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Towards Ecosystem Based Management of Fisheries: What Role can Economics Play

Optimal Quota Allocation in Multispecies Environment

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Abstract

Multispecies fisheries pose a considerable management difficulty with respect to quota allocation between species. The applicability is to single vessel and its individual quotas, as well as to the fleet as a whole. Negative externalities may be created if Total Allowable Catches (TACs) are not set in optimal proportions. That includes creation of unbalanced predator-prey relationships in the environment. This paper aims to develop a methodological framework for assessing the composition and distribution of TACs within heterogeneous fleet in a multispecies interaction system. The model is based on the individual technical efficiency dependent upon the vessel characteristics and associated flexibility with respect to utilizing quotas throughout the year. An empirical application is provided for the Polish Baltic Sea fleet, where the most valuable target species is cod. Multispecies interactions are incorporated as separate submodels for cod, herring, and sprat species, which are linked through predation. The regulatory body sets the annual quota based on the target fishing mortality varying between scenarios. The net present value of the fishery in each scenario is compared by simulating stock changes over time and paired with stock collapse probability estimates.

INTRODUCTION

Individual quotas are commonly advocated tools in fisheries management. It is believed that the implementation of secure catch shares reverses the global trend toward widespread fisheries collapse [1]. In the case of overall limits for the fleet in the form of Total Allowable Catch (TAC), the Individual Vessel Quotas (IVQs) allow better planning at the individual vessel level and guarantee that 'race to fish' situations do not occur. Thus, the costs can be minimized and rents improved. However, because most of the worldwide fisheries are multispecies, setting IVQs pose a considerable problem with respect to choice of allocation between various species.

The biggest threat of individual quotas in multispecies fisheries with joint production is the discard of excess production at sea that results in additional fish mortality and hinders the expected conservation benefits [2]. In cases of low selectivity, the quota set for one species has a direct effect on its bycatch. However, there is evidence that many fisheries exhibit some ability to target and avoid certain species [3-5]. In cases of good selectivity, there is yet another threat introduced by unbalancing the environment via direct control over the harvest. In extreme cases, this distortion may cause a regime shift and transition between high and low trophic level fish dominance [6,7]. 'Fishing down the food web' [8,9] may decrease the populations at the top of the food web, implying an increase in prey. By contrast, the overlooked conservation efforts regarding predators with no closer look at the prey species may considerably decrease the stocks at lower trophic levels, which in turn may inhibit the recovery process through limiting the food supply [10].

Moreover, the economic conditions for the multispecies fishery are often not well understood and therefore ignored when formulating new fishing guidelines [7]. Analyzing interacting species apart, as well as separating their biology from economy, significantly reduces the model reliability for defining management goals. A management-induced shift may lead to changes in the regional distribution of profits and conflicts on the ground of unfairly distributed benefits associated with the management scheme or required compensation payments [11]. The individual economic incentives also play a great role. The quotas are only fished if a given unit finds it feasible and until it is seen as profitable. Otherwise, they have no value to the owner and do not contribute to the net social value of the sector. The underharvest of certain quotas and spillovers into different fisheries may occur as an undesirable consequence. Thus, there are multiple advantages of combining economic and ecological factors in one model [12]. However, relatively little attempt has been made to coordinate the TAC setting in multispecies fisheries [13], particularly in the context of individual decision-making processes. Against this background, the objective of this article is to present a methodology for multispecies modeling with integrated ecological and economic realism. The developed model incorporates predator-prey interactions and joint fishery production by heterogeneous fleet. The purpose is to evaluate the long term implications of the imposed regulations that can be used for better policy guidance. The utilization of specific TAC composition is examined in terms of profitability and probability of any of the stock collapse.

The developed model is applied to the Baltic Sea case where there are multiple links connecting cod, herring and sprat, both from an ecological and economic point of view. There are clear biological interactions between the mentioned species with cod being the main predator of herring and sprat. On the other hand, the possibility of spillovers to other fisheries must be taken into account when considering individual fisherman decisions on harvest. 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. The management objective, on the other hand, is to ensure the profitability while maintaining minimum risk of stock collapse.

This paper adds to the fairly abundant literature on the interconnected structure of the main Baltic Sea species that have been thoroughly studied from a biological perspective [14-17] or economic perspective at the aggregate fleet level [18,19,11]; however, previous studies lack the link to individual harvest decisions.

CASE BACKGROUND

The investigated case is the central Baltic Sea with its interacting fish community dominated by three species: cod (*Gadus morhua*), herring (*Clupea herengus*) and sprat (*Sprattus sprattus*) [20]. Cod plays an important structuring role in this ecosystem as a top predator of herring and sprat. By contrast, herring and sprat, species belonging to the clupeid family, prey on cod eggs, thus creating a feedback loop that strongly ties these species together. The reproductive success of Baltic Sea cod is also strongly dependent on hydrographic conditions, particularly on the salinity and oxygen concentration in spawning areas. These areas depend on irregular water inflows from the North Sea [21,22].

In the past several decades, the stocks of cod and sprat have shown strong fluctuations in spawning stock biomass (SSB), whereas herring SSB was decreasing until the early 2000s and then started to improve thereafter (fig. 1). The presented figure clearly shows, starting in the 1980s, the transition from predator-dominated environment to an ecosystem that is characterized by a high abundance of planktivorous species, in this case mainly sprat [23]. This transition can be considered as an ecological regime shift [24].

The cause of the shift was mainly the significant increase in fishing pressure on cod, starting in the 1980s, due to improvements in technology, an increase in harvest capacity and an increase in fishing effort [25]. The deteriorating condition of the stock became a growing concern at the end of the 1990s, and a series of management plans with objectives to increase biomass and maintain reproductive potential were introduced [26]. The latest management plan that is currently enforced (Council Regulation 1098/2007) is an integral part of the Common Fisheries Policy (CFP). It establishes specific procedures regarding the distribution and enforcement of total allowable catches (TACs) that are set on an annual basis according to the target fishing mortality. The TACs for sprat and herring are set following the International Council for the Exploration of the Sea (ICES) recommendation based on the maximum sustainable yield (MSY) approach. The allocation between the European Union (EU) members is based on the principle of relative stability, which implies that each country receives a fixed share of each TAC [27]. The distribution of national TAC between vessels or individual fishermen is the responsibility of individual EU countries.

The TACs given to Poland, a member of the EU since 2004, are redistributed between vessels in the form of IVQs, based on the vessel's length [28]. The Polish fishery in the Baltic Sea accounts for over 88% when looking at the revenue of cod, herring and sprat [29]. The most valuable is cod, which alone creates over 32% of the total revenue. However, although cod is the most important commercial fishery, its TAC is underutilized over the last years, reaching as low as 68% in 2012 [30]. This may be related to the fact that the harvest of cod, herring and sprat is interconnected, as they are often targeted by the same vessels that have the option to divide their effort to demersal and pelagic harvest through flexible gear changes [31].

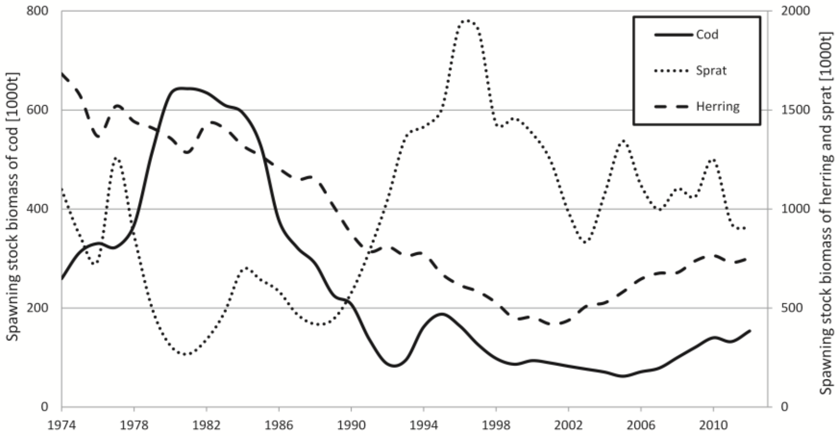


Fig. 1: Historical fluctuations of the spawning stock biomass of cod (Eastern Baltic stock), sprat (Baltic stock) and herring (Central Baltic stock).

METHODOLOGY

Multispecies Interaction Model

The purpose of the multispecies interaction model is to realistically simulate changes over time in stock sizes by taking the ecosystem structure into consideration. The developed model includes three separate dynamically updating submodels for cod, herring and sprat linked through predation. In addition, the sensitivity of cod to the salty water inflows from the North Sea is incorporated in the model by adding the salinity index describing the environmental conditions. The model follows methodology by Heikinheimo [7], whereas the parameters are reestimated using the latest data [32]. Its general structure is presented in figure 2.

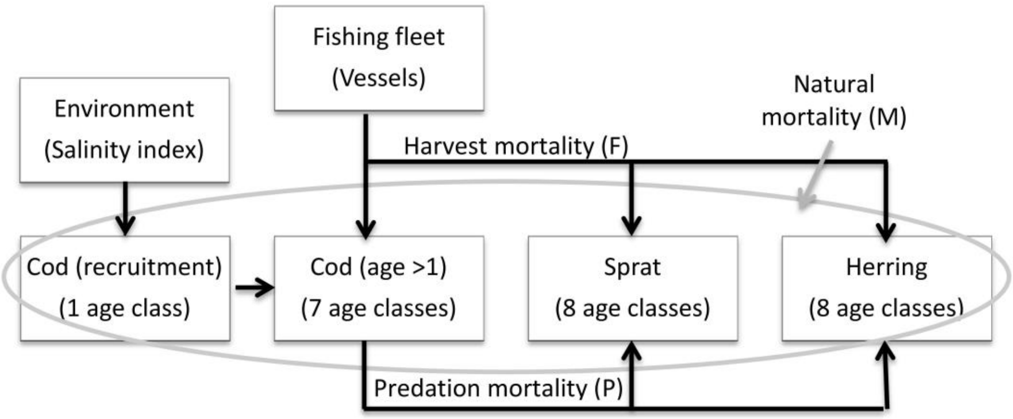


Fig. 2: Model structure.

Harvest under Two Management Scenarios

Fish stocks described by the multispecies interaction model are also subject to commercial harvest by the existing fleet. 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 harvest control rules (HCRs) based on target fishing mortality (F) 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 2013). Under the current cod management plan, the goal in terms of *F* is equal to 0.3 for cod ages between 4 and 7 with reduction in fishing activity assuring improvement of a minimum of 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 a maximum of a 15% TAC change for both herring and sprat to avoid high fluctuations, following the general tendencies within the EU. The second scenario assumes that TAC is chosen according to the multispecies maximum sustainable yield (MMSY) mortality rate for the Baltic Sea species derived by the ICES (ICES advice 2013). These values are 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 with 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 allocation system is summarized by the equation 1:

$$q_{i,n,t} = \frac{w_{i,n} TAC_{i,t}}{\sum_{n \in N} w_{i,n}} \qquad \text{(Eq. 1)}$$

where $q_{i,n,t}$ 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,[a] and thus unused quotas in a given year are lost. Moreover, the model proceed under full compliance with the given allocations.[b] The redistribution coefficients in the model are based on values currently in use.

Individual Behavior

The individual vessel ($n \epsilon N$) is considered here a decision unit optimizing its own behavior that is simplified to assume profit maximization.[c] The profit is calculated as revenue form landings with deducted costs that depend on the input level, defined as time spent at sea. Input, in turn, is a function of harvest and individual technical efficiency. The firm's efficiency is a measure of the input requirement for a given set of outputs derived as a deviation from the best-practice frontier. Allowing for impact of random factors (e.g. weather), the specific values for a given fleet can be derived with a use of a stochastic frontier function. As within the model framework the stock size is assumed to affect the harvest, catch in the estimation is replaced by partial fishing mortality [33]. The advantage of the method is that specifying flexible functional form such as translog there is no *ad hoc* assumption about selectivity between species. In addition, the model assumes the upper bound for effort denoted by $\widetilde{e_n}$ that can be considered a feasibility constraint. Thus, the harvest plan is adjusted from initial quota allocation according to economic incentives (profitability criteria) and subject to effort restriction (feasibility criteria). This can be stated in mathematical terms, assuming constant prices and added cost variables, as follows:

$$\max \pi_{n,t} = \sum_{i \in I} p_i \, y_{i,n,t} - c_{v,n} e_{n,t}(\boldsymbol{Y_{n,t}}, u_n) - c_{f,n} \qquad \text{(Eq. 2)}$$

subject to:

$$y_{i,n,t} \leq q_{i,n,t} \qquad \text{(Eq. 2a)}$$

$$e_{n,t} \leq \widetilde{e_n} \qquad \text{(Eq. 2b).}$$

The final profit of the vessel is based on landing composition denoted by vector $\boldsymbol{Y_{n,t}}$, which defines the effort applied by vessel n at time t ($e_{n,t}$). Regarding further notations, p_i indicates the price of output i, $y_{i,n,t}$ is the harvest of species i by vessel n at time t bounded by quota allocation $q_{i,n,t}$, c_v is variable cost per unit of effort assigned to vessel n, and $c_{f,n}$ are annual fixed costs[d] of vessel n. By optimizing equation 2, subject to constraints 2a and 2b, the solution is individual vessel optimum harvest choice, later denoted by $y^*_{i,n,t}$.

Management Objectives

The management objective is to ensure the profitability while maintaining minimum risk of stock collapse. The intertemporal profit in the fishing industry can be assessed by aggregating value of discounted annual profits of each unit over time:

$$NPV = \sum_{t \in T} \sum_{n \in N} \rho^t \pi^*_{n,t} \qquad \text{(Eq. 3).}$$

Here, the NPV is the net present value of the fishery under evaluated management plan and $\pi_{n,t}^*$ is optimized individual profit according to equation 2. The constant ρ indicates a discount factor.
On the other hand, the biomass development is uncertain. The stochasticity of biological factors has been highlighted already by Reed [34], Ludwig and Walters [35], whereas environmental uncertainty has been stressed by Beddington and May [36]. The presented model includes the environmental variable that value is uncertain and fluctuates randomly. In addition, the recruitment function coefficients with their standard errors provide uncertain outcome on a yearly basis. For the purpose of evaluating the second objective, not putting species into risk of collapse, the environmental factor is introduced as a variable with a standard normal distribution. Moreover, the recruitment function coefficients with the given standard errors produce fluctuations in the stock size. The simulation of the management scenario identifies the risk posed on the environment by determining the probability of reaching an undesirable state by following the established HCR based on target fishing mortality. The manager sets the TAC according to HCR already in place, whereas the recruitment creating the youngest harvestable year class is based on stochastic parameters that in turn are based on derived distributions. Thus, the TAC choice is based on currently available information and the most probable outcome, whereas the final result in a given year is random. However, assuming that the TAC is set annually, the management in place can be considered adaptive [37], as total catch is adjusted every year to meet the management plan target as close as possible. The risk potential is evaluated as the probability of reaching the limit reference points for SSB set by the ICES and the probability of stock collapse. The limit reference point in terms of SSB refers to the minimum spawning biomass, which permits a long-term sustainable exploitation of the stock. The levels below are considered to be possibly dangerous for the capacity of self-renewal of the stock [38].

DATA

Detailed data on harvest by the Polish fishing fleet in the Baltic Sea is obtained from the Polish Fisheries Monitoring Centre in Gdynia for the period 2008-2012. The available logbooks contain information at the individual vessels level on harvest volumes (fresh weight) by species, vessel parameters and effort derived as the time the vessel spent at sea, i.e., from the time of leaving the port until return. Landing prices in the model originate from the supplementary material of the 2013 Annual Economic Report on the EU Fishing Fleet available through the Scientific, Technical and Economic Committee for Fisheries (STECF). Both variable and fixed costs (excluding capital cost) are derived as a function of capital and based on the 2010 sample of annual cost reports received from the Polish Marine Institute in Gdynia (Kuzebski E., personal communication). The maximum number of days at sea indicates the maximum effort for a given size category within the model: 160 days for vessels over 12 m, 120 days for units between 10-12 m and 90 for category 8-10 m. The limitations are associated partially by regulations, as well as sea conditions, weather, etc.

RESULTS

Fleet Heterogeneity

The individual efficiencies are estimated with the use of input oriented stochastic frontier (the ’sfpanel’ package for Stata [39]). Separate models were used for three length categories, as vessels of length 8-10 m and 10-12 m represent a different type of fishery that has limited focus on pelagic harvest. The fleet in question presents a considerable degree of heterogeneity in input efficiency what can be clearly seen in figure 3. The average efficiency in the fleet in 2012 was approximately 76%, with higher deviation for smaller vessels.

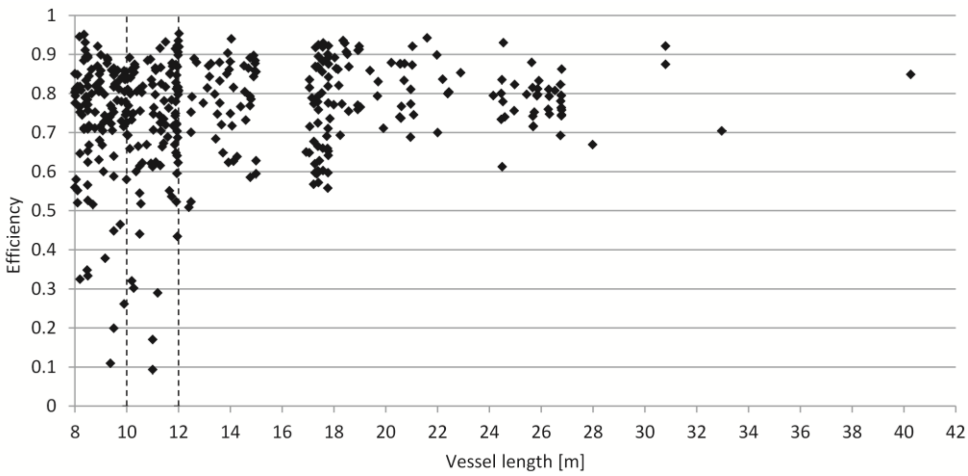
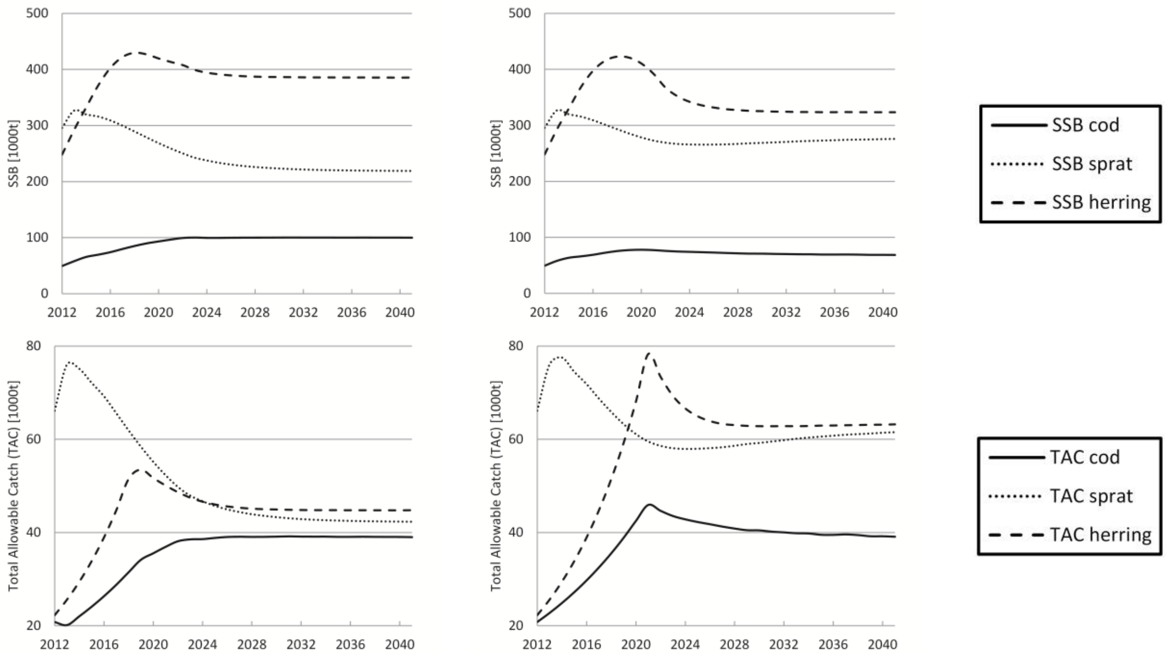
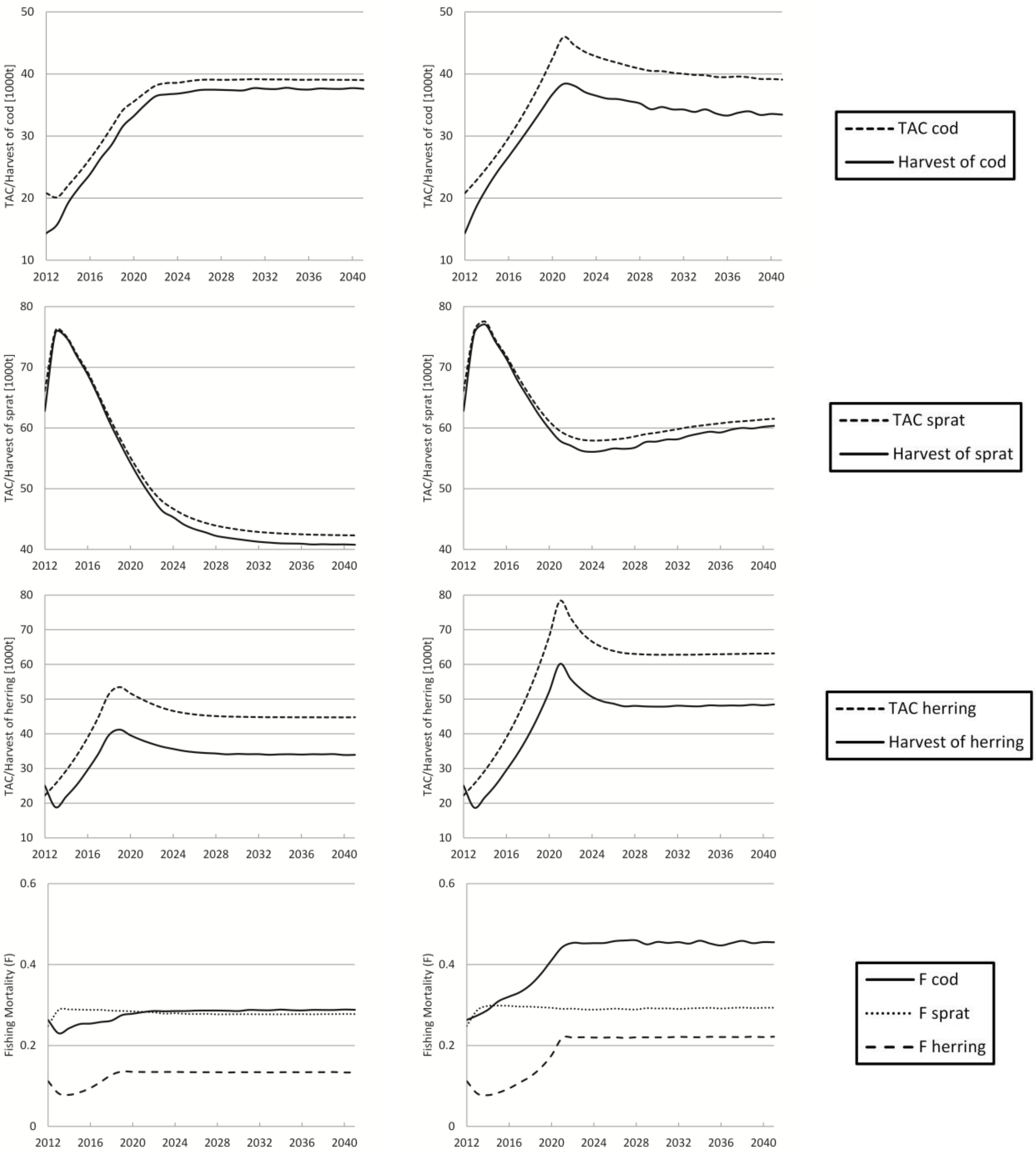


Fig. 3: Estimated efficiencies (2012 values) according to the vessel length.

Biomass Simulation

The model uses 2012 age-structured stock estimates [32] as starting values. As the paper's focus is the Baltic Sea harvest limited to Polish vessels and the national fleets in the Baltic Sea are considered to vary in their activity, the model does not attempt to impose *ad hoc* generalizations based on data from Poland. Instead, it looks at the limited scope in which each stock is appropriately scaled. The simulation period is T=30 years, which is long enough to derive steady state values under given assumptions for both scenarios. To account for innovations and progress in fisheries over such a long period, technical change was exogenously imposed directly on efficiency level. The chosen value was 1%, as derived for bottom trawl cod fishery in Norway [40]. The optimal quota allocation in each scenario is derived with the use of Differential Evolution (DE) [41,42]. This technique uses an algorithm similar to classic genetic algorithms to determine the global minimum of large non-convex systems [43]. The simulation results for the two described scenarios are presented in the form of graphs in figure 4. The results include the evolution of Spawning Stock Biomass (SSB), Total Allowable Catch (TAC), TAC utilization as a comparison of TAC with the expected harvest and fishing mortalities (F) for the three species providing the basis for the model (cod, herring and sprat).





Scenario 1 Scenario 2

Fig. 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 approximately 10 years, which is a result of strict cod management plan. This has a direct impact on mostly sprat, where the SSB decreases to a level that is visibly lower compared to that in scenario two. This is caused to a high degree by increased predation, as sprat is the preferable food source for cod, whereas its status quo fishing mortality is close to MMSY. In addition, under this scenario herring benefits from lower harvest and arrives at a higher biomass. In scenario two, the cod stock biomass is stable and stays at a level close to the initial level. The SSB do not fall below a biologically safe limit in any of the cases. The TAC for cod increases to a similar value, approximately 40 thousand tons, under both scenarios. The TAC for pelagic species is higher under scenario two, approximately 50% in each case.

The TAC utilization graphs precisely show the range of the gap between the 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 and quota size. In the case of cod, the gap exists persistently, whereas it increases in size under scenario two after several years. A similar situation can be observed in the case of pelagic species as a result of generally higher quotas and therefore more flexibility regarding harvest choice. This includes harvesting more of the species that generate high rents and 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 that the individual quotas can be well targeted if it is found to be profitable. The implied fishing mortalities, the direct result of TAC utilization, are close to the target in the scenario one, whereas slight deviance is observed in scenario two.

Management Evaluation

The NPV of the fishery, although negligibly different (approximately 7% in total), under scenario two is higher. The difference in monetary terms is approximately 222 million PLN over the period of simulation. This implies that the fleet in question, which is given more flexibility via higher quotas, is benefiting from the option of making individual harvest choices. However, when approaching the steady state, the difference dissipates. Profits in the future are discounted with the constant discount rate of 4%.

Repeating 100 times the simulation of the preferable, second management scenario identifies the risk posed on the environment by determining the probability of reaching an undesirable state by following the established HCR. Here, the uncertain parameters are introduced as values randomly drawn from their distributions. The average outcome and the 95% confidence interval for SSBs is plotted in figure 5. The results suggest neither the risk of stock collapse nor the arrival at the limit reference point. There is a possibility of the stock to fluctuate around the limit reference point only in the case of sprat under less favorable conditions.

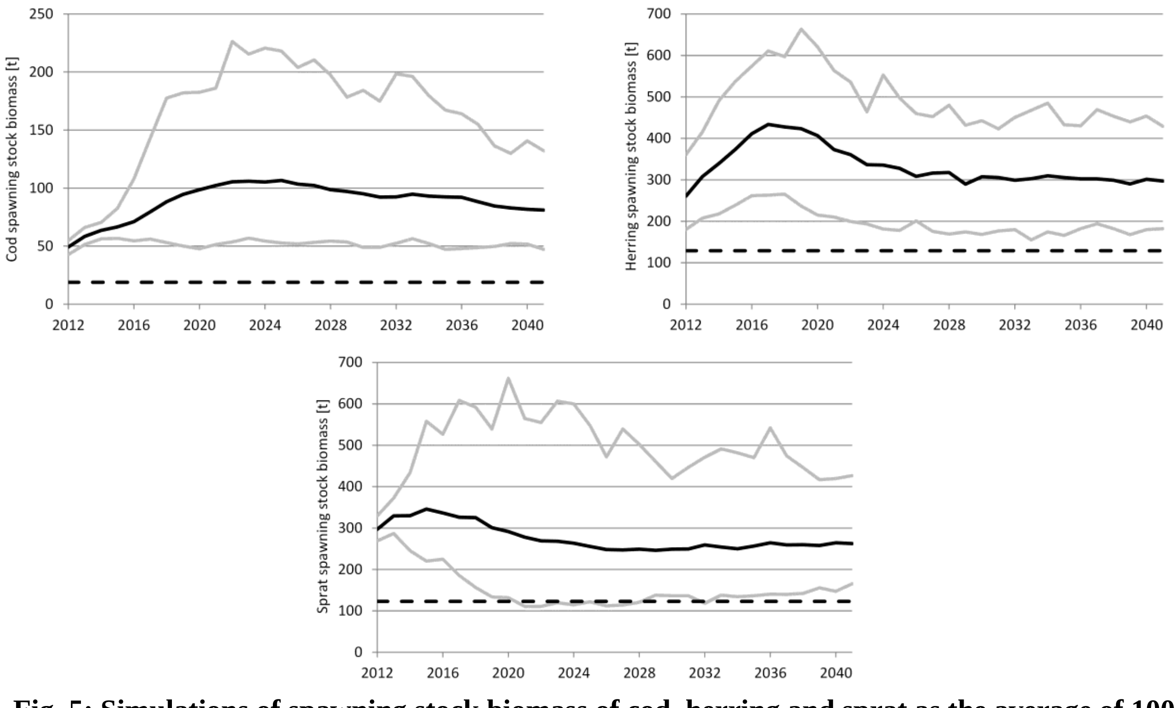


Fig. 5: Simulations of spawning stock biomass of cod, herring and sprat as the average of 100 simulations with 95% confidence limits. Dashed lines indicate minimum reference points.

CONCLUDING REMARKS

The purpose of this paper is twofold. First, it shows TAC utilization taking into account heterogeneity of the fleet. Second, it compares the biomass development in the Baltic Sea under present management plan with scenarios based on scientific advice (following MMSY). The presented model is based on individual vessel efficiency derived from available logbook 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 a given quota allocation. Each vessel is constrained by the maximum time it can spend at sea, whereas it also has room for individual harvest decision. The model assumes economic rationality and harvest based on positive marginal profit. Following this assumption, the existence of a gap between TAC and harvest is straightforward. Vessels vary in their characteristics as well as their optimum harvest choices.

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

The model presents an argument that the current regulations and tendencies regarding TAC may be too strict and that relaxing the TAC would be beneficial for fleet profitability without causing a collapse risk to the species in question. Increasing fishing mortalities to the levels recommended within the MMSY framework safeguards the future reproduction potential of the stocks and assures healthy populations while having positive impact on the fishing sector. The results imply that the fleet in question, given more flexibility via higher quotas, is benefiting from the possibility of making individual harvest choices rather than being fully constrained by non-tradable IVQs. Moreover, if the profit results are similar between scenarios, the more flexible option may have additional advantages. These potentially include lower management costs, decreased costs of enforcement (e.g., monitoring, observers onboard) or faster improving efficiency by adapting to the individually chosen target species group.

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

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ENDNOTES

[a] Carrying unused quota back to the previous year's allocation or forward to next year's allocation.
[b] National authorities under coordination by the European Fisheries Control Agency (EFCA) conduct the control over Illegal, Unreported and Unregulated (IUU) fishing (surveillance, inspections, data collection and enforcement). The enforcement legal basis is Council Regulation (EC) No 1224/2009.
[c] The model follows the general economic assumption of profit maximization. Although rare, a risk-averse response may also occur [44], e.g., selecting coastal waters to avoid risk.
[d] Excluding capital costs; equivalent to assuming that capital investment is a sunk cost.