwAM (Pearson correlation factor 0.95).

The trawl-swept seabed area is quantified using a model from Nilsson and Ziegler (2007), assuming that all fishing effort is performed using single trawls. Single trawling is the dominant practice according to logbooks, although an increase in the use of double trawls can be noted in recent years.

Results

Development of economic and stock indicators, 1991–2012

The fishable stock has declined since the mid-1990s, as indicated by reduced landings (yield), landings-per-unit-effort (LPUE), economic yield (profit), and LFI in the Eastern Baltic cod fishery (Figure 1). Even after the management objective of F_{MSY} was achieved in 2009, revenue has continued declining and yield has remained constant despite increased total allowable catches (TACs), i.e. the utilized proportion of available fishing quotas has diminished (ICES, 2013).

Management options

Maximizing sustainable yield in biomass, global MSY

As illustrated by the predicted yields at $L_\infty = 50$, 90, and 120 cm shown in Figure 2, there is no optimal combination of L_c and *F*; although the yield curve is doom-shaped with respect to L_c, increasing *F* above the given interval would theoretically lead to higher yields, i.e. higher global MSY. The predictions also imply that the highest yield, given the restriction in *F*, is obtained with increasing L_c and L_∞. However, to obtain higher yields from the stock, it is of greater interest to increase or sustain the growth potential, L_∞, than to modify L_c and *F* (Table 3).

Maximizing economic yield

Unlike for biomass yield, true optima can be defined for economic yield for given combinations of L_c and *F* (Figure 3). Given the present low growth status (c. $L_\infty = 50$) of Eastern Baltic cod, profitability is attainable only within certain combinations of *F* and L_c (Figure 3, upper panel). For example, at $L_\infty = 50$, $F \leq 0.5$ and $L_c < 35$–45 cm would result in positive returns at the fleet level, whereas MEY is obtained at $L_c = 24$ cm and $F = 0.2$ (Table 3).

Enhanced growth potential is crucial not only for increasing biomass yields but also for the profitability of the industry (Figure 3 and Table 3). For $L_\infty = 90$ or 120 cm, besides an initial increase in MEY with increasing *F*, profitability declines steeply from an optimal ridge at higher and lower levels of L_c. The hypothetical gains from increasing L_c and *F* are less pronounced at $L_\infty = 90$ cm

Table 3. Total outcome for yield, revenue, CO_2 emissions, trawl-swept seabed area, and LFI under three productive states (i.e. $L_\infty = 50$, 90, or 120 cm; other relevant life history parameter values are given in Table 2), prioritizing either yield close to MSY at $F = 1.5$, fleet profitability at MEY, preventing density-dependence (PDD), or profitability of the individual fishing enterprise (Ind. MEY).

Management options by growth potential	L_c and *F*, respectively	Yield (tonnes)	Revenue (million SEK)	Fuel use (million l)	CO_2 emissions (million kg)	Seabed area (1 000 km^2)	LFI (%)
$L_\infty = 50$							
Global MSY	34, 1.5	42 000	−553	34.9	88.6	105	0.6
MEY	24, 0.2	23 700	109	4.6	11.8	14	22
PDD	30, 0.2	23 000	102	4.6	11.8	14	21
Ind. MEY	30, 0.1	14 300	79.6	2.3	5.9	7	26
$L_\infty = 90$							
Global MSY	62, 1.5	176 000	1332	34.9	88.6	105	73
MEY	62, 0.6	162 000	1774	13.9	35.4	42	74
PDD	30, 0.3	120 000	1256	7.0	17.7	21	74
Ind. MEY	30, 0.1	83 700	982	2.3	5.9	7	84
$L_\infty = 120$							
Global MSY	82, 1.5	303 000	3556	35	89	105	89
MEY	82, 0.6	292 000	3977	14	35	42	89
PDD	30, 0.2	192 000	2366	4.6	12	14	86
Ind. MEY	30, 0.1	179 000	2333	2.3	5.9	7	91

The profitability is maximized in the PPD under the constraint that $L_c = 30$ cm. At the individual MEY, L_c is set at 30 cm and *F* at 0.1.

compared with the higher productivity state at $L_\infty = 120$ cm. This is due to the predicted increase in the share of bigger fish in the catch, rendering higher market prices.

Preventing density-dependence

If lower selectivity was a prerequisite for preventing density-dependence, for example, by setting $L_c = 30$ cm, the highest economic returns would be expected at $F = 0.2-0.3$ irrespective of growth performance (Table 3). This management approach gives an equal yield in biomass for $L_\infty = 50$ cm, whereas for higher growth potentials, the declines in biomass yield are theoretically considerable compared with the MEY option, i.e. 40 000 tonnes less for $L_\infty = 90$ cm and 100 000 tonnes less for $L_\infty = 120$ cm (Table 3). The economic revenues at the fleet level are also clearly lower, given that fishing at such high levels of selectivity would not seriously affect individual growth in the stock.

Aiming for individual MEY

Unlike fleet profitability, economic returns for individual fishers will always decline with increasing *F*, as LPUE will decrease with increasing effort. The profit per kWh with respect to L_c and *F* is very similar in shape regardless of L_∞, though the higher the L_∞ the higher the revenues (Figure 4). The choice of selectivity is of minor importance at low levels of *F* and L_c, whereas the profit per kWh decreases exponentially with increasing *F*.

Minimize trade-offs in ecological cost of fishing

Besides the option of not fishing at all, policies striving to increase L_∞ while minimizing *F* will invariably reduce fuel consumption and the trawl-swept-area, as well as allowing the size distribution to be as "natural" as possible (Table 3). The lowest environmental impacts in terms of greenhouse gas emissions and trawl-swept seabed area as well as the highest LFI values are found with the

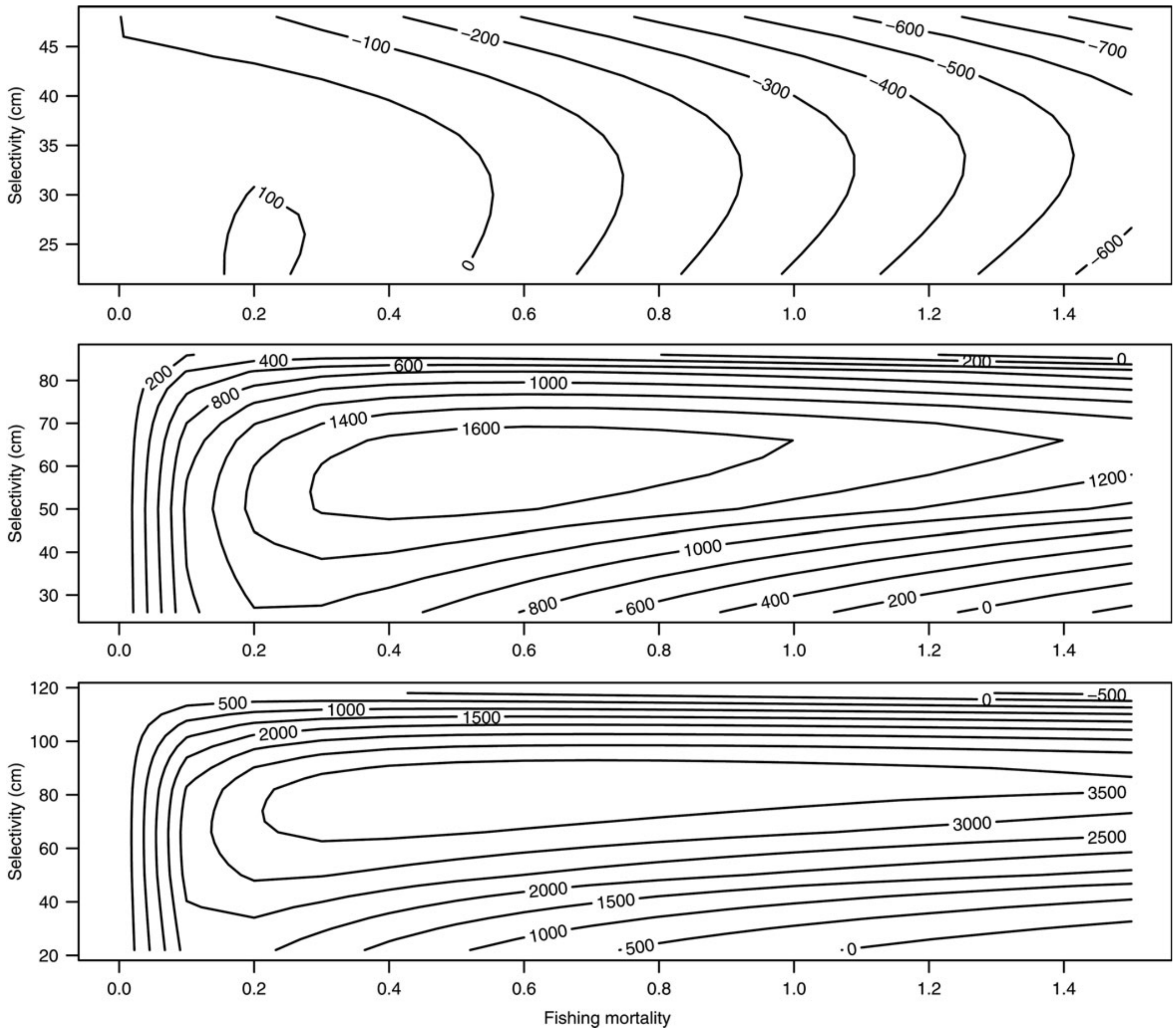

Figure 3. Total profit in SEK million for the fishing fleet as a function of fishing mortality, *F*, and selectivity, L_c, at different growth potentials: upper panel, $L_\infty = 50$; middle panel, $L_\infty = 90$; and lower panel, $L_\infty = 120$.

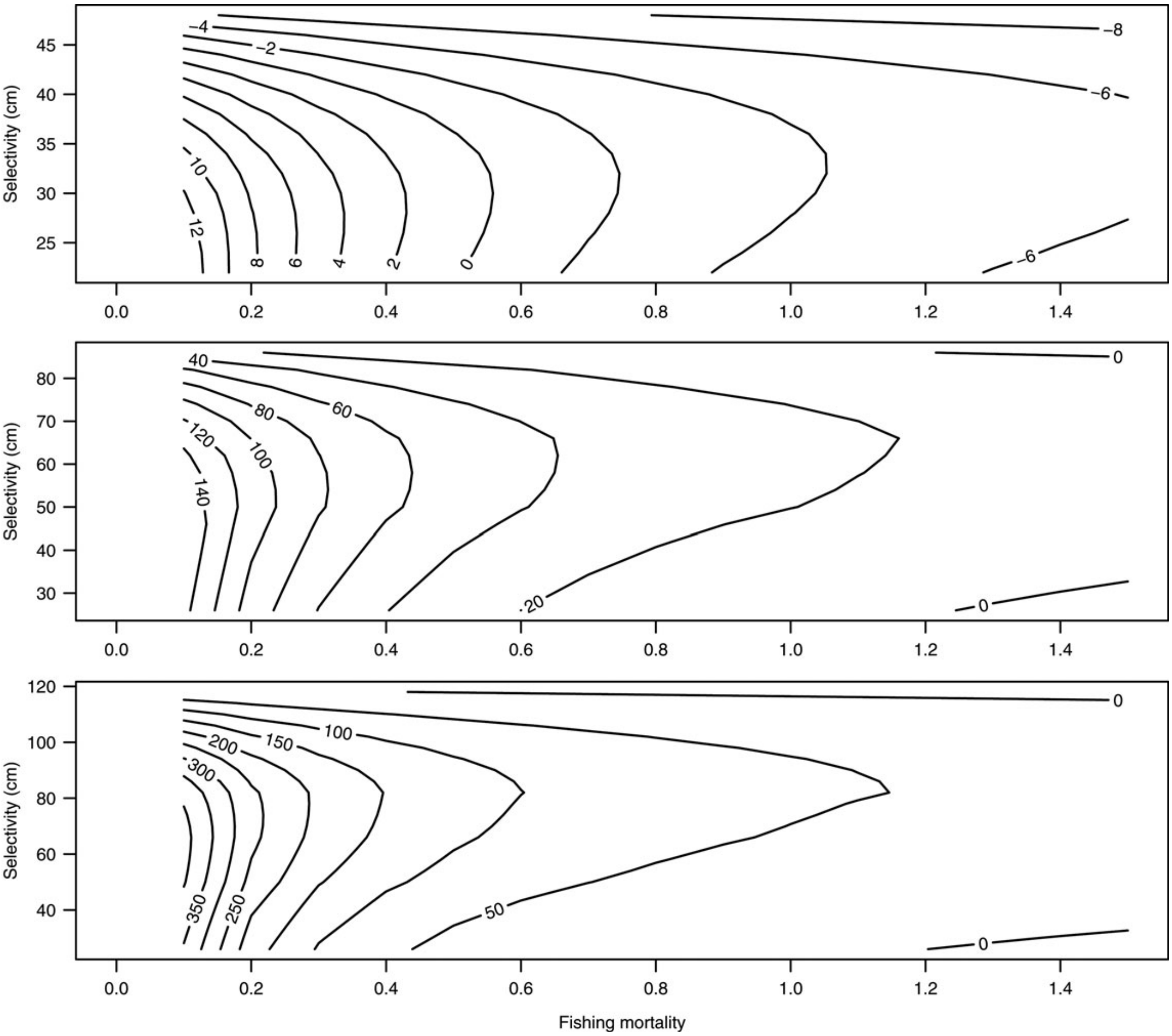

Figure 4. Profit per kWh (SEK kWh^{-1}) as a function of fishing mortality, F, and selectivity, L_c, at different growth potentials: upper panel, $L_\infty = 50$; middle panel, $L_\infty = 90$; and lower panel, $L_\infty = 120$.

management options of preventing density-dependence and individual MEY, i.e. at low levels of F.

The predicted LFI and length distribution at $L_c = 30$ cm and $L_\infty = 50$, 90, and 120 cm illustrate the importance of higher L_∞ values for size distribution at low levels of F (Figures 5 and 6). Low L_∞ will naturally result in a small number of big fish, but the differences in length distribution between growth potentials are less pronounced at higher F, although larger cod will still be present in the stock at higher L_∞, unlike at $L_\infty = 50$ cm (Figure 5). On the other hand, LFI is influenced less by F and more by L_∞ (Table 3). At $L_\infty = 50$, LFI scores are very low and are very insensitive to changes in selectivity, except when L_c approaches the value of L_∞ (Figure 6, upper panel).

Discussion

This study confirms a continuous decline in the growth of the Eastern Baltic cod stock since the mid-1990s (Svedäng and Hornborg, 2014), with associated reductions in fleet profitability. In fact, our analysis demonstrates that the cod population size structure and fishery profitability have deteriorated under the current management framework, in contrast to the objectives of the multi-annual management plan for the Eastern Baltic cod stock (EC, 2007) as well as to the objectives of sustainable development and of ecosystem approaches to fisheries (United Nations, 2002; FAO, 2003). This emphasizes the need to develop new management strategies by exploring various options and their trade-offs in yield, economic revenue, and ecological impact.

If fisheries are to be sustainably developed, management policies should be evaluated from the perspective of several objectives (Larkin, 1977; Beverton, 1998; Pauly *et al.*, 2003; Longhurst, 2010). Although policies to promote MSY represent a step towards preventing impaired recruitment and combating growth overfishing (Lassen *et al.*, 2014), it must again be emphasized that global MSY is unattainable, as F would have to be infinitely high (Beverton and Holt, 1957). What is usually sought is a local msy (distinguished by small caps) at much lower selectivity than L_{opt} (the optimal selectivity at global MSY). At such a level of selectivity (e.g. at $L_c = 30$ cm), shown in the second option presented here, msy is achievable. However, is

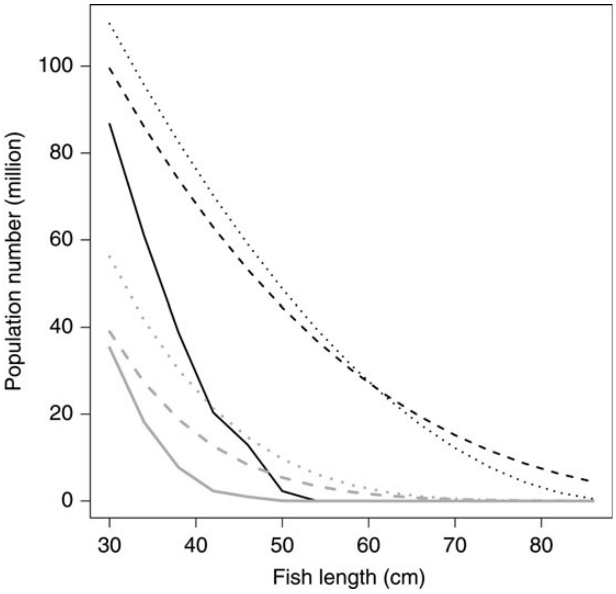

Figure 5. Length distribution (numbers at given lengths in million) as a function of fishing mortality, F ($F = 0.3$, in black; $F = 1.0$, in grey), at $L_c = 30$ cm for different growth potentials: $L_\infty = 50$ (solid line), $L_\infty = 90$ (dotted line), and $L_\infty = 120$ (dashed line).

fulfilling such an objective really desirable? With less effort than is required for msy, a more ecologically robust situation will emerge with a restored size structure. As this involves a state with higher fishable biomass in the ecosystem than is required for msy objectives, this will in turn bring higher revenues for fishers, as demonstrated in our analysis [see also Grafton *et al.* (2007)].

From a broader perspective, this arguably more risk-averting strategy also reveals great improvement potentials in terms of resource use and environmental impacts. However, aiming for MEY at $L_\infty = 50$ leads to low L_c and F, whereas at $L_\infty = 90$ and 120 cm, F is rather high and L_c equals L_{opt}. The latter two cases are due to the increased market value of larger cod. Of note, the total value figures obtained here for the different options should be interpreted with caution and regarded as merely indicative, reflecting improvement potentials in a wider sense. This observation nonetheless indicates an important caveat regarding the MEY strategy: if density-dependence is at risk of being induced by increasing selectivity, suboptimal solutions in relation to both the msy and MEY options must be sought, as the theoretical maxima of msy and MEY are unattainable. From the individual fisher's perspective, a lower F would be even more advantageous, as profitability (SEK kWh^{-1}) increases rapidly at levels below $F = 0.3$. Aiming for high profitability for individual fishers, instead of treating the fishing industry as a single "fleet", by setting L_c at 30 cm and F at 0.1, therefore leads to generally lower total revenues but higher profitability. Unsurprisingly, there is a conflict of interest between optimizing the economic yield of the entire industry and optimizing the economic returns of individual fishers who remain in the fishery even after the fishing effort has been reduced.

As an alternative harvest strategy, we suggest that if L_c was lowered to 30 cm, as it was in the early 1990s, density-dependence might be prevented, while F should be adjusted downwards to maximize economic revenue. This suboptimal strategy would lead to 29 and 41% reductions in profit at $L_\infty = 90$ and $= 120$ cm, respectively. These "suboptimal" levels of profitability, however, are considerably better than the present situation. Yet it must be emphasized that lower selectivity should not be combined with too high a fishing mortality rate. The proposed lower selectivity will aim at a selectivity ratio at or below 0.3, corresponding to the size at maturity of a fish population. It is therefore vital with stronger effort restrictions as intensive fishing could risk impairing recruitment.

Arguably, reducing the mesh size will result in an increased proportion of smaller, less desirable fish in landings, fish of little value to the processing industry, and of little interest to consumers. This also has a bearing on the newly enforced landing obligations for the Baltic Sea that will result in smaller size classes of Eastern Baltic cod in landings. Policies aiming at reducing fishing effort rather than increasing selectivity may, however, be more beneficial from a seafood sustainability perspective, as high LPUE values reduce fuel use per landing (Ziegler and Hornborg, 2014) as well as associated emissions and trawl-swept seabed area, the latter of no less importance to mitigate in the Baltic compare with other areas (Caddy, 2000; Korpinen *et al.*, 2013). In 2009, when the cod fishery was regarded as sustainably fished (Eero *et al.*, 2012a), the fuel use per kg of cod landed ranged, depending on vessel size category, between 0.2 and 0.8 l (Ziegler and Hornborg, 2014); in many other cod fisheries, the lower end of this range is predominant (Ziegler *et al.*, 2013). It is therefore important to scrutinize the short-term economic losses of the fishing industry stemming from mesh size changes and resulting size composition of landings in relation to the long-term ecological and economic gains from setting lower objectives for yield in tonnes; reducing fleet overcapacity is one important measure, but changes in market preferences are also needed.

The differences in yield between the growth potentials explored here highlight the importance of restoring growth potential. With mesh sizes having significantly increased over the past 20 years (Madsen, 2007; Feekings *et al.*, 2013), and with the rather strong negative correlation between selectivity and growth potential (Svedäng and Hornborg, 2014), density-dependence likely caused the poor growth performance, although other factors could have also played a role (e.g. Sinclair *et al.*, 2002a; Teschner *et al.*, 2010). Either way, management actions are needed that aim at either increasing the abundance of forage fish in areas where cod are concentrated (Eero *et al.*, 2012b) or lowering selectivity back to levels previously prevalent in the Baltic Sea, to deliberately reduce the abundance of cod in a certain size interval (Svedäng and Hornborg, 2014).

Size-selective processes may be enforced by the combined effects of changed growth and mesh sizes (Sinclair *et al.*, 2002b). In fact, Baltic cod have decreased in size over the millennia (Limburg *et al.*, 2008). However, even if poor cod growth has been noted before in shorter periods of time, for example, in the 1980s when cod biomass was very high in the Baltic Sea (evident as changes in weight-at-age; ICES, 2013), it has become more pronounced in recent years, suggesting a faster change in size distribution than is likely to occur on evolutionary scales (cf. Olsen *et al.*, 2004).

It should also be acknowledged that Baltic cod population diversity has decreased, as two out of three spawning grounds have ceased contributing to cod production, putting further strain on the potential for the Eastern Baltic cod fisheries. This means that the potential yield from the existing stock is systematically exaggerated in regular assessments and elsewhere (e.g. Voss *et al.*, 2014)—and, presumably, also in the present study. As the Baltic Sea is unique due to its specific environmental conditions and associated genetic diversity, management strategies related to the genetic population diversity might

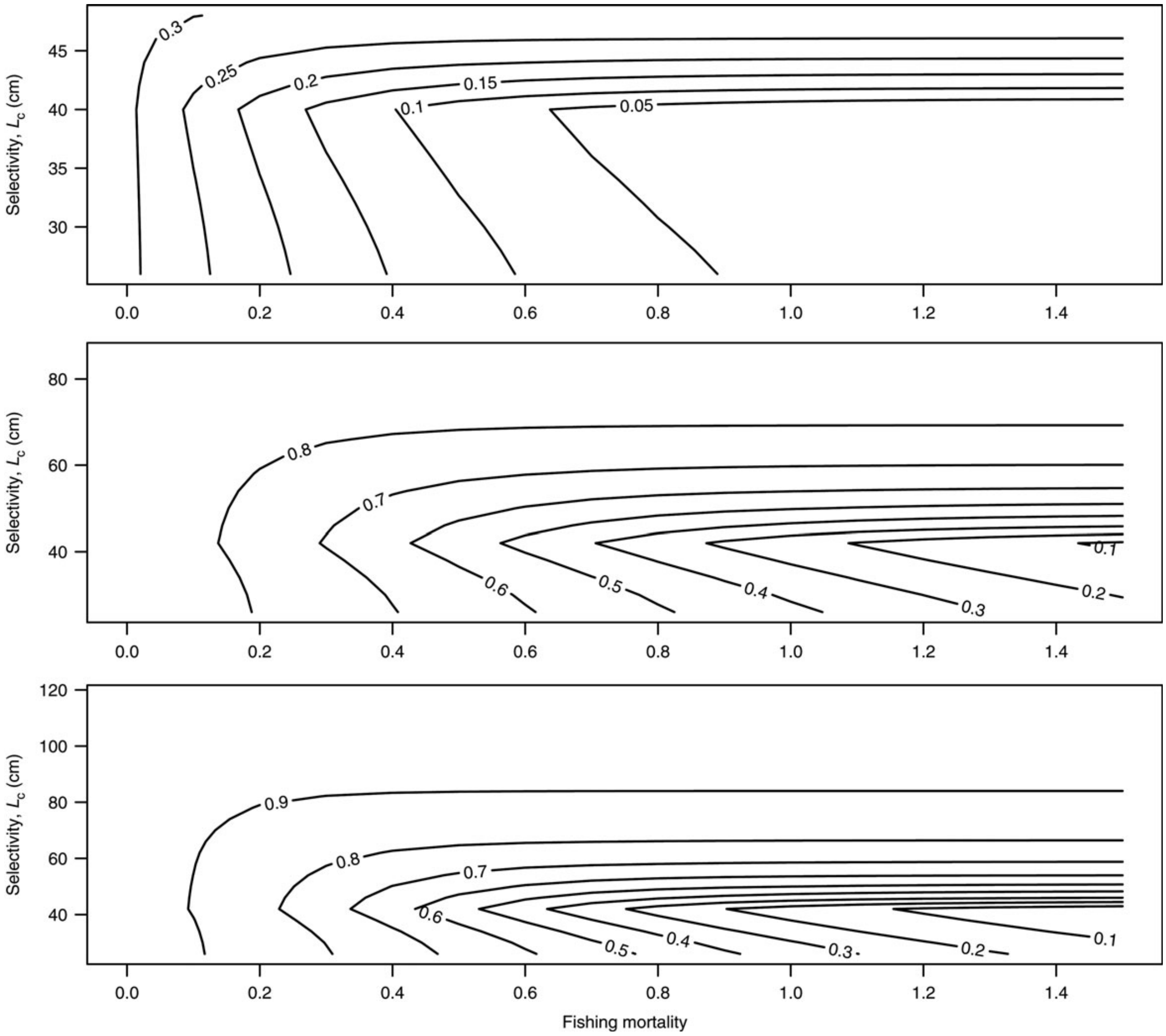

Figure 6. LFI as a function of fishing mortality, F, and selectivity, L_c, at different growth potentials: upper panel, $L_\infty = 50$; middle panel, $L_\infty = 90$; and lower panel, $L_\infty = 120$.

require more adaptation than is the case today (Laikre *et al.*, 2005). In fact, due to the strong requirements for specific adaptations for the Baltic Sea ecosystem, the importance of big and old fish might even be greater than in other areas (e.g. Cardinale and Arrhenius, 2000).

Voss *et al.* (2014) recently opened the floor for wider discussion of various management objectives besides yield maximization, i.e. profitability, conservation, and equity considerations, by trying to take account of all three major species in the Baltic Sea: cod, herring (*Clupea harengus*, Clupeidae), and sprat (*Sprattus sprattus*, Clupeidae). However, their work assumes that the production level of cod in the 1980s can be regained and retained. Even more important, they also assume that the major ecological constraint can be summarized in the Ricker stock–recruitment (SR) relationship, i.e. that the number of recruits limits the production and that cannibalism (implicit in the Ricker SR curve) should be prevented. Our approach is less fine-tuned. By using steady-state relationships developed by Beverton and Holt (1957) and acknowledging density-dependent growth, we limit our perspective to the single-species management of cod. Lowered growth potential is by far the most important factor in determining whether yield and recruits are in surplus (Svedäng and Hornborg, 2014), so cannibalism should be favoured as a means to adjust the population density of individuals under ~40 cm in length. This implies that increasing F as a means to reduce the cannibalism of recruits (ICES, 2013) is an inappropriate strategy considering the occurrence of density-dependent growth.

From a longer term perspective, ecological risk-averting strategies in fisheries may be even more important. As climate change is difficult to halt quickly, besides considering fuel use, management strategies also must focus on local mitigation. Relief from other stressors, such as fishing mortality, would be the best short-term adaptive measure to cope with synergetic stressors such as climate change and various hydrographical conditions inducing impaired cod production (MacKenzie *et al.*, 2011; Meier *et al.*, 2012).

If fisheries managers paid less attention to the total yield of the Eastern Baltic cod stock and acknowledged their role in fostering sustainable seafood production for the future, this approach would benefit both the environment and the industry.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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References

Bagge, O., Thurow, F., Steffensen, E., and Bay, J. 1994. The Baltic cod. Dana, 10: 1–24.

Baltfish. 2013. Common proposal for 2014 Baltic Seas TACs and quotas. BALTFISH High Level Group under the Latvian Presidency. http://www.fishsec.org/2014/05/07/final-discussions-on-a-discard-ban-plan-for-the-baltic-sea-discussed-in-baltfish/.

Beverton, R. 1998. The Larkin lecture: Fish, fact and fantasy: A long view. Reviews in Fish Biology and Fisheries, 8: 229–249.

Beverton, R. J., and Holt, S. J. 1957. On the Dynamics of Exploited Fish Populations. Fisheries Investment Series 2. Vol. 19. U.K. Ministry of Agriculture and Fisheries, London.

Beverton, R. J., and Holt, S. J. 1964. Tables of Yield Functions for Fishery Assessment. FAO Technical Paper Vol. 38. Fisheries Division, Biology Branch, Food and Agriculture Organization of the United Nations, Rome.

Beverton, R. J. H. 1992. Patterns of reproductive strategy parameters in some marine teleost fishes. Journal of Fish Biology, 41: 137–160.

Caddy, J. F. 2000. Marine catchment basin effects versus impacts of fisheries on semi-enclosed seas. ICES Journal of Marine Science, 57: 628–640.

Cardinale, M., and Arrhenius, F. 2000. The influence of stock structure and environmental conditions on the recruitment process of Baltic cod estimated using a generalized additive model. Canadian Journal of Fisheries and Aquatic Sciences, 57: 2402–2409.

Cardinale, M., and Hjelm, J. 2012. Size matters: Short-term loss and long-term gain in a size-selective fishery. Marine Policy, 36: 903–906.

Cardinale, M., and Svedäng, H. 2011. The beauty of simplicity in science: Baltic cod stock improves rapidly in a "cod hostile" ecosystem state. Marine Ecology Progress Series, 425: 297–301.

Casini, M., Hjelm, J., Molinero, J-C., Lövgren, J., Cardinale, M., Bartolino, V., Belgrano, A., *et al.* 2009. Trophic cascades promote threshold-like shifts in pelagic marine ecosystems. Proceedings of the National Academy of Science, 106: 197–202.

EC. 2007. Council Regulation (EC) no. 1098/2007 establishing a multi-annual plan for the cod stocks in the Baltic Sea and the fisheries exploiting those stocks, amending regulation (ECC) no. 2847/93 and repealing regulation (EC) no. 779/97; 2007.

EC. 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive).

Eero, M., Köster, F. W., and MacKenzie, B. R. 2008. Reconstructing historical stock development of the eastern Baltic cod (*Gadus morhua*) before the beginning of intensive exploitation. Canadian Journal of Fisheries and Aquatic Sciences, 65: 2728–2741.

Eero, M., Köster, F. W., and Vinther, M. 2012a. Why is the Eastern Baltic cod recovering? Marine Policy, 36: 235–240.

Eero, M., MacKenzie, B. R., Karlsdottir, H. M., and Gaumiga, R. 2007. Development of international fisheries for the eastern Baltic cod (*Gadus morhua*) from the late 1880s until 1938. Fisheries Research, 87: 155–166.

Eero, M., Vinther, M., Haslob, H., Huwer, B., Casini, M., Storr-Paulsen, M., and Köster, F. W. 2012b. Spatial management of marine resources can enhance the recovery of predators and avoid local depletion of forage fish. Conservation Letters, 5: 486–492.

Elmgren, R. 1989. Man's impact on the ecosystem of the Baltic Sea: Energy flows today and at the turn of the century. Ambio, 18: 326–332.

EU. 2013. Regulation No. 1380/2013 of the European Parliament and the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No. 1954/2003 and (EC) No. 1224/2009 and repealing Council Regulations (EC) No. 2371/2002 and (EC) No. 639/2004 and Council Decision 2004/585/EC.

FAO. 2003. Fisheries management. 2. The ecosystem approach to fisheries. FAO Technical Guidelines for Responsible Fisheries No. 4. Food and Agriculture Organization of the United Nations, Rome. 112 pp.&&

Feekings, J., Lewy, P., and Madsen, N. 2013. The effect of regulation changes and influential factors on Atlantic cod discards in the Baltic Sea demersal trawl fishery. Canadian Journal of Fisheries and Aquatic Sciences, 70: 534–542.

Garcia, S. M., Kolding, J., Rice, J., Rochet, M-J., Zhou, S., Arimoto, T., Beyer, J. E., *et al.* 2012. Reconsidering the consequences of selective fisheries. Science, 335: 1045–1047.

Grafton, R. Q., Kompas, T., and Hilborn, R. W. 2007. Economics of overexploitation revisited. Science, 318: 1601.

Hornborg, S., Nilsson, P., Valentinsson, D., and Ziegler, F. 2012. Integrated environmental assessment of fisheries management: Swedish *Nephrops* trawl fisheries evaluated using a life cycle approach. Marine Policy, 36: 1193–1201.

ICES. 2011. Report of the Working Group on the Ecosystem Effects of Fishing Activities (WGECO), 13–20 April, Copenhagen, Denmark. International Council for the Exploration of the Sea, Copenhagen. ICES CM 2011/ACOM: 24. 166 pp.

ICES. 2013. Report of the ICES advisory committee. ICES Advice, Books 1-11. International Council for the Exploration of the Sea, Copenhagen.

Jennings, S., and Le Quesne, W. J. F. 2012. Integration of environmental and fishery management in Europe. ICES Journal of Marine Science, 69: 1329–1332.

Korpinen, S., Meidinger, M., and Laamanen, M. 2013. Cumulative impacts on seabed habitats: An indicator for assessments of good environmental status. Marine Pollution Bulletin, 74: 311–319.

Köster, F. W., Möllmann, C., Hinrichsen, H-H., Wieland, K., Tomkiewicz, J., Kraus, G., Voss, R., *et al.* 2005. Baltic cod recruitment: The impact of climate variability on key processes. ICES Journal of Marine Science, 62: 1408–1425.

Laikre, L., Palm, S., and Ryman, N. 2005. Genetic population structure of fishes: Implications for coastal zone management. Ambio, 34: 111–119.

Larkin, P. A. 1977. An epitaph for the concept of maximum sustained yield. Transactions of the American Fisheries Society, 106: 1–11.

Lassen, H., Kelly, C., and Sissenwine, M. 2014. ICES advisory framework 1977–2012: From $F_{\max}$ to precautionary approach and beyond. ICES Journal of Marine Science, 71: 166–172.

Limburg, K. E., Walther, Y., Hong, B., Olson, C., and Stora, J. 2008. Prehistoric versus modern Baltic Sea cod fisheries: Selectivity across the millennia. Proceedings of the Royal Society: Biological Sciences B, 275: 2659–2665.

Lindegren, M., Andersen, K. H., Casini, M., and Neuenfeldt, S. 2014. A metacommunity perspective on source–sink dynamics and management: The Baltic Sea as a case study. Ecological Applications, 24: 1820–1832.

Lindegren, M., Möllmann, C., Nielsen, A., and Stenseth, N. C. 2009. Preventing the collapse of the Baltic cod stock through an ecosystem-based management approach. Proceedings of the National Academy of Sciences, 106: 14722–14727.

Longhurst, A. 2010. Mismanagement of Marine Fisheries. Cambridge University Press, Cambridge. 320 pp.

MacKenzie, B. R., Ojaveer, H., and Eero, M. 2011. Historical ecology provides new insights for ecosystem management: Eastern Baltic cod case study. Marine Policy, 35: 266–270.

Madsen, N. 2007. Selectivity of fishing gears used in the Baltic Sea cod fishery. Reviews in Fish Biology and Fisheries, 17: 517–544.

Meier, H. M., Andersson, H. C., Arheimer, B., Blenckner, T., Chubarenko, B., Donelly, C., Eilola, K., *et al.* 2012. Comparing reconstructed past variations and future projections of the Baltic Sea ecosystem: First results from multi-model ensemble simulations. Environmental Research Letters, 7: 034005.

Meyer, P. F. 1952. Die Dampferfischerei in der Ostsee während der Kriegsjahre 1939/45 und ihre Bedeutung für die Fischwirtschaft und Fischereiwissenschaft [The steamer fishing in the Baltic Sea during the war years 1939/45 and its importance for the fishing industry and fisheries science]. Berichte der Deutchen Wissenschaftlichen Kommission für Meeresforschung, 12: 168–209.

MSC. 2014. Websites for MSC Certification of Swedish, Danish and German fisheries for Eastern Baltic cod. http://www.msc.org/track-a-fishery/fisheries-in-the-program/certified/north-east-atlantic/sweden-eastern-baltic-cod; http://www.msc.org/track-a-fishery/fisheries-in-the-program/certified/north-east-atlantic/Denmark-Eastern-Baltic-cod; http://www.msc.org/track-a-fishery/fisheries-in-the-program/certified/north-east-atlantic/germany-eastern-baltic-cod (last accessed 26 February 2014).

Needle, C. 2012. Fleet Dynamics in Fisheries Management Strategy Evaluations. PhD thesis, University of Strathclyde. http://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.576261.

Nilsson, P., and Ziegler, F. 2007. Spatial distribution of fishing effort in relation to seafloor habitats in the Kattegat, a GIS analysis. Aquatic Conservation: Marine and Freshwater Ecosystems, 17: 421–440.

Olsen, E. M., Heino, M., Lilly, G. R., Morgan, M. J., Brattey, J., Ernande, B., and Dieckmann, U. 2004. Maturation trends indicative of rapid evolution preceded the collapse of northern cod. Nature, 428: 932–935.

Orton, D. C., Makowiecki, D., de Roo, T., Johnstone, C., Harland, J., Jonsson, L., Heinrich, D., *et al.* 2011. Stable isotope evidence for late medieval (14th–15th C) origins of the Eastern Baltic Cod (*Gadus morhua*) fishery. PLoS ONE, 6: e27568.

Österblom, H., Hansson, S., Larsson, U., Hjerne, O., Wulff, F., Elmgren, R., and Folke, C. 2007. Human-induced trophic cascades and ecological regime shifts in the Baltic Sea. Ecosystems, 10: 877–889.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. Journal du Conseil International pour l'Exploration de la Mer, 39: 175–192.

Pauly, D., Alder, J., Bennett, E., Christensen, V., Tyedmers, P., and Watson, R. 2003. The future for fisheries. Science, 302: 1359–1361.

Quinn, T. J., II, and Deriso, R. B. 1999. Quantitative Fish Dynamics. Oxford University Press, Oxford. 542 pp.

Righton, D. A., Andersen, K. H., Neat, F., Thorsteinsson, V., Steingrund, P., Svedäng, H., Michalsen, K., *et al.* 2010. Thermal niche of Atlantic cod *Gadus morhua*: Limits, tolerance and optima. Marine Ecology Progress Series, 420: 1–13.

Sinclair, A. F., Swain, D. P., and Hanson, J. M. 2002a. Disentangling the effects of size-selective mortality, density, and temperature on length-at-age. Canadian Journal of Fisheries and Aquatic Sciences, 59: 372–382.

Sinclair, A. F., Swain, D. P., and Hanson, J. M. 2002b. Measuring changes in the direction and magnitude of size-selective mortality in a commercial fish population. Canadian Journal of Fisheries and Aquatic Sciences, 59: 361–371.

Sterner, T., and Svedäng, H. 2005. A net loss: policy instruments for commercial fishing with focus on cod in Sweden. Ambio, 34: 84–90.

Svedäng, H. 2014. Comments to Froese *et al.* (2008). Size matters: Ne quid nimis. Fisheries Research, 149: 74–75.

Svedäng, H., and Hornborg, S. 2014. Selective fishing induces density-dependent growth. Nature Communications, 5: 4152.

Teschner, E. C., Kraus, G., Neuenfeldt, S., Voss, R., Hinrichsen, H-H., and Köster, F. 2010. Impact of hypoxia on consumption of Baltic cod in a multispecies stock assessment context. Journal of Applied Ichthyology, 26: 836–842.

United Nations. 2002. Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August to 4 September 2002. Technical Report No. A/CONF.199/20. United Nations, New York.

Vallin, L., Nissling, A., and Westin, L. 1999. Potential factors influencing reproductive success of Baltic cod, *Gadus morhua*: A review. Ambio, 28: 92–99.

Voss, R., Quaas, M. F., Schmidt, J. O., and Hoffmann, J. 2014. Regional trade-offs from multi-species maximum sustainable yield (MMSY) management options. Marine Ecology Progress Series, 498: 1–12.

Zeller, D., Rossing, P., Harper, S., Persson, L., Booth, S., and Pauly, D. 2011. The Baltic Sea: Estimates of total fisheries removals 1950–2007. Fisheries Research, 108: 356–363.

Ziegler, F., and Hornborg, S. 2014. Stock size matters more than vessel size: The fuel efficiency of Swedish demersal trawl fisheries 2002–2010. Marine Policy, 44: 72–81.

Ziegler, F., Winther, U., Hognes, E. S., Emanuelsson, A., Sund, V., and Ellingsen, H. 2013. The carbon footprint of Norwegian seafood products on the global seafood market. Journal of Industrial Ecology, 17: 103–116.

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