Barbara Hutniczak

PhD at the Department of Environmental and Business Economics

University of Southern Denmark, Esbjerg

Management and Economics of Resources and the Environment

Tel. +45 6550 4188 / +45 5274 6712

E-mail: bhu@sam.sdu.dk

Niels Bohrs Vej 9, DK-6700 Esbjerg, Denmark

Balancing Total Allowable Catches in a multispecies context

Abstract

A fishing vessel can be thought of as a firm which, in most cases, represents multiproduct joint production. Therefore, because of multispecies interactions, individual fishing quotas potentially create considerable negative externalities if not set in optimal proportions. Take, for example, discarding excess production at sea that results in unnecessary fish mortality or creating unbalanced predator-prey relations in the environment. This paper aims to develop a methodological framework for assessing the composition and distribution of Total Allowable Catches (TACs) in a multispecies interaction system. The model is based on the individual vessel technical efficiency dependent upon vessel characteristics and associated flexibility with respect to utilizing quotas throughout the year. These characteristics were modeled by a multiproduct distance function in which individual efficiency dictates minimum input level for a harvest that is subject to limits established by a regulatory body to prevent biological overfishing and conditional on capital endowment. The model reveals the rational reaction to initial quota allocation and provides explanation of the fact, that in some cases the TAC is not fully utilized. Furthermore, it shows potential for ecological regime shift created by regulations. An empirical application is provided for the Polish Baltic Sea fleet where the most valuable target species is cod. Multispecies interactions were incorporated as separate submodels for cod, herring, and sprat, species that are linked through predation. The regulatory body sets the annual quota based on target fishing mortality varying between scenarios. The net present value of the fishery in each scenario is compared by simulating stock changes over time.

Keywords: Baltic Sea, technical efficiency, multispecies, TAC

JEL Q22

Introduction

Individual quotas are commonly advocated tool in fisheries management. Highlighting the most important, the implementation of secure catch shares reverses the global trend towards widespread fisheries collapse (Costello, et al., 2008). In case of overall limit for the fleet in form of Total Allowable Catch (TAC), the Individual Vessel Quotas (IVQs) allow better planning at the individual vessel level and guarantee no situation of so called ‘race-to-fish’. Thus, the costs can be minimized and rents improved. However, since most of the fisheries worldwide are multispecies, setting IVQs pose a considerable problem when it comes to choosing the right allocation between various species.

The biggest threat of individual quotas set in wrong proportions is discarding of excess production at sea that result in additional fish mortality and hinders expected conservation benefits (Squires and Kirkley, 1995). In case of low selectivity, the quota set for one species has a direct effect on its bycatch. If the quota is tradable or exchangeable, the fishermen have a possibility to build up a quota portfolio closely matching their catch (Branch and Hilborn, 2008). Elsewise, one of the species becomes limiting one and the fishing activity in a given season ends or overharvest is discarded and remaining quota is fished.

On the other hand, there are evidences that in most fisheries there is some ability to target and methods for avoiding certain species (Campbell and Nicholl, 1994; Quirijns, et al., 2008). Although in case of good selectivity, there is another threat introduced by unbalancing the environment via direct control of the harvest. This distortion, in extreme cases, may cause regime shift and transition between high- and low-trophic-level fish dominance (Österblom, 2006). 'Fishing down the food web' (May, et al., 1979; Pauly, et al., 1998) may decrease the populations at the top of the food web, implying increase in prey. On the other hand, the overlooked conservation efforts regarding predator with no closer look at the prey species, may considerably decrease the stocks at lower trophic level what in turn may inhibit the recovery process through limiting the food supply. Such management-induced shift may lead to changes in regional distribution of profits and conflicts on the ground of unfairly distributed benefits associated with the management scheme or required compensation payments (Voss, et al., 2014).

Then on top, the individual behavior affected by mostly economic incentives plays a role. The non-transferable quotas, even if summing to optimal and well balanced catch composition, are only fished if a given unit finds it feasible and until it is seen profitable. Otherwise they have no value to the owner nor contribute to the net social value of the sector. The individual fisherman with allocated quotas has to make a decision that is based on expected profit. The quotas are fished only if the marginal value for the given activity is positive[1] and thus underharvest of certain quotas may be disrupting the ecosystem.

All in all, relatively little attempt has been made to coordinate TAC setting in multispecies fisheries (Sanchirico, et al., 2006), especially in the context of individual decision process. Catch-quota balancing is difficult task (Copes, 1986). Limitations in getting it right are numerous and include uncertain stock dynamics (Garza-Gil, 1998) or impact of environment (Wallace and Brekke, 1986). Thus, the common alternative to balance the system are regulations introduced alongside. Depending on the fishery, overharvest of quota has been addressed by allowing retrospective balancing, trades after landing or non-trading mechanisms. The last ones include carrying quota forward or back, fees for landings over quota, permission to surrender or discard anything over limit or cross-species quota exchanges at predefined ratios. Such mechanisms introduce flexibility regarding harvest. However, this comes at the price that may include loss of TAC management precision, risk of overexploitation or increase in administrative costs (Sanchirico, et al., 2006). Thus, getting the TAC right in the multispecies context is an important topic for investigation.

The case background

The empirical application is provided for the Polish fishing fleet in the Baltic Sea. The fishery in question relies in over 88% looking at revenue on cod (*Gadus morhua*), herring (*Clupea herengus*) and sprat (*Sprattus sprattus*) (STECF, 2013). The most valuable is cod, creating itself over 32% of total revenue. The harvest of these species is interconnected as they are often targeted by the same vessels that have a possibility to divide their effort to demersal and pelagic harvest through flexible gear change (Hutniczak, 2014).

The stocks are managed by TAC redistributed between vessels in form of non-tradable individual vessel quotas (IVQs). The distribution of TAC over years and species, together with its utilization is presented in table 1. The table highlights an interesting feature. While over last years the utilization of TAC for pelagic species increased, the cod allocation was used in lesser amount. The situation regarding pelagic species has a straightforward explanation, namely the decreasing absolute allocation and also, partially, increasing prices (Kuzebski, 2012). However, the utilization of cod TAC does not have such a direct interpretation. The quota that increased significantly in 2012 was caught in only 68%. This would be an expected implication in case of limiting capacity. But due to regulation in place, the fleet allowed to catch cod in 2011 was

[1] The marginal profit of harvesting one of the quotas can be negative if it is complement to another of positive and higher marginal value.

about 55% smaller comparing to 2012[2] (Regulation 225/1497 from December 19, 2008 [in Polish]). Thus, looking at TAC utilization together with fleet dynamics, the outcome is somewhat surprising. Therefore, the individual vessel behavior is investigated in the context of final profit that is influenced by a combination of individual efficiency, initial quota allocation and flexibility regarding substitution.

Table 1: TAC, harvest and TAC utilization for Polish fishing fleet.

Year	TAC cod	Harvest cod	TAC utilization	TAC sprat	Harvest sprat	TAC utilization	TAC herring	Harvest herring	TAC utilization
2008	11700	10082	86%	133435	55273	41%	43824	17023	39%
2009	11300	11178	99%	117424	84625	72%	39315	22528	57%
2010	13230	12191	92%	111553	58843	53%	34439	24747	72%
2011	15441	10946	71%	83680	55892	67%	29930	29763	99%
2012	21870	14836	68%	66128	63115	95%	22256	27121[(1)]	122%

NOTE. Based on series Wiadomosci Rybackie [in Polish] (issues from 2008-2013). Cod includes Eastern and Western Baltic stocks; herring includes Central and Western Baltic stocks.

[(1)] The government partially balanced herring quota in 2012 with sprat quota.

Furthermore, there are multiple advantages of combining economic and ecological factors in one model. In this case, there are clear biological interactions between mentioned species. Cod is main predator of herring and sprat, whereas these pelagic species prey on cod eggs. The cannibalism behavior among cod is also observed. Thus, the natural mortalities are not constant and for realistic results have to be set in form of appropriate relations. The development over years of the harvestable biomass for these three stocks (cod of minimum age 2, pelagic species of minimum age 1) is presented in figure 1. To specify the area of interest, the model treats three particular stocks:

- Cod in ICES subdivisions 25-32 (Eastern Baltic Cod)
- Sprat in ICES subdivisions 22-32
- Herring in ICES subdivisions 25-29 and 32 (excluding Gulf of Riga)

[2] This translates directly into capacity as the composition of the vessels not allowed to fish cod between 2009-2011 were chosen proportionately to the total numer in different size categories.

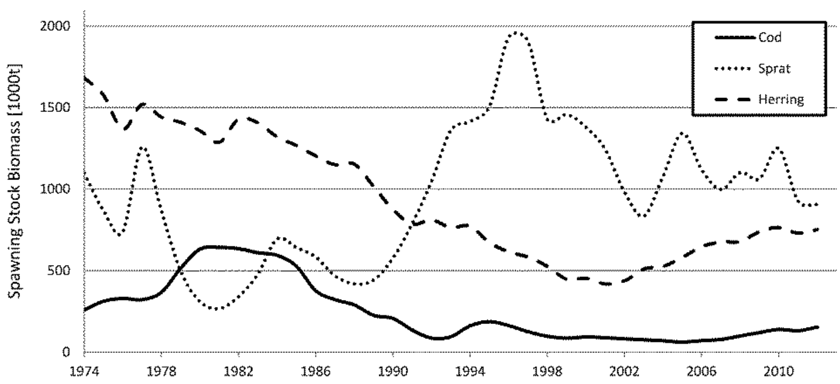


Figure 1: Historical fluctuations of the harvestable biomass.

Concluding, there are multiple links connecting these three species, both from biological and economic point of view. Thus, analyzing them apart, as well as separating their biology from economy, is significantly reducing the reliability of such model. Therefore, the model combining individual vessel profit with multispecies interactions is developed. This paper adds to the fairly abundant literature on the interconnected structure of the main Baltic Sea species thoroughly studied from the biological perspective (e.g. Sparre, 1991; Magnusson, 1995; Horobowy, 2005; Heikinheimo, 2011) or economic at aggregate fleet level (e.g. Skonhoft, et al., 2012; Nieminen, et al., 2012), while lacking link to individual harvest decisions.

The paper is structured as follows. The introduction section is followed by a presentation of a biological multispecies interaction model serving a base for a simulation of harvestable biomass of the species of interest. What follows are theoretical introduction and empirical results for estimating individual vessel efficiency what directly translates into rational harvest strategy for a given size and composition of received quotas. The paper closes with elaborated discussion on the results from the model applied to the presented case and conclusions regarding the optimal TACs distribution.

Multispecies interaction model

The paper develops the Baltic Sea multispecies interaction model to simulate changes over time in stock sizes. It includes three separate submodels for cod, herring and sprat linked through predation. Its general structure is presented in figure 2. The model assumes spatially uniform distribution of each species and lack of dependence of cod growth and reproduction rates on consumption rates. This can be interpreted as there is an alternative food source, although less preferable. Each submodel includes 8 year-classes with last category covering adults of age 8 and higher. Disaggregating adult population into multiple age categories is assumed to better describe age-structured management that imposes minimum mesh size and minimum landing size on the fishing fleets in the region and therefore welfare gains estimations are more precise (Thøgersen & Hoff, 2013; Quaas, et al., 2013).

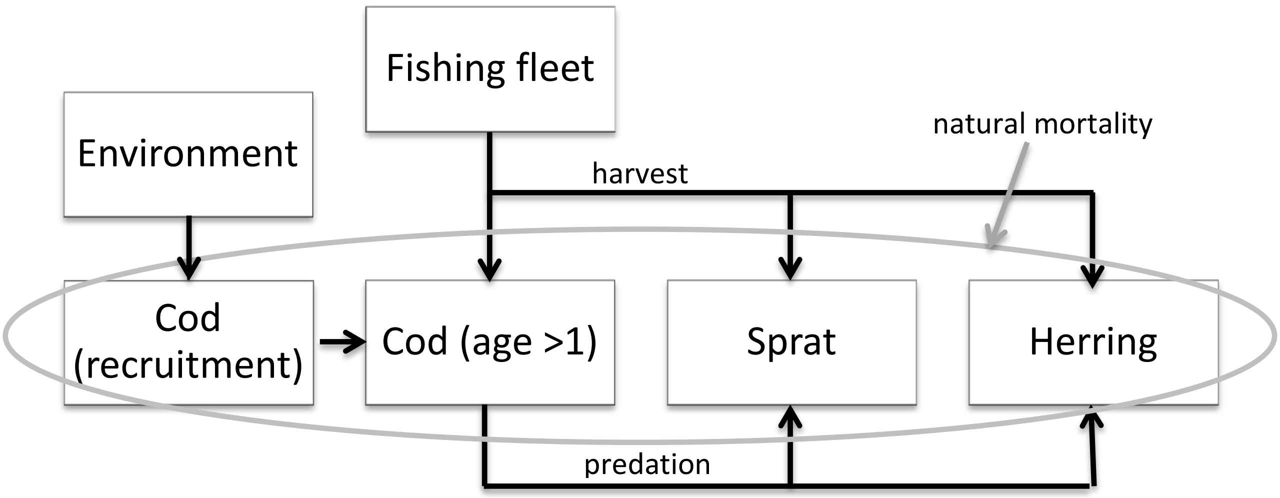


Figure 2: Model structure.

The population dynamics follows the standard age-structured modeling methodology (Tahvonen, 2009). Let i, i∊(c, h, s) denote species that are included in the model, cod, herring and sprat respectively. Let a, a=1, …, 8 denote age class and t the time period, t∊T. The recruitment of age class one dependent on Spawning Stock Biomass (SSB) is given by (Ricker, 1954). In addition, cod recruitment is found to be dependent on the environmental conditions described by average deep-water salinity (Heikinheimo, 2008) and therefore recruitment function incorporates environmental variable denoted by E. The salinity index was derived as annual average salinity in three major Baltic Sea deeps, Bornholm Deep (station BY59), Gotland Deep (station BY15) and Landsort Deep (Station BY31)[3] at depths of minimum 90m for BY5, and minimum 100m for BY15 and BY31[4], for period between April and August (spawning season) and standardized to variable with mean of zero and standard deviation of one. Heikinheimo (2008) only uses Landsort Deep, whereas major spawning areas are Bornholm and Gotland Deeps (Margonski, et al., 2010), therefore the original method is updated, similarly as in Thøgersen, et al. (2013).

The parameters are estimated using data from the Report of the Baltic Fisheries Assessment Working Group (ICES, 2013) providing annual stock assessment of major Baltic Sea species. Because ICES (2013) provides estimates for cod recruitment of age 2, equation includes two

[3] This data, that has been used within this paper, comes from the SMHI’s database SHARK (Svenskt HavsARKiv). The data has been generated within the Swedish coordinated environmental monitoring programme by the Swedish EPA.
[4] Arkona basin (BY2) was omitted as less important spawning area, however such activity is observed.

period lag. As the model considers recruits of cod at age 1, similarly to Quaas, et al. (2013), juvenile cod is assumed to have constant mortality and derived prospectively (from year ahead cod age 2) with positive natural mortality rate of 0.2 and no harvest at this age. Thus, direct cannibalism impact on juvenile cod population is disregarded. However, this factor is considered to have negligible effect on the recruitment (Uzars & Plikshs, 2000). The functional forms for recruitment are according to equations (1a) and (1b). The parameters of stock-recruitment relationship for each species, together with standard errors, are presented in table 2.

$$x_{i,a=1,t+1} = SSB_{it}\exp(\alpha_i + \beta_i SSB_{it}), \quad i \in (h,s) \tag{1a}$$

$$x_{i,a=2,t+2} = SSB_{it}\exp(\alpha_i + \beta_i SSB_{it} + \gamma E_t), \quad i \in (c) \tag{1b}$$

Here $x_{i,a,t}$ denotes a population of species i at age a and time t in number of fish.

Table 2: Recruitment functions coefficients.

Species	α	β	γ
Cod	0.430***	-1.67*10^{-3}***	0.458***
	(0.129)	(2.69*10^{-4})	(0,083)
Sprat	4.956***	-4.53*10^{-4}	NA
	(0.372)	(3.04*10^{-4})	
Herring	3.630***	-7.10*10^{-4}***	NA
	(0.157)	(1.42*10^{-4})	

NOTE. Significance levels: *** at 1%, ** at 5%, * at 10%.

The modelled SSB is derived from the latest estimation of maturity ogive (table 3). The average cod weight in SSB in the available data was about 0.91 kg. However, this value overestimates the biomass of mature cod in recent years what is due to observed in last few years significant drop of weight. The possible explanation is higher predation mortality of cod. There are evidences of impact of increasing grey seal (*Halichoerus grypus*) population on the adult stock (MacKenzie, et al., 2011) and climate change (Koster, et al., 2005). Thus, for future simulation, the average weight from last 15 years is used (ϑ_c=0.76kg). Sprat weight in SSB, as suggested by Heikinheimo (2008), appears to have a linear relationship with sprat stock ($\vartheta_{s,t}$=1.035*10^{-2}-1.019*10^{-8} $\sum_{a=1}^{8} x_{s,a,t}$), whereas herring weight log-linear relationship with cod stock of minimum age of two ($\vartheta_{h,t}$=0.016 ln($\sum_{a=2}^{8} x_{c,a,t}$)-0.063). The weights are bounded with minimum of 0.06kg for sprat, whereas minimum of 0.025kg and maximum of 0.05kg for herring.

Table 3: Maturity ogive.

Age	1	2	3	4	5	6	7	≥8
Cod	0.00	0.13	0.44	0.81	0.94	0.96	0.97	0.99
Sprat	0.17	0.93	1.00	1.00	1.00	1.00	1.00	1.00
Herring	0.00	0.70	0.90	1.00	1.00	1.00	1.00	1.00

NOTE. Based on (ICES, 2013)

Each species is subject to simultaneous fishing (F), natural mortality (M) and in case of prey species, predation (P). The development of the age classes a≥2 is given by:

$$x_{i,a+1,t+1} = exp(-F - M - P)x_{i,a,t}, \quad i \,\epsilon (h,s) \tag{2a}$$

$$x_{i,a+1,t+1} = exp(-F - M)x_{i,a,t}, \quad i \epsilon (c) \tag{2b}$$

The last age category (8) is considered a reservoir for all adults of ages ≥8[5]. The natural mortality from causes other than predation (M) is assumed constant and equal to 0.2 for all species. The exception is increased M to 0.3 for cod at age 2 at high cod stock level (over 1.2 million fish). The predation mortality of herring and sprat (P) caused by cod is modelled in form of functional responses (Heikinheimo, 2011). The rate is linearly related to number of predators and dependent on relative density of prey in the relevant age category and diet preference coefficient derived from cod stomach content composition. Thus, number of fish of species iϵ(s,h) at age a eaten by cod population of age b in year t is given by:

$$p_{i,a,b,t} = \frac{x_{c,b,t} C_b \left(\sum_{i\prime \in (s,h)} \sum_{a\prime=1}^{8} x_{i\prime,a\prime,t}\right)^n}{\left(\left(\sum_{i\prime \in (s,h)} \sum_{a\prime=1}^{8} x_{i\prime,a\prime,t}\right)^n + D_{sh}{}^n\right)} \frac{\lambda_{iab} x_{iat}}{\sum_{i\prime \in (s,h)} \sum_{a\prime=1}^{8} (\lambda_{i\prime a\prime a} x_{i\prime a\prime t})} \tag{3}$$

where C_b is maximum consumption of herring and sprat by one cod at age b, D_{sh} is half saturation constant, estimated to be 260 billion individuals[6] (Heikinheimo, 2011), n is functional response constant, assumed to be equal 2 and λ_{iab} is relative consumption preference of cod at age b over species i at age a derived according to stomach content (Tomczak, et al., 2012) as in Thøgersen, et al. (2013). The preference coefficients are presented in table 4. The annual maximum consumption of pelagic species (C_b) was estimated at 30, 100 and 135 for cod at age 1, 2 and older than 2 respectively (Heikinheimo, 2011).

[5] This implies $x_{i,8,t+1} = exp(-F - M - P)\,x_{i,7,t} + exp(-F - M - P)x_{i,8,t}$, $i \;\epsilon(h,s)$ and $x_{i,8,t+1} = exp(-F - M)\,x_{i,7,t} + exp(-F - M)x_{i,8,t}$, $i\epsilon(c)$.

[6] Size of sprat and herring stock together when consumption was half of the maximum

Table 4: Cod diet preference coefficients (λ).

	Cod age 1	Cod age 2	Cod adult (age > 2)
Sprat age 1	0.462	0.431	0.369
Sprat age ≥2	0.267	0.254	0.256
Herring age 1	0.192	0.202	0.216
Herring age 2	0.068	0.082	0.101
Herring age ≥3	0.011	0.031	0.058

NOTE. Values based on (Tomczak, et al., 2012) and (Thøgersen, et al., 2013)

Harvest

Fish stocks described by the multispecies interaction model are also subject to commercial harvest by the existing fleet. This version of the model assumes no entries, nor permanent exit, whereas introducing such a possibility is acknowledged as an interesting future extension. The maximum harvest of cod, herring and sprat within the model is given as a single species TAC. The total catch allowance is derived according to target fishing mortality under two scenarios. In the first scenario, the cod mortality follows regulations currently in place (Council Regulation (EC) No 1098/2007 for cod) whereas herring and sprat are at F equal to status quo (ICES advice 2014). Under current cod management plan, the goal in terms of F is equal to 0.3 for cod age between 4 and 7 with reduction in fishing activity assuring improvement of minimum 10% annually until the target is reached. Moreover, the yearly TAC is constructed in the way that the change between consecutive years does not exceed 15% unless it would lead to mortality higher than 0.6. The status quo values are 0.29 for sprat (age 3-5) and 0.18 for herring (age 3-6). The model applies maximum of 15% TAC change for herring and sprat as well in order to avoid high fluctuations what follows the general tendencies within EU. The second scenario assumes that TAC is chosen according to the multispecies maximum sustainable yield (MMSY) mortality for the Baltic Sea species derived by ICES (annual advice brochures). That is 0.55, 0.3 and 0.3 for cod, sprat and herring respectively, for the same age categories.

The TAC at time *t* is allocated between all eligible vessels in accordance to the redistribution system currently in use (regulation 282/1653 from December 23, 2011 [in Polish]). The total allowance of species *i* ($TAC_{i,t}$) is divided among units according to the coefficient that in turn depends on the vessel size. The redistribution coefficients are presented in table 5, whereas the allocation system is summarized by the equation:

$$q_{i,n,t} = \frac{w_{i,n} TAC_{i,t}}{\sum_{n \in N} w_{i,n}} \qquad (4)$$

Here, $q_{i,n,t}$ is individual quota of species *i* given to vessel *n* at time *t* and $w_{i,n}$ is redistribution coefficient for species *i*, assigned to the vessel *n* according to its length. The model does not permit rollover allowances[7], thus unused in a given year quota is lost. Moreover, the model carries on under full compliance with given allocation, no illegal landings are permitted.

Table 5: TAC redistribution coefficients.

Vessel length	Cod	Sprat	Herring
8-9.99m	0.40	0	0.40
10-11.99m	0.69	0	0.40
12-14.99m	0.86	0.20	0.40
15-18.49m	1	0.40	0.60
18.5-20.49	0.97	1	1
20.5-25.49	0.97	2.00	2.00
25.5-30.49	0.97	3.50	4.00
over 30.5m	0.27	4.00	4.00

NOTE. Based on Polish regulation (Dz. U. Nr 282, poz. 1653 [in Polish])

Technical efficiency

The fishing fleet consists of vessels that maximize individual profits subject to regulations, owned capital and individual technical efficiency. In this context, the regulation of particular validity is management plan allocating quotas for each species. Each unit employs effort as input. The amount of effort used defines the technical efficiency and, in turn, the feasibility of utilizing the quota allocation in full. The individual technical efficiency is derived with the use of multiproduct distance function. The production technology *P(**Y**)* represents input *e* that can produce output vector ***Y***. The multiproduct distance function with input oriented specification can be defined as (Shephard, 1970):

$$D(e,\boldsymbol{Y})^I = max\{\theta : (e/\theta) \in P(\boldsymbol{Y})\} \quad (5)$$

where $D(e,\boldsymbol{Y})^I$ is the distance from the inner boundary of the input set with following properties: it is nondecreasing, positively linear homogenous and concave in *e* and increasing in ***Y***. Frontier is where the lowest amount of effort is used to produce given landings of species included in the set ***Y***, whereas *Θ* indicates technical level of efficiency. The fully efficient firm is at the frontier what requires $D(e,\boldsymbol{Y})^I = \Theta = 1$ and therefore function $D(e,\boldsymbol{Y})^I$ can only take values ≥1. Additionally each firm is conditional on fixed input in form of capital k that describes the vessel's size. A logarithmic specification for i outputs (i,i'ϵI), one input in form of effort (e) and including time changes through dummies D_t (tϵT), for firm n at time t is given as:

$$lnD^I{}_{n,t} = \alpha_0 + \sum_{i\in I} \alpha_i \ln(y_{i,n,t}) + \alpha_e \ln(e_{n,t}) + \alpha_k \ln(k_{n,t}) + 0.5 \sum_{i\in I}\sum_{i'\in I} \alpha_{ii'} \ln(y_{i,n,t}) \ln(y_{i',n,t}) + 0.5\,\alpha_{ee} \ln(e_{n,t}) \ln(e_{n,t}) + 0.5\,\alpha_{kk} \ln(k_{n,t}) \ln(k_{n,t}) + \sum_{i\in I} \alpha_{ie} \ln(y_{i,n,t}) \ln(e_{n,t}) + \sum_{i\in I} \alpha_{ik} \ln(y_{i,n,t}) \ln(k_{n,t}) + \alpha_{ek} \ln(e_{n,t}) \ln(k_{n,t}) + \sum_{t\in T} \alpha_t D_t \quad (6)$$

[7] Carrying forward unused quota or carry back next year's allocation.

The function has imposed symmetry through condition $\alpha_{ii'}=\alpha_{i'i}$, whereas homogeneity requires $\alpha_e=1$, $\alpha_{ee}=0$, $\Sigma_{i\epsilon I}\alpha_{ie}=0$ and $\alpha_{ek}=0$. The homogeneity is imposed through normalizing the function with the effort such that:

$$\ln\left(\frac{D^{I}{}_{n,t}}{e_{n,t}}\right) = \alpha_0 + \sum_{i\in I}\alpha_i \ln(y_{i,n,t}) + \alpha_k \ln(k_{n,t}) + 0.5\sum_{i\in I}\sum_{i'\in I}\alpha_{ii'}\ln(y_{i,n,t})\ln(y_{i',n,t}) + 0.5\,\alpha_{kk}\ln(k_{n,t})\ln(k_{n,t}) + \sum_{i\in I}\alpha_{ik}\ln(y_{i,n,t})\ln(k_{n,t}) + \sum_{t\in T}\alpha_t D_t = TL(e^*, Y, k) \qquad (7)$$

The above equation can be rewritten as:

$$-\ln(e_{n,t}) = TL(e^*, Y, k) + u_n + v_{n,t} \qquad (8)$$

where $v_{n,t}$ is stochastic error term and u_n strictly positive inefficiency term[8]. The estimation goal is firm specific efficiency and therefore the time-invariant option is chosen[9]. The input specification of the distance function requires that $D^{I}_{n,t}\epsilon$<1, ∞) and therefore the term $u_n\epsilon$<0,∞). This means that with inefficiency approaching infinity, the infinite amount of input is needed to produce given output. The one-sided inefficiency term takes one of the following distributional forms: half-normal, truncated normal or exponential. The above expression may be estimated with the use of stochastic production frontier method for panel data, e.g. as described by (Pitt & Lee, 1981) assuming u_n half-normally distributed with constant variance. For the estimation procedure, the negative sign in front of the output used for normalization is omitted[10] and therefore the final coefficients need to be reversed. The derived for each vessel u_n is a measure of individual efficiency. The advantage of the method is no *ad hoc* assumption about selectivity between species. The estimated coefficients explain whether the relationship between harvested species has complementary or substitution character.

The summary of the data used to estimate the distance function is presented in table 6. The outputs include four groups of harvested species, cod (*c*), herring (*h*), sprat (*s*) and linearly aggregated group of other species (*o*). For the capital variable describing the vessel (*k*), the power of main engine was chosen. The function was simplified for the smallest vessels for which capital was excluded and harvested species included only cod (*c*) and other species (*o*), in this case covering minor pelagic harvest. The coefficients for small vessels were derived separately for units of 8-10m and 10-12m. The observation accounting for less than 24h of effort per year were excluded as lacking character of commercial harvest. Prior to estimation, the data has been scaled with the use of the sample means.

[8] Nonpositive term $u_{n,t}$ will occur in output specification since then $D_{n,t}\epsilon$(0, 1> and therefore the term $\ln D_{n,t}\epsilon$(-∞,0>.

[9] The time-specific changes in the period over which data was used are accommodated by time dummies.

[10] For the estimation purpose the value $\ln(y_1)$ is used instead of $-\ln(y_1)$. This gives better consistency of the estimates with the conventional production function (Pascoe, et al., 2007)

Table 6: Summary of the available data.

	Vessels over 12m		Vessels 10-12m		Vessels 8-10m	
	Mean	SD	Mean	SD	Mean	SD
Effort [h]	1757.781	942.780	1154.949	808.963	568.549	455.804
Harvest of cod [t]	48.621	53.699	29.610	26.206	12.787	16.392
Harvest of herring [t]	129.573	301.936	6.937	18.932	5.917	17.671
Harvest of sprat [t]	377.937	852.110	0.041	0.416	0.001	0.020
Harvest of other species [t]	36.725	69.905	22.973	33.335	8.916	16.070
Power [kW]	250.692	132.945	77.612	31.913	50.754	25.655
Number of observations	842		338		424	
Number of groups	284		128		171	

The estimation results together with standard errors adjusted for clusters identified by observation for the same vessel over years are presented in table 7. The model specification tests are available in table 8. In each case non-jointness, as well as Cobb-Douglas specification were rejected implying that using full set of second order coefficients was a right choice. The average efficiency in the fleet was about 74%, with higher standard deviation for smaller vessels. This relation is depicted in figure 3.

Table 7: Estimated distance functions coefficients.

	Vessels over 12m			Vessels 10-12m			Vessels 8-10m		
	Value	SE		Value	SE		Value	SE	
α_c	0.703	0.050	***	0.423	0.066	***	0.405	0.037	***
α_h	0.166	0.025	***						
α_s	0.152	0.025	***						
α_o	0.101	0.016	***	0.143	0.030	***	0.142	0.027	***
α_k	-0.326	0.104	***						
α_{cc}	0.105	0.018	***	0.075	0.018	***	0.064	0.011	***
α_{ch}	0.028	0.008	***						
α_{cs}	0.022	0.008	***						
α_{co}	0.002	0.006		-0.054	0.009	***	-0.029	0.008	***
α_{hh}	0.047	0.007	***						
α_{hs}	-0.012	0.003	***						
α_{ho}	0.000	0.003							
α_{ss}	0.052	0.007	***						
α_{so}	-0.011	0.003	***						
α_{oo}	0.026	0.005	***	0.011	0.010		0.005	0.009	
α_{kk}	-0.237	0.155							
α_{ck}	-0.096	0.030	***						
α_{hk}	-0.009	0.021							
α_{sk}	0.020	0.020							
α_{ok}	-0.014	0.016							
α_{2008}	-0.020	0.041		-0.149	0.063	**	0.042	0.047	
α_{2009}	-0.189	0.051	***	-0.340	0.085	***	-0.043	0.076	
α_{2010}	-0.232	0.051	***	-0.137	0.086		-0.051	0.074	
α_{2011}	-0.251	0.052	***	-0.046	0.062		0.057	0.069	
α_0	-0.359	0.057	***	0.696	0.080	***	0.663	0.058	***
σ_u	0.395	0.042	***	0.715	0.103	***	-0.043	0.076	***
σ_v	0.357	0.011	***	0.316	0.030	***	-0.051	0.074	***

Log-likelihood	-434.81		-188.37		-263.15	
u	0.267	0.132	0.403	0.376	0.401	0.368
Efficiency	0.772	0.097	0.704	0.175	0.705	0.181

NOTE. Significance levels: *** at 1%, ** at 5%, * at 10%.

Table 8: Model Specification tests.

Model specification / tested coefficients	Vessels over 12m		Vessels 10-12m		Vessels 8-10m	
Cobb-Douglas	$\chi^2_{(15)}$=733.87	***	$\chi^2_{(3)}$=81.42	***	$\chi^2_{(3)}$=70.59	***
Jointness	$\chi^2_{(7)}$=175.31	***	$\chi^2_{(1)}$=39.44	***	$\chi^2_{(1)}$=13.41	***
Time dummies	$\chi^2_{(4)}$=30.09	***	$\chi^2_{(4)}$=27.90	***	$\chi^2_{(4)}$=5.18	

NOTE. Significance levels: *** at 1%, ** at 5%, * at 10%.

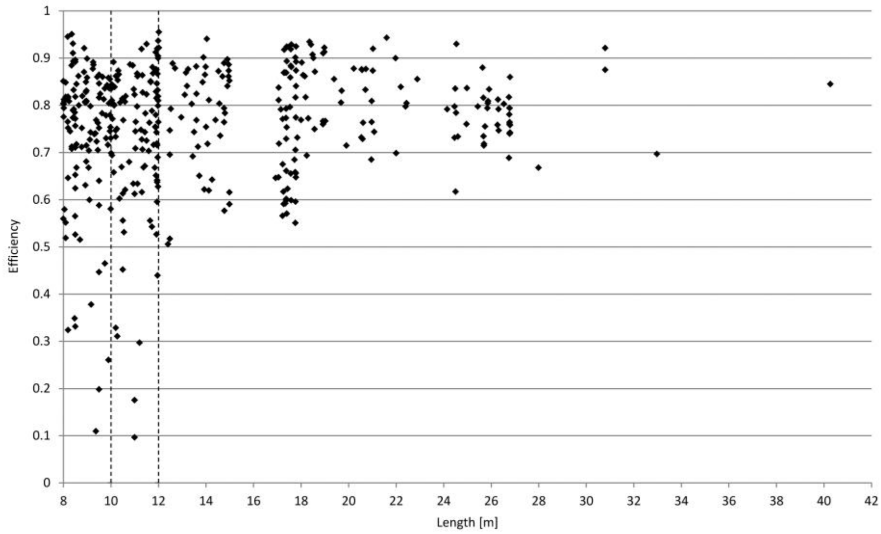


Figure 3: Estimated efficiencies according to size (vertical lines indicate split between categories of estimation).

The derived distance function estimates together with their relatively low standard errors (SE) suggest a good fit of the proposed model to the observed data. All first-order coefficients and the majority of second-order coefficients are significant. Moreover, all first-order terms, that due to scaling can be interpreted as elasticities, are observed to have expected signs. The highest value of α_c suggests that the amount of effort required to harvest one unit of cod is the highest comparing to other species. The first-order output coefficients summing to value greater than one in case of vessels over 12m indicate the presence of decreasing returns to scale at the mean (Coelli and Perelman, 2000). The opposite, the increasing returns to scale, can be observed among smaller vessels.

Positive own second-order coefficients for outputs (α_{ii}>0 for all $i\epsilon I$) imply that effort required to harvest one unit of fish volume is decreasing with the absolute volume of the given catch.

The second-order terms ($\alpha_{ii'}$ for all $i,i' \epsilon I,\ i \neq i'$) expressing substitution or complementarity character of outputs vary between output combinations what is incorporated in the individual decision model directly. Furthermore, in case of vessels group over 12m, the results suggest that vessels with more capital (bigger engine power) are more suitable for harvest of sprat, whereas cod is preferable species for smaller vessels.

Individual behavior in the model

Optimizing the individual behavior, here considered as maximizing profit, requires decision process that leads to the feasible solution with the highest revenue from landings at the lowest input level. Within this model the effort, defined as time spent at sea, is a limiting factor. Thus at each step, the expected effort for harvesting the whole set of quotas is calculated. If the required effort is below the maximum, the solution is considered feasible. Otherwise, the harvest has to be adjusted in order to meet the constraint. In this case, the adjustment is based on economic incentives and continues by decreasing the quota utilization of the species with the lowest marginal profit until the limit is met. The second harvest condition is profitability. The given quota is only utilized if the marginal profit is positive. The maximum number of days at the sea indicating the maximum effort for a given size category is 160 days for vessels over 12 m, 120 days for units between 10-12m and 90 for category 8-10m. The limitations are associated partially by regulations, but also sea condition, weather etc.

The profit of vessel n at time t is calculated as value of landings, assuming constant prices, with subtracted costs:

$$\pi_{n,t} = \rho^t \left(\sum_{i \in I} p_i y_{i,n,t} - c_{v,n} e_{n,t} - c_{f,n} \right) \tag{9}$$

where p_i indicates output prices, $y_{i,n,t}$ is harvest of species i by vessel n at time t such that $y_{i,n,t} \leq q_{i,n,t}$, c_v is variable cost per unit of effort assigned to vessel n, $e_{n,t}$ is effort of vessel n at time t and $c_{f,n}$ are annual fixed costs of vessel n. The constant ρ indicates discount factor equal to $1/(1+\delta)$ where δ is discount rate.

The variable cost used in the model is based on unit cost per day at the see, derived as a function of capital. Both variable and fixed costs are based on the sample of annual cost reports received from the Polish Marine Institute in Gdynia (Kuzebski E., personal communication). The variable cost per 24h of effort is defined as a function of capital (c_v=338+19.5k [PLN]), whereas functional form for fixed costs is c_f=356.8k [PLN]. The variable costs include fuel expenditure, maintenance, gear, ice, and other variable costs, as well as crew wages. Fixed cost sums up all other expenditures that do not depend on time spend at the sea, e.g. insurance, port fees, although exclude capital costs. Such approach equals to assuming that the investment in vessel is a sunk cost. All prices are deflated to 2010 PLN. Profits in the future are discounted with constant discount rate of 4%. The model can be extended here to include capital decay and investment possibilities, as well as exits. Then, vessels are assumed to have a positive exit incentive if the realized profit is negative.

Age-structure harvest

The derived total harvest of each species $Y_i = \Sigma_{n\epsilon N} y_{i,n}$ is separated into age categories according to:

$$h_{i,a,t} = \frac{Y_i \, sel_{i,a} x_{i,a,t}}{\sum_{a=1}^{8} sel_{i,a} x_{i,a,t} w_{i,a}} \tag{10}$$

where sel_{ia} is harvest selectivity coefficient for species i at age a and $h_{i,a,t}$ is harvest of species i of age a at time t in number of fish. This means that the separation is density dependent with certain preferences revealed by the applied fishing technique. Selectivity coefficients were derived through minimizing sum of squared residuals calculating above formula using 2008-2012 data (ICES, 2013) reflecting modern fishing tendencies, technological progress and conservation efforts (e.g. minimum mesh sizes) in recent years. To transform data to numbers, average weights in age categories were used (2008-2012). The harvest of cod is assumed to have and additional impact on the stock and therefore in order to arrive with realistic catch values, the landings were multiplied by discard rate ($d_{c,a}$,) given for each age category (based on 2010-2012 values). The harvest parameters, selectivity coefficients, weights of landings (in grams) and discard rates for cod, are presented in table 9[11].

Table 9: Harvest parameters.

Age	1	2	3	4	5	6	7	≥8
Selectivity - cod	*	0.012	0.100	0.181	0.200	0.180	0.162	0.165
Selectivity - sprat	0.051	0.099	0.129	0.139	0.131	0.144	0.151	0.154
Selectivity- herring	0.031	0.061	0.094	0.130	0.147	0.171	0.183	0.184
Weight – cod	*	682	759	874	1056	1350	1969	3108
Weight – sprat	5	9	10	11	11	11	11	12
Weight – herring	13	22	26	31	37	40	45	50
Discard rate - cod	*	2.343	1.311	1.131	1.089	1.041	1.011	1.000

NOTE. Based on ICES (2013); * indicates no harvest activity in given age category.

The fishing mortality for cod at age a and time t ($F_{c,a,t}$) was derived via solving nonlinear function including discard rate:

$$d_{c,a} h_{cat} = \frac{f_{c,a,t} x_{c,a,t} (1 - e^{-f_{c,a,t} - M})}{f_{c,a,t} + M} \tag{11}$$

[11] The surprisingly decreasing selectivity coefficient for cod at age categories starting from 6 may be explained by the fact, that such old specimens are rare, as well as potentially have a better chance to escape the net.

In case of pelagic species that are subject to predation ($p_{i,a,t} = \sum_{a\prime=1}^{8} p_{i,a,b,t}$, *i*ϵ*(s,h)*), deriving fishing mortality requires solving a system of two equations with predation mortality ($P_{i,a,t}$) as follows:

$$\begin{cases} h_{iat} = \frac{F_{i,a,t} x_{i,a,t} (1-e^{-F_{i,a,t}-P_{i,a,t}-M})}{F_{i,a,t}+P_{i,a,t}+M} \\ p_{iat} = \frac{P_{i,a,t} x_{i,a,t} (1-e^{-F_{i,a,t}-P_{i,a,t}-M})}{F_{i,a,t}+P_{i,a,t}+M}, \end{cases} \quad i \epsilon (s,h) \tag{12}$$

In each case, the constant natural mortality (M) is assumed.

Within the model framework, the stock size is assumed to affect the harvest, directly or indirectly[12]. The alternative to using catch in the multiproduct distance function is to derive measures of partial fishing mortality (Pascoe, et al., 2007). Such a measure represents a part of the stock removed by individual unit and is calculated simply as harvest divided by stock estimate in a given time period. This fact imposes implicit assumption of unitary harvest elasticity with respect to stock size which is adopted in this paper.

Simulation scope

The paper focus is the Baltic Sea harvest limited to Polish vessels. As the national fleets performing their activity in the Baltic Sea are considered varying in their activity, therefore the model does not attempt to impose *ad hoc* the generalization based on data from Poland. Instead, it looks at the limited scope in which each stock is incorporated partially, as a whole stock multiplied by scaling factor. Although it is a less realistic assumption regarding long time period simulation, it can be considered a benchmark that can be extended and updated with each new data, similarly to the concept of Bayesian Belief Networks.

Narrowing the focus requires also scaling the recruitment functions. This is done in the following way:

$$\varphi x_{i,a=1,t+1} = \varphi SSB_{it} \exp(\alpha_i + \beta_i SSB_{it}), \quad i \, \epsilon (h,s) \tag{13a}$$

$$\varphi x_{i,a=2,t+2} = \varphi SSB_{it} \exp(\alpha_i + \beta_i SSB_{it} + \gamma E_t), \quad i \, \epsilon (c) \tag{13b}$$

where φ is the scaling factor. The applied scaling assures that $SSB_{i,t}$ generating maximum recruitment for the unscaled function, once scaled, generates recruitment of equally scaled value. Furthermore, the scaling requires adjusting half-saturation constant. The scaling factor is calculated based on average 2012 Polish share of TAC in the Baltic Sea, accounting for about 30% (cod – 32%, herring – 28%, sprat – 29%). The shares are constructed in the way that each

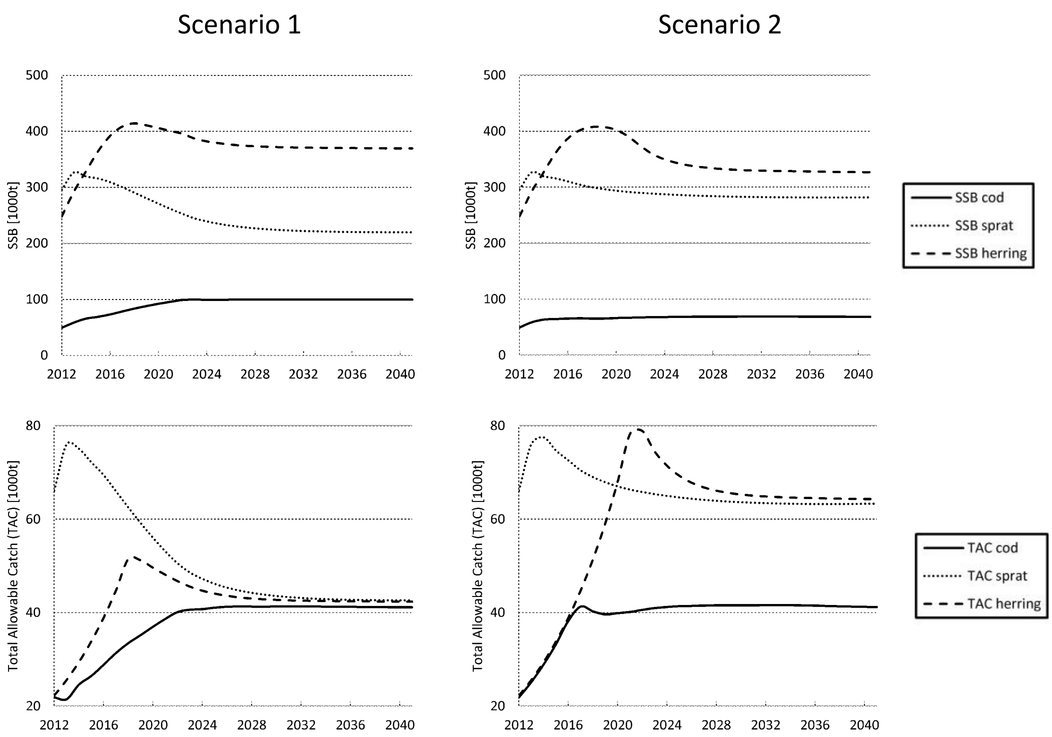
[12] The indirect effects of stock size on catch include, for example imposed regulations or gear restrictions. This can be interpreted as institutionally hampered catch at low stock sizes, especially applicable to schooling fisheries that with use of modern technologies can be found at even very low stock levels.

includes the whole allowance for a given species divided by EU allocation for the stock included in simulation[13]. This is equivalent to the assumption that the whole allowance is harvested within ICES zones 25 and 26 to which the biological model is mainly applicable.

Simulation strategy and results

The model uses 2012 age structured stock estimates by ICES (2013) as starting values. The simulation period is 30 years which is long enough to derive steady state values under given assumptions for both scenarios. In order to account for innovations and progress in fisheries over such a long period, technical change was exogenously imposed directly on efficiency level. The value chosen was 1%, as derived for bottom trawl cod fishery in Norway by Eide, et al. (2003).

The simulation results for two described scenarios are presented in form of graphs in figure 4. The results include evolution of Spawning Stock Biomass (SSB), Total Allowable Catch (TAC), TAC utilization as a comparison of TAC with expected harvest and fishing mortalities (F) for three species providing the basis for the model, cod herring and sprat.



[13] Polish TAC for Eastern and Western cod are summed and divided by EU TAC for Eastern cod stock. Similarly, for Western and Central herring stocks.

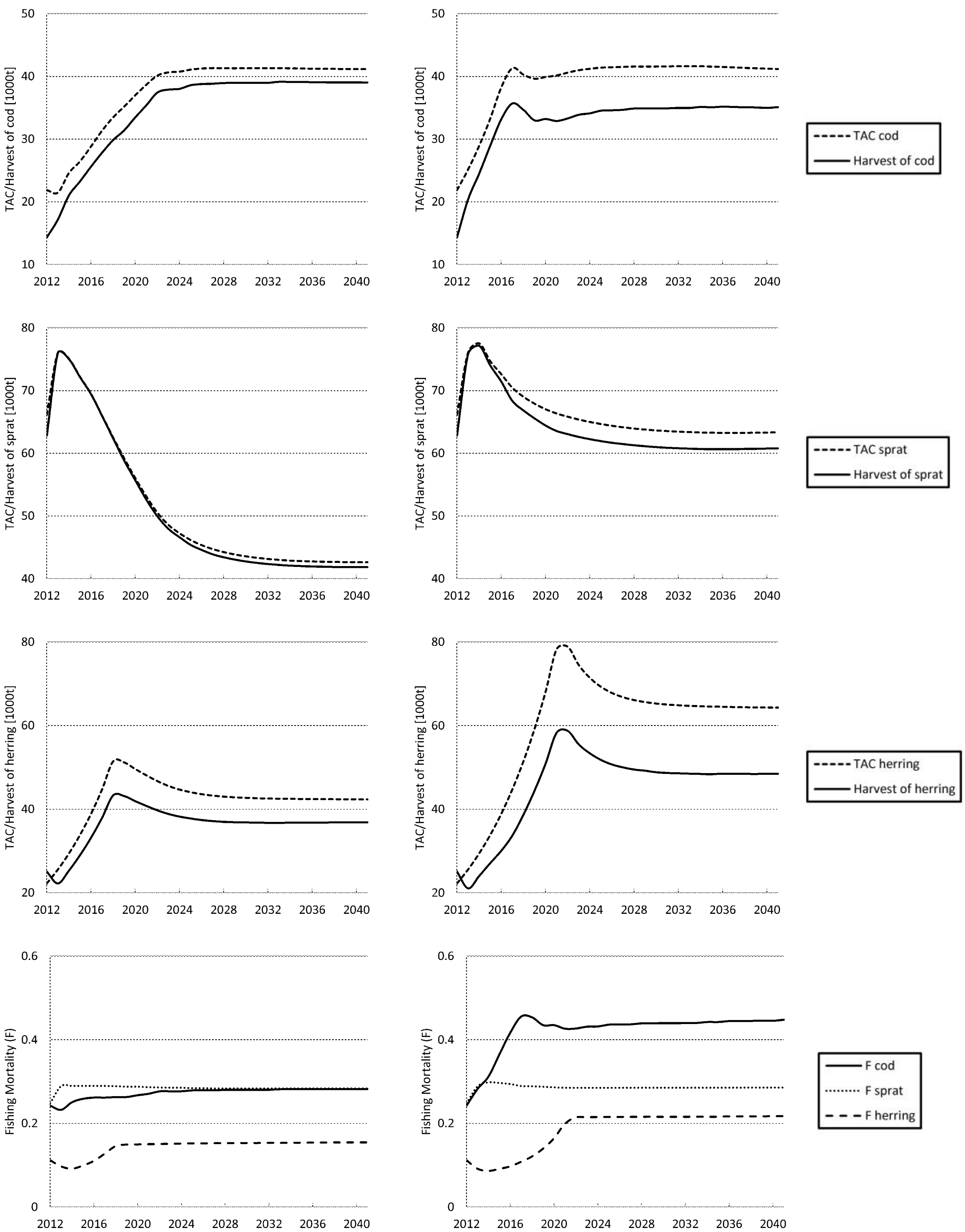


Figure 4: Graphic representation of the simulation scenarios (SSB, TAC, TAC vs. expected harvest and fishing mortalities for cod, sprat and herring).

Under scenario one, the SSB of cod doubles within about 10 years what is a result of strict cod management plan. This has a direct impact on mostly sprat, which SSB falls down to the level visibly lower comparing to scenario two. This is caused to high degree by increased predation as sprat is preferable food source for cod which stock condition is improving, whereas its status quo fishing mortality is close to MMSY. Also, under this scenario herring benefits from lower harvest and arrives at higher biomass. In scenario two, the cod stock biomass is stable and stays at level close to initial. In none of the cases the SSB falls below biologically safe limit implying no risk of collapse. The TAC for cod builds up to similar value, about 40 thousand tons, under both scenarios. However, under current management plan, the steady state occurs in a longer time horizon. The TAC for pelagic species is higher under scenario two, about 50% in each case. Thus, the scenario two can be considered as clupeid dominated.

The TAC utilization graphs show precisely the range of the gap between sum of received quota and its use. The gap is a consequence of varying harvest costs that depend on asymmetries in technical efficiency between vessels, stock condition as well as quota size itself. In case of cod, the gap exists persistently, whereas it increases its size under scenario two after few years. Similar fact can be observed in case of pelagic species what is result of higher in general quotas and therefore more flexibility regarding harvest choice. This includes harvesting more of species generating high rents, whereas surrendering quotas of lower or no positive marginal profit within the feasibility domain. Moreover, the harvest relatively closely follows the TAC pattern in each case implying that the fishery in question represents good selectivity and the individual quotas can be well targeted if it is found profitable. The implied fishing mortalities, direct result of TAC utilization, are close to the target in the scenario one, whereas in scenario two some deviance is observed.

The graphic representation of the simulation continues with comparison of discounted profits over time (figure 5). Although negligibly different (about 5% in total), the profit under scenario two is higher. The difference in monetary terms is of the range of 126 million PLN over the period of simulation.This implies that the fleet in question, given more flexibility via higher quotas is benefiting from possibility of making individual harvest choices.

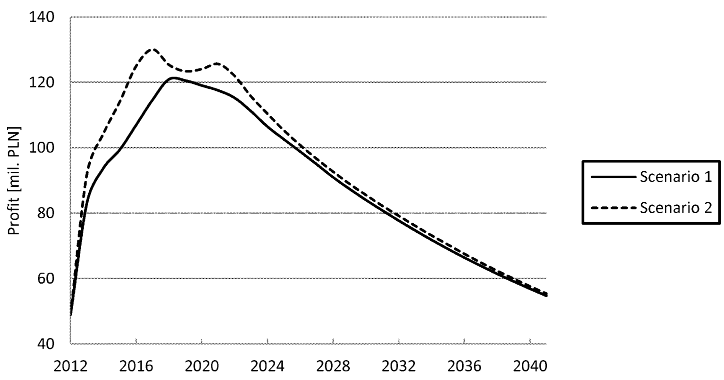


Figure 5: Comparison of profits under two investigated scenarios.

Another interesting fact revealed by the model is that under successfully carried cod management plan (scenario one), the cod IVQs not only are expected to increase in volume, but also in value. The densities of Marginal Profit (MP) from harvesting cod for three points in time for both scenarios are presented in figure 6. What can be read from the figures is that MPs under scenario one are shifting towards higher values. On the other hand, following scenario two, the densities are stable, no specific tendencies can be observed. This is a result of stock rebuilding to higher biomass and therefore lower costs of harvest.

Scenario 1 Scenario 2

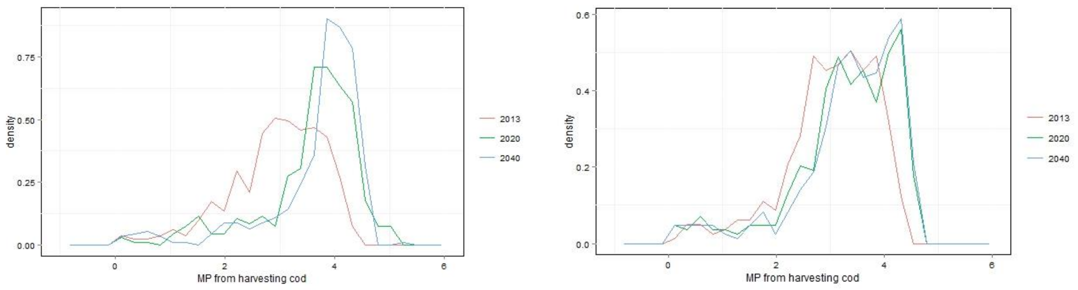


Figure 6: Marginal profit from harvesting cod at three points of simulation under two scenarios.

Concluding remarks

The purpose of this paper is twofold. Firstly, it answers to the question why TAC for the primary target species of the highest value is significantly underutilized under current regulations. Secondly, it compares the development of Polish fishery sector in the Baltic Sea under present management plan with scenario based on scientific advice (following MMSY).

The presented model is based on individual vessel efficiency derived from available log book data as a stochastic frontier function. The asymmetries between vessels with respect to harvest process are clear. The efficiency here dictates the amount of effort required to harvest given quota allocation. Each vessel is constrained by maximum time it can spend at the sea, whereas it also has a room for individual harvest decision. The model assumes economic rationality and harvest based on positive marginal profit. Following this assumption, the existence of gap between TAC and harvest is straightforward. Vessels vary in their characteristics and so do their optimum harvest choices.

The described rationality regarding harvest decision is accommodated in the multispecies model serving a basis for future biomass development prediction. The model presents realistic view of the ecosystem in question by taking into account major interactions between species, mainly predation, which has been proven to play an important role in the development of pelagic species biomass. The advantage of presented approach combining multispecies biological model with economic model of individual vessel decision is possibility to analyze the harvest choice in the context of dynamic and changing conditions where each action has its consequence for the future.

The model presents an argument that the regulations and tendencies regarding TAC currently in place may be too strict and relaxing it would be beneficial for the fleet profitability without putting species in question into risk of collapse. Increasing fishing mortalities to the levels recommended within MMSY framework safeguards the future reproduction potential of the stocks and assures healthy populations while having positive impact on the fishing sector. The model shows that restrictive regulations, going even further than scientific advice, do not have to have a positive ecosystem impact while causing loss of profits. The results imply that the fleet in question, given more flexibility via higher quotas, is benefiting from possibility of making individual harvest choices rather than being fully constrained by IVQs. Moreover, if the profit results are close between scenarios, the more flexible option may have additional advantages. These potentially include lower management costs, decrease in cost of enforcement (e.g. monitoring, observers onboard) or faster improving efficiency by adapting to individually chosen target species group.

Furthermore, the cause for concern is development of marginal values of cod quota. In the current management plan scenario the marginal price of cod builds up gradually over years. In context of general tendency to introduce Individual Transferable Quotas (ITQs) worldwide, the IVQ hold at the current moment may be considered an asset of increasing value over next years. This, in turn, may be a reason the vessels are reluctant to exit. Thus, fleet dynamics and fleet structural changes may play an important role in the situation evolvement under both scenarios. On top, there are individual, not strictly economic preferences, affecting the complex fishermen behavior. The variations falling in the model under error term cannot be accommodated in the simulation. Last but not least is a range of outcomes change depending on the environmental factor trends. The salinity index used here can be directly linked to global warming and give long term predictions based on climate change scenarios.

Concluding, the developed model combining biological interactions with economic incentives, although complex, is still traceable and gives realistic results for the long-term predictions. It presents advanced methodology that can be considered a management tool for setting appropriate targets for fishery policies. Its advantage is evaluation of expected outcomes both in terms of biomass development as well as profits. The paper finalizes with recommendation relevant to the fishery in question. In particular, it suggests relaxing the regulation regarding cod in the Baltic Sea.

Literature

Branch, T. & Hilborn, R., 2008. Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behavior under individual transferable quotas. *Canadian Journal of Fisheries and Aquatic Sciences,* pp. 1435-1446.

Campbell, H. & Nicholl, R., 1994. Can Purse Seiners Target Yellowfin Tuna?. *Land Economics,* 70(3), pp. 345-353.

Coelli, T. & Perelman, S., 2000. Technical efficiency of European railways: a distance function approach. *Applied Economics,* 32(15), pp. 1967-1976.

Copes, P., 1986. A critical review of the individual quota as a device in fisheries management. *Land Economics,* 62(3), pp. 278-291.

Costello, C., Gaines, S. & Lynham, J., 2008. Can Catch Shares Prevent Fisheries Collapse?. *Science,* Volume 321, pp. 1678-1681.

Eide, A., Skjold, F., Olsen, F. & Flåten, O., 2003. Harvest Functions: The Norwegian Bottom Trawl Cod Fisheries. *Marine Resource Economics,* Volume 18, pp. 81-94.

Garza-Gil, D., 1998. ITQ Systems in Multifleet Fisheries, An Application for Iberoatlantic Hake. *Environmental and Resource Economics,* Volume 11, pp. 79-92.

Heikinheimo, O., 2008. Average salinity as an index for environmental forcing on cod recruitment in the Baltic Sea.. *Boreal Environment Research,* Volume 13, pp. 457-464.

Heikinheimo, O., 2011. Interactions between cod, herring and sprat in the changing environment of the Baltic Sea: A dynamic model analysis. *Ecological Modelling,* Volume 222, pp. 1731-1742.

Horobowy, J., 2005. The dynamics of the Baltic fish stocks based on a multispecies stock production model. *Journal of Applied Ichthyology,* Volume 21, pp. 198-204.

Hutniczak, B., 2014. Increasing pressure on unregulated species due to changes in Individual Vessel Quotas: an empirical application to trawler fishing in the Baltic Sea. *Marine Resource Economics,* 29(3).

ICES, 2013. *Report of the Baltic Fisheries Assessment Working Group (WGBFAS),* Copenhagen: ICES.

Koster, F. et al., 2005. Baltic cod recruitment - the impact of climate variability on key processes. *ICES Journal of Marine Science,* Volume 62, pp. 1408-1425.

Kuzebski, E., 2012. Połowy bałtyckie w 2011 roku.. *Wiadomości rybackie [in Polish],* Volume 186, pp. 5-7.

MacKenzie, B., Eero, M. & Ojaveer, H., 2011. Could Seals Prevent Cod Recovery in the Baltic Sea?. *PLoS ONE,* 6(5), p. e18998.

Magnusson, K., 1995. An overview of the multispecies VPA - theory and applications. *Reviews in Fish Biology and Fisheries,* 5(2), pp. 195-212.

Margonski, P., Hansson, S., Tomczak, M. & Grzebielec, R., 2010. Climate influence on Baltic cod, sprat, and herring stock–recruitment relationships. *Progress in Oceanography,* Volume 87, pp. 277-288.

May, R. et al., 1979. Management of Multispecies Fisheries. *Science,* 205(4403), pp. 267-277.

Nieminen, E., Lindroos, M. & Heikinheimo, O., 2012. Optimal Bioeconomic Multispecies Fishery Management: A Baltic Sea Case Study. *Marine Resource Economics,* Volume 27, pp. 115-136.

Österblom, H., 2006. *Complexity and Change in a Simple Food Web– Studies in the Baltic Sea (FAO Area 27.IIId),* Stockholm: Stockholm University.

Pascoe, S., Koundouri, P. & Bjørndal, T., 2007. Estimating Targeting Ability in Multi-Species Fisheries: A Primal Multi-Output Distance Function Approach. *Land Economics,* 83(3), pp. 382-397.

Pauly, D. et al., 1998. Fishing down marine food webs. *Science,* Volume 279, pp. 860-863.

Pitt, M. & Lee, L., 1981. The Measurement and Sources of Technical Inefficiency in the Indonesian Weaving Industry. *Journal of Development Economics,* Volume 9, pp. 43-64.

Quaas, M., Klauer, B., Petersen, T. & Schiller, J., 2013. *Windows of opportunity for sustainable fisheries management: The case of Eastern Baltic cod.* Cambridge, Bioecon.

Quaas, M. et al., 2013. Incentives for Optimal Management of Age-Structured Fish Populations. *Resource and Energy Economics,* Volume 35, pp. 113-134.

Quirijns, F., Poos, J. & Rijnsdrop, A., 2008. Standardizing commercial CPUE data in monitoring stock dynamics: accounting for targeting behaviour in mixed fisheries.. *Fisheries Research,* Volume 89, pp. 1-8.

Ricker, W., 1954. Stock and Recruitment. *Journal of the Fisheries Research Board of Canada,* 11(5), pp. 559-623.

Sanchirico, J., Holland, D., Quigley, K. & Fina, M., 2006. Catch-quota balancing in multispecies individual fishing quotas. *Marine Policy,* Volume 30, pp. 767-785.

Shephard, R., 1970. *Theory of Cost and Production Functions.* Princeton, NY: Princeton University Press.

Skonhoft, A., Vestergaard, N. & Quaas, M., 2012. Optimal Harvest in an Age Structured Model with Different Fishing Selectivity. *Environmental and Resource Economics,* Volume 51, pp. 525-544.

Sparre, P., 1991. Introduction to multispecies virtual population analysis. *ICES Marine Science Symposia,* Volume 193, pp. 12-21.

Squires, D. & Kirkley, J., 1995. Resource rents from single and multispecies individual transferable quota programs. *ICES Journal of Marine Science,* Volume 52, pp. 153-164.

STECF, 2013. *The 2013 Annual Economic Report on the EU Fishing Fleet (STECF-13-15),* Luxembourg: Publications Office of the European Union.

Tahvonen, O., 2009. Economics of harvesting age-structured fish populations. *Journal of Environmental Economics and Management,* Volume 58, pp. 281-299.

Thøgersen, T. & Hoff, A., 2013. *Age structure in dynamic bio-economic models: Is there anything to gain?,* Copenhagen: Department of Food and Resource Economics, University of Copenhagen.

Thøgersen, T., Hoff, A. & Frost, H., 2013. *Fisheries management responses to climate changes in the Baltic Sea,* Copenhagen: Department of Food and Resource Economics, University of Copenhagen.

Tomczak, M., Niiranen, S., Hjerne, O. & Blenckner, T., 2012. Ecosystem flow dynamics in the Baltic Proper—Using a multi-trophic dataset as a basis for food–web modelling. *Ecological Modelling,* Volume 230, pp. 123-147.

Uzars, D. & Plikshs, M., 2000. Cod (Gadus morhua L.) cannibalism in the Cental Baltic: interannual variability and influence of recruit abundance and distribution. *ICES Journal of Marine Science,* Volume 57, pp. 324-329.

Voss, R., Quaas, M., Schmidt, J. & Hoffmann, J., 2014. Regional trade-offs from multi-species maximum sustainable yield (MMSY) management options. *Marine Ecology Progress Series,* Volume 498, pp. 1-12.

Wallace, S. & Brekke, K., 1986. Optimal Fleet Size When National Quotas can be Traded. *Marine Resource Economics,* 2(4), pp. 315-329.