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Abstract

Optimal management of herring, mackerel and blue whiting in the North East Atlantic is analyzed. The main motivation is to quantify the potential gain from implementing multi-species management compared to traditional single-species management. The objective is to maximize discounted net revenue; in other words a sole-owner perspective. The results are derived from an empirically based surplus growth type of model with three species. The biological interaction in the model is mainly competition for food. An important result is that discounted net revenue could have been up to 30% higher if the stocks had been optimally managed from a multi-species perspective.

Keywords: Straddling fish stocks, Multi-species management, Norwegian spring-spawning herring, Northeast Atlantic mackerel, Atlantic blue whiting

JEL Classification: Q22 Q34 Q57

Introduction

The Northeast Atlantic sustains a number of pelagic fish stocks, the most important of which are Norwegian Spring Spawning (NSS) herring, Northeast Atlantic blue whiting and Northeast Atlantic mackerel (Skjoldal et al. 2004). All these stocks are classified as straddling stocks in the sense that they not only cross boundaries between the EEZs of coastal states, but also traverse the high seas areas between those boundaries (Bjørndal and Munro 2003). NSS herring mainly inhabit Norwegian waters throughout the life cycle, but can migrate into Russian waters during the juvenile phase, and into Faroese, Icelandic and international waters as adults during the feeding period in the summer (Holst et al. 2004). The feeding migration pattern, especially for large herring, has changed several times over the last 60 years (Holst et al. 2002; Utne et al. 2012), varying with the size of spawning stock biomass and possibly ocean conditions as well. Mackerel spends most of the year in EU waters, but a large part of the stock migrates into the eastern part of the Norwegian Sea and the North Sea from June to October (Belikov et al. 1998; Iversen 2004). In recent years Icelandic waters have also been inhabited by mackerel (Nøttestad and Jacobsen 2009) possibly due to changing water temperatures. Blue whiting is mainly found in the Norwegian Sea throughout the year, but spawns west of the British Isles in February-May (Bailey 1982). The stock is located in Norwegian, Icelandic, Faroese and EU waters, but the large scale distribution pattern varies and is related to total stock size and water temperatures (Utne et al. 2012).

During the period 2006-2009 there has been a strong build up of biomass of planktivorious fish (herring, mackerel and blue whiting[1]) in the Norwegian Sea. The negative relationships between length at age and stock biomass, the pronounced reduction in zooplankton abundance witnessed in the Norwegian Sea in recent years, and the expansion in spatial distribution of fish indicate that the biomass of planktivours fish in the area has been close to the carrying capacity (Huse et al. 2012). All stocks showed

[1]These zooplankton feeding stocks have substantial spatial and dietary overlap, and are often collectively referred to as the 'pelagic complex' in the Norwegian Sea.

signs of density-dependent length growth, whereas for herring and blue whiting there were also significant indications of interspecific competition. Huse et al.'s results support the hypothesis that the planktivorous fish populations feeding in the Norwegian Sea have interactions that negatively affect individual growth, mediated through depletion of their common zooplankton resource. It will be important to include these findings in the future ecosystem based management of the Norwegian Sea.

The migratory patterns of these stocks have undoubtedly made it more difficult to attain and to uphold international agreements on catch quotas. While agreements on less migratory demersal stocks (cod and haddock, for example) between Russia and Norway have remained unchanged since the early 1980s, the agreements on the pelagic stocks have sometimes broken down or taken a long time to establish (Bjørndal and Ekerhovd 2014).

An agreement on the NSS herring was established in 1996, several years after its recovery, but it broke down in the period 2003-2006 due to disagreement over allocation of national quotas. However, in January 2007 the EU, the Faroe Islands, Iceland, Norway, and the Russian Federation signed an agreement on the management of this stock for 2007. Since then the relative quotas have remained unchanged. An agreement on blue whiting was reached in 2005, after many years of intensive exploitation where total catches in some years were four fold the recommended ICES quota (Bjørndal 2009).

In this article an empirically based multi-species dynamic optimization model is developed for the three stocks. The rationale for developing such a model is to provide empirical results that may assist policy-makers in the countries around the Northeast Atlantic to improve the management in the sense that it will resolve conflicts of interest and, thus, generate greater economic rents. It is also an objective to unveil for which of the species the economic potential of improved management is highest. Furthermore, to detect how much is lost by sticking to tradtional single-species management instead of implementing a multi-species approach to management.

The bioeconomic model is represented by a model of population dynamics combined with an economic model. In addition, multi-species models must take into account inter-specific effects between the fish populations. Some simplifications are of course necessary. We resort to an aggregated biomass model which permits analysis of optimal management and quota decisions, but still maintains species interactions and stock dynamics. Ekerhovd and Kvamsdal (2013) have estimated the parameters of a generalized surplus growth ecosystem model of the pelagic fish stocks in the Norwegian Sea with the Ensemble Kalman Filter. In order to reduce the parameter dimensionality, the species are modeled to rely on a common carrying capacity. In a follow-up study, Ekerhovd and Kvamsdal (2014) takes further steps to deal with a still higher number of parameters. The best models captures much of the observed dynamics in the fish stocks, while the estimated model error is moderate (Ekerhovd and Kvamsdal 2014).

The relevance of our research is clearly emphasized by the recent mackerel dispute between Norway and EU on one side and Iceland and the Faroe Islands on the other, the so-called mackerel war (Hannesson 2013b). There has for several years been an unsolved dispute between these nations about the size of their respective quotas. Norway and EU had originally an agreement with 10-years duration about the size and distribution of mackerel quotas. Then the mackerel started to change its migration pattern such that a larger share of the stock entered Iceland's and the Faroe Islands' economic zones. This caused these two countries to multiply their previous harvest of mackerel. Norway has responded by refusing landings of mackerel from Iceland and the Faroe Islands in Norway, and EU has recently warned that they may do the same. The present threat is that if this dispute is not solved fairly soon and sustainable harvesting is resumed, the increased harvest pressure on the mackerel may cause the whole stock to collapse implying severe problems both for fishermen and the pelagic fishing industry in all countries involved for a long period. The scientific advice for total harvest in 2011 was 650 000 tonnes whereas actual harvest was about one million tonnes. So far no agreement has been reached. Even if an agreement is reached, it may be interesting to compare it with an agreement based on bioeconomic optimization under various scenarios, and therefore this research is of interest no matter what actually happens. The so-called mackerel war is a classic example of the commons problem for which the relevance and importance of bioeconomic modeling and analysis is well established.

Although the literature on straddling fish stocks is extensive, with several contributions in recent years, no study addresses these issues in a multispecies context (Bailey et al. 2010; Hannesson 2011; Bjørndal and Munro 2012). The present work will be a step toward closing this gap by developing a methodology that can be used for empirical analysis of such systems. Numerical methods will be used to determine optimal policies in terms of maximising net present value.

In the next section we present a profit function linking the management of the pelagic fisheries to the stock dynamics. Before we present the results, we outlay the empirical basis for the multi-species model, the price-landings relationship, the cost function parameters, and the single-species models. Finally we summarize and discuss our findings.

The bioeconomic model

The model is discrete surplus-growth type multi-species model with competition between species.

Multi-species management

The profits from each commercial fishery are calculated for each time period as the difference between revenue and costs. Harvest from stock i at time t, $S_{i,t}$ is defined as:

$$H_{i,t} = S_{i,t} - X_{i,t}, \tag{1}$$

where $X_{i,t}$ is escapement.

The income from fishery i is defined as $R_{i,t} = (p_i - \gamma_i H_{i,t}) \times H_{i,t}$ and the cost as a fraction of the income $C_{i,t} = \frac{\beta_i}{1-b_i}(S_{i,t}^{1-b_i} - X_{i,t}^{1-b_i}) \times R_{i,t}$. Thus, revenues from fishery i in period t are given by

$$\pi_{i,t} = \Big(p_i - \gamma_i H_{i,t}\Big) H_{i,t} \times \Big(1 - \frac{\beta_i}{1-b_i}(S_{i,t}^{1-b_i} - X_{i,t}^{1-b_i})\Big), \tag{2}$$

where p is the price of fish when total landings approaches zero and γ is a factor indicating how much the price declines when total landings increase, β_i are the cost parameters, and b_i are the catch elasticities with respect to the stock size, $0 < b_i < 1$.

The harvest of each fishery affects the profits and the stocks sizes' of the others and reduces its own future stock size. The optimal escapement strategy will balance the marginal profits from each fishery to equal the marginal revenues foregone in the other fisheries in the system in the current season and in the future. The objective of the fishery manager is to maximize the discounted net benefits from the pelagic fisheries through optimal choice of escapement levels for the three fisheries. In the beginning of every season, the manager observes the size of the stocks $S_{i,t}$ and then chooses the optimal vector of escapement levels X_t, where $X_t = \{X_{1,t}, X_{2,t}, X_{3,t}\}$. The net economic benefits for the fisheries as a whole, $\Pi(S_t, X_t)$, depend on states of the fish stocks S_t and the escapement levels X_t.

The fishery sole owner manager seeks a sequence of escapement level policies, $X\{\cdot\}$, which prescribes the escapement levels $X_t = X_t^\star(S_t)$ that in a given state and period will maximize the expected net present value of the current and future harvest over an infinite time horizon.

$$\Pi(S_t, X_t) = \max_{0 \le X \le S} \sum_{t=0}^{\infty} \sum_{i=1}^{3} \Big\{ \Big(p_i - \gamma_i (S_{i,t} - X_{i,t})\Big) \Big(S_{i,t} - X_{i,t}\Big) \times \Big(1 - \frac{\beta_i}{1-b_i}(S_{i,t}^{1-b_i} - X_{i,t}^{1-b_i})\Big) \Big\} \delta^t, \tag{3}$$

where the discount factor, δ, is based on the discount rate ρ,
subject to the state transition equations $S_{1,t} = G(S_{i,t-1}, X_{i,t-1})$ presented in Table 1 and some initial constraints, for $i = 1, 2, 3$.

Table 1: The elements of the state vector S_t and transition vector $S_t = G(S_{t-1}, X_{t-1})$

Stock	State variable	State transition equation $g_i(S_{t-1}, X_{t-1})$ for stock i as function of S_{t-1} and X_{t-1}
Norwegian spring-spawning herring	$S_{1,t}$	$g_1(S_{t-1}, X_{t-1}) = X_{1,t-1} + \alpha_1 X_{1,t-1}^{m_1}\left(1 - \frac{X_{1,t-1}+X_{2,t-1}+X_{3,t-1}}{K})\right)$
Northeast Atlantic mackerel	$S_{2,t}$	$g_2(S_{t-1}, X_{t-1}) = X_{2,t-1} + \alpha_2 X_{2,t-1}^{m_2}\left(1 - \frac{X_{1,t-1}+X_{2,t-1}+X_{3,t-1}}{K})\right)$
Atlantic blue whiting	$S_{3,t}$	$g_3(S_{t-1}, X_{t-1}) = X_{3,t-1} + \alpha_3 X_{3,t-1}^{m_3}\left(1 - \frac{X_{1,t-1}+X_{2,t-1}+X_{3,t-1}}{K})\right)$

The growth functions, which in general can be written $f(x_i) = \alpha_i X_i^{m_i} (1 - \sum_i X_i/K)$, derive from the classic logistic growth function, where the parameters α_i are the growth rates and the parameter K is the common carrying capacity, but are modified in the following ways (Ekerhovd and Kvamsdal 2014). The positive term has an additional exponent m_i that allow a band of low stock levels with near zero growth and a right-skewed growth profile. Essentially, m_i modifies the growth function such that growth has a degree of depensation. Pelagic stocks often display violent dynamics that to some degree can be accounted for with depensated growth functions. For example, in a model of the Barents Sea foodweb, depensated growth was found crucial to capture the dynamics in the pelagic species (Kvamsdal and Sandal 2014). The negative term, which in the classic logistic measures the biomass relative to the the carrying capacity, measures the total biomass in the system relative to a common carrying capacity.

Single species management

Single species growth $G(X)$ can be described by the well known logistic growth function:

$$G(X_{i,t}) = X_{i,t+1} - Xi,t + H_{i,t} = r_i X_{i,t} - \frac{r_i}{K_i} X_{i,t}^2 + \epsilon_t, \qquad (4)$$

where r_i are the intrinsic growth rates and K_i are the individual carrying capacities for the NSSH, mackerel, and blue whiting stocks, denoted $i = 1, 2, 3$, respectively.

The traditional single species management objective has been the maximum sustainable yield (MSY) for target species. Under MSY, we attempt to maximize the average weight of catch over an infinite time horizon. MSY is relatively easy to estimate, but it is not as reliable a measure as once thought (Hilborn and Walters 1992). The variability and complexity of the factors that affect fish stocks are too great to effectively develop an accurate MSY for any given fishery. In recent years, management objectives have begun to reflect not only the biological yield of fisheries (MSY), but have included economic and social considerations, as well. The maximum economic yield (MEY) concept incorporates economic and social aspects by combining MSY with evaluations of the economic benefit to the area in the creation of jobs and money being added to the local economy and social benefits of maintaining traditional ways of life. A simple economic objective is to maximize the net revenue from the fishery, essentially maximization of the difference between the landed value and the harvesting costs.

Now assume that the sole owner's objective is the maximization of of the total discounted net revenues derived from exploitation of the stock. If $\rho > 0$ is a constant denoting the rate of discount, this objective may be expressed as maximizing Equation 2 subject to Equation 4 and the constraints $X_{i,t} \geq 0$ and $H_{i,t} \geq 0$. An implicit equation for the optimal stock size, $X_i^\star$, (*Golden Rule*) deduced from optimal control theory (Grafton et al. 2004) is simply

$$\rho = \frac{\partial G(X_i^\star)}{\partial X_i^\star} + \frac{\partial \pi_i / \partial X_i^\star}{\partial \pi_i / \partial H_i^\star}, \tag{5}$$

where π is a function of X and H.

MEY equals MSY if $\rho = 0$ and $\partial \pi / \partial X = 0$, simultaneously. However, positive discount rate and positive partial derivative of the revenue with respect to the escapement level have opposite effects; while discounting lowers the harvest levels, the marginal value of future stock sizes increases the harvest levels, and these two effects might cancel each other out making MEY equal to MSY.

Table 2: Subscripts, variables, and parameters

Symbol	Definition	NSSH	Mackerel	Blue Whiting	Unit	Submodel
i	Subscript	1	2	3	Stock/fishery	All
t	Time				Year	All
π_i	Revenue				million NOK	Equation 2
Π	Present value				million NOK	Equation 3
α_i	Growth rate	.000324	.099182	.000428		
K	Carrying capacity		29,807		Thousand tonnes	Table 1
m_i	Modification term	1.85	1.25	1.9		
p_i	Price, intercept	5.49	10.61	2.46	Norwegian Kroner (NOK)	Equation 6
γ_i	Price, slope	-.0017	-.0016	-.00064		
β_i	Cost parameter	.00124	.00124	.00174		Equation 7
b_i	Catch elasticity	.174	.174	.295		
ρ	Discount rate		5.0		%	$\delta = 1/(1+\rho)$
r_i	Intrinsic growth rate	.35	.42	.31		Equation 4
K_i	Carrying capacity	14,303	7,327	19,963	Thousand tonnes	
MSY_i	Maximum sustainable yield	1,250	765	1,569	Thousand tonnes	Equation 5
MEY_i	Maximum economic yield	1,127	763	1,547	Thousand tonnes	

Empirical analysis and numerical specification

Multi-species models

Table 2 shows the parameter values of the growth functions (Table 1) estimated by Ekerhovd and Kvamsdal (2014) using the Ensemble Kalman Filter and appear to capture much of the dynamics in the system as well as the interactions between the different species. The interactions are competitive, mutually destructive interactions, where NSS herring, mackerel and blue whiting prey upon the same food source(s), thus, limited by a common ‘carrying capacity’. Increase in one species’ biomass leads to reduced growth for all three species (Ekerhovd and Kvamsdal 2014). The chosen parameter values are based on node number 16 that out of the 20 “top” nodes presented in Ekerhovd and Kvamsdal (2014) Table 4, page 21, which appear to reproduce the historic stock developments best, cf. Figure 2.

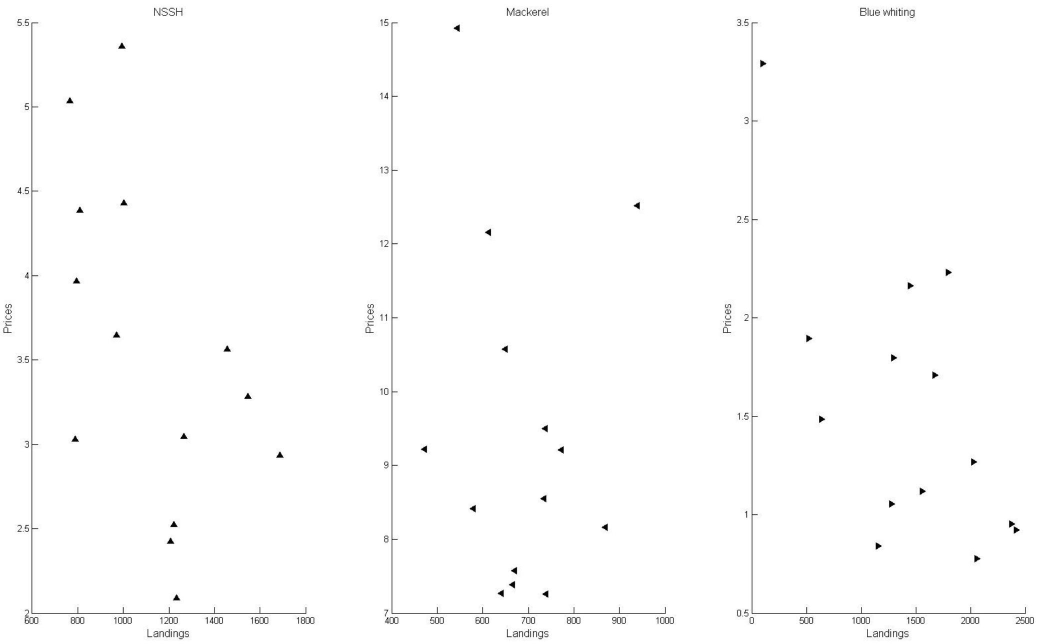

Figure 1: Total landings (thousand tonnes) plotted against deflated (2011) Norwegian first hand fish prices (NOK), 1998-2011

Price-landings relationship

Figure 1 details Norwegian fish prices plotted against total annual yield in the NSS herring (a), mackerel (b), and blue whiting (c) fisheries, 1998–2011.[2] Figure 1 indicates negative relationships between the prices obtained and the quantity caught, *i.e.*, prices decline if the total yield increases. A linear relationship is assumed,

$$P_{i,t} = p_i - \gamma_i \times H_{i,t} + \epsilon_t, \tag{6}$$

where $P_{i,t}$ is the price of fish per unit of $H_{i,t}$, the total annual yield in the NSSH, mackerel, and blue whiting fisheries, denoted $i = 1, 2, 3$, respectively. The results from fitting Equation 6 to the data in Figure 1 are shown in Table 2.

For herring and blue whiting, assuming linear relationship between prices and landings

[2] The information on Norwegian prices is from the Norwegian Directorate of Fisheries annual profitability survey for the Norwegian fishing fleet - comprising whole-year-operating vessels 8 meters overall length and above (Fiskeridirektoratet 2012).

appear to be plausible. Referring to the Table A-1, Appendix, the intercept terms (p_i) and the blue whiting coefficient were statistically significant at the 5% level, while the herring slope coefficient were statistically significant at the 10% level. The model does not fit well with the mackerel price-quantity data. However, over the nineties, Kennedy (2003) report, there was a strong negative correlation between mackerel price and harvest. Moreover, upon inspection of Figure 1 we can identify three possible outliers in the mackerel data set: i) the 2005 observation, where the Norwegian mackerel price was 14.93 NOK/kg while the total mackerel landings that year were the second lowest quantity in the data set with 543.49 thousand tonnes, ii) the 2006 observation (472.7 thousand tonnes and 9.22 NOK/kg), and iii) the 2011 observation (938.82 thousand tonnes and 12.52 NOK/kg). Deleting the outlier observations ii) and iii) prior to estimation improved the fit, such that the adjusted R^2 became positive and the intercept and slope coefficients statistically significant at the 1% and 10% level, respectively.

Costs

The instantaneous harvest production function will be specified as $H_i = ES_i^{b_i}$, where E stands for fishing effort, ans S is the stock size. The parameter b is the catch elasticity with respect to stock size, which takes the value of one if the stock maintains a uniform distribution, and zero if the stock keeps its density constant when harvested. There exists a literature on catch elasticities with respect to stock size, where it is thought that for pelagic fish species the elasticity is close to zero (Ulltang 1980; Butterworth 1981; Bjørndal 1987). The total cost becomes $C = \beta_i E$, where β is a cost parameter. The instantaneous cost per unit harvested is $c_i = \beta_i S_i^{-b_i}$. The total harvest costs can be expressed as $C_i = \beta_i \int_{X_i}^{S_i} u^{-b_i} \mathrm{d}u = \frac{\beta_i}{1-b_i}(S_i^{1-b_i} - X_i^{1-b_i})$, for $0 < b_i < 1$ (Ekerhovd 2008)[3].

Lacking information on the total costs for the combined harvest of NSSH, mackerel

[3]As harvest is $H = S - X$, with S given initially in every period, $X \leq S$, $X = S - H$, $X_H < 0$, and $C(X) = C(S(H))$, and $H = ES^b$, $X = S - ES^b$, $X_E = -S^b$, the properties of the cost function are $C_H = C_X X_H \geq 0$ and $C_{HH} = -C_{XX} X_H = C_{XX} \geq 0$, and $C_E = -C_X X \geq 0$ (where subscripts denote the derivatives).

Table 3: Operation costs and revenues (thousand NOK) in the licensed Norwegian purse seine fishery)

Year	Costs	Revenues
1998	1,690,619	2,170,486
1999	1,700,301	2,139,637
2000	1,976,584	2,314,011
2001	2,377,269	3,331,399
2002	2,435,700	3,322,888
2003	2,122,438	2,562,092
2004	2,388,695	3,098,507
2005	2,555,278	3,508,971
2006	2,223,311	2,864,208
2007	2,488 765	3,167,900
2008	2,668,611	3,451,929
2009	2,580,008	3,262,486
2010	2,867,380	3,970,387

and blue whiting we used total operation costs of all licensed Norwegian purse seiners in million NOK, divided by their total operation income published by the Norwegian Directorate of Fisheries profitability survey of the Norwegian fishing fleet 1998-2011, shown in Table 3[4], as proxy-variables for total costs C_t. The idea is that although we do not know the total costs we assume that all fleets harvesting on these stock has cost-income relationship similar to the licensed Norwegian purse seiner fleet. According to Lappo (2013) Norwegian fishermen not only fetch the highest prices but also have the lowest cost per tonne harvest compared to their colleagues in Scotland and Iceland. Although having a relatively low cost-income ratio, the Norwegian purse seiner fleet have substantial share in the pelagic fisheries in the North East Atlantic. The differences in cost-income ratios can be seen as relatively minor, and, furthermore, from a sole-owner perspective we can imagine that the most effective technology will be used.

The costs of the total harvest expressed as

[4]Over the period 1998 - 2010, the mean cost-income ratio was 0.77 with a minimum of 0.71 and a maximum of 0.85.

$$C_t = \left(\sum_i \beta_i \frac{S_{i,t}^{1-b_i} - X_{i,t}^{1-b_i}}{1-b_i} \right) + \omega O_t + \epsilon_t, \tag{7}$$

where $i = 1, 2, 3$ denotes NSS herring, mackerel and blue whiting, respectively. The cost parameters are β_i, and b_i represent catch elasticities with respect to the stock size where $0 < b_i < 1$. C_t is the cost-income ratio for all licensed Norwegian purse seine vessels, $S_{i,t}$ is the stock size before fishing commence and $X_{i,t}$, is the escapement stock size after fishing has stopped, and O_t is the catch of all other species, except NSS herring, mackerel and blue whiting, landed by licensed Norwegian purse seine vessels.

We estimated the β_i's and b_i's in Equation 7 by nonlinear least squares using the stock size estimates and catch[5] observations provided by the International Council for the Exploration of the Seas (ICES 2012). The ICES stock and harvest levels are later shown in Figure 2, left panel, upper middle and centre, for herring, mackerel, and blue whiting, respectively. The results from this exercise are shown in Table 2.

Table 2 shows the results of trying to calibrate the cost function to the licensed Norwegian purse seine vessel's cost share of the the fleets total revenue. As herring and mackerel are quite similar with respect to harvesting technology, we decided to constrain the cost parameters for mackerel to be equal those for herring. Herring and mackerel are also assumed have similar schooling behavior. There are possible trade-offs between the calibration parameters β_i and b_i. For the cost parameters the β_i there is little information in the literature that can guide our evaluation of the calibrated β parameter shown in Table 2. The stock elasticities with respect to catches of herring, mackerel and blue whiting for Norwegian purse seine fishing vessels has been previously estimated by Nøstbakken (2006) using a translog cost function. She estimated the elasticities for herring, mackerel and blue whiting to be 0.157, 0.056, and 0.083, respectively. From

[5]The stock data provided by the International Council for the Exploration of the Seas (ICES 2012) are generated using Virtual Population Analysis (VPA) that is rich in its coverage of catch, mortality and stock size information. However, mortality and stock size are generated variables based on biological assumptions, actual catch levels, and assumed decay functions (Jennings et al. 2001). Moreover, the generated regressors are endogenous, and a least square estimator produces inconsistent and inefficient estimates. Thus, we use instrumental variable techniques to address this issue (Ekerhovd and Gordon 2013).

Table 2 we see that our estimate for herring and mackerel is approximately equal to Nøstbakken's estimate for herring. However, for blue whiting the estimated elasticity quite high compared to Nøstbakken's estimate.

Single-species models

The results from fitting Equation 4 to the stock and harvest (ICES 2012) data are shown in Table 2.

Using longer time series, other studies (Arnason et al. 2000; Ekerhovd 2003; Hannesson 2013a) found the single species intrinsic growth for herring, mackerel, and blue whiting rates to lie between 0.3 and 0.5, and the single species carrying capacities estimates lies between 4 and 15 million tonnes. Here the estimates, shown in Table 2, for intrinsic growth rates appear to be of the same levels as in the earlier studies. The carrying capacity estimates shown in Table 2, for mackerel and blue whiting in particular, appears to be somewhat higher than found in other studies.

The MEY harvest levels are always lower than MSY, whereas MEY stock levels very often are higher than the corresponding MSY stock levels. The difference between MSY and MEY harvest is about 17% for mackerel, 10% for herring, and about 1% for blue whiting.

Results

In this section, first the quality and reliability of the multi-species model is examined by looking at how well it is able to reproduce actual stock development, for three stocks simultanously, when actual harvest is given. The more stocks involved, the more difficult it is to reproduce such actual patterns. Thereafter, optimal policies and optimal pay-off from the multispecies approach is compared to the policies and aggregate pay-offs resulting from three separate single-species models. The single-species models are derived from the same data. Also, the basic structure of the single-species models is the same as the basic structure of the multi-species model. Figure 2 compares the actual stock sizes and harvest levels with modelled stock development conditioned on actual harvest levels over the 15 years period 1997-2011. The modelled stock developments of herring and blue whiting (Figure 2, right upper and bottom, respectively) are very similar to the actual stock size pattern (Figure 2, left). The modelled mackerel stock development with actual catches (Figure 2, right middle), on the other hand, shows higher stock size levels than observed (Figure 2, left middle). However, the stock developments follow roughly the observed patterns: as the herring and blue whiting stocks declines toward the end of the period, the mackerel stock starts to increase.

Figure 3, left column, shows the stock sizes and harvest levels following the optimal multi-species policy of solving Equation 3 subject to the constraints in Table 1, over a 15 year period, with approximately the same initial stock sizes as shown in Figure 2. Furthermore, Figure 3 shows the stock sizes following the multi-species state vector development of Table 1 with the single species harvest rates objectives of MSY and MEY (Figure 3 middle and right columns, respectively) imposed.

Table 4 summarizes the net present values (NPV) obtained in the fisheries assuming i) actual policy (catch) and actual stock sizes, ii) actual policy and modelled stocks as shown in Figure 2, left and right panel, respectively, iii) optimal policy (MSM) over 15 years shown in Figure 3, left panel, with approximately the same initial stock sizes as shown in Figure 2, iv) MSY policy over 15 years shown in Figure 3, middle panel, and v) MSY policy over 15 years shown in Figure 3, middle panel. In cases iii - v the optimization is performed over 45 years to get the long-term perspective, but only the first 15 years are reported in order to compare with the actual policy. If we compare the actual catch and actual stock scenario (i) with the scenario where the stock developments are modelled while the catch levels are the historic catches 1997 - 2011 (ii), we observe that for mackerel and blue whiting the modelled scenario results in lower costs. The catch revenues are identical in both scenarios. For herring, on the other hand, we experience the opposite; higher costs with modelled stock development compared to the actual.

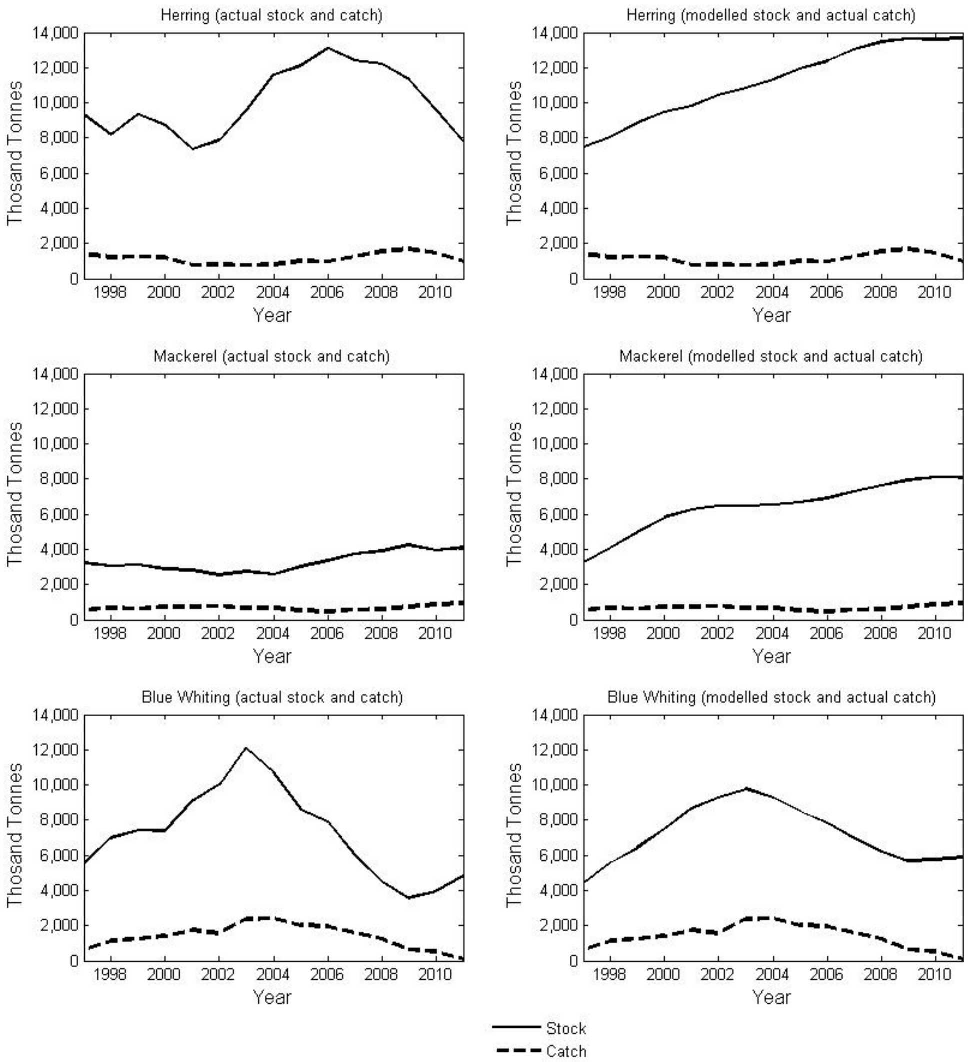

Figure 2: Comparison of Stock and Catch, between actual catch and stock size (left) and actual catch and modelled stock sizes (right) over 15 years (1997-2011). Herring (upper), Mackerel (middle), and Blue Whiting (bottom).

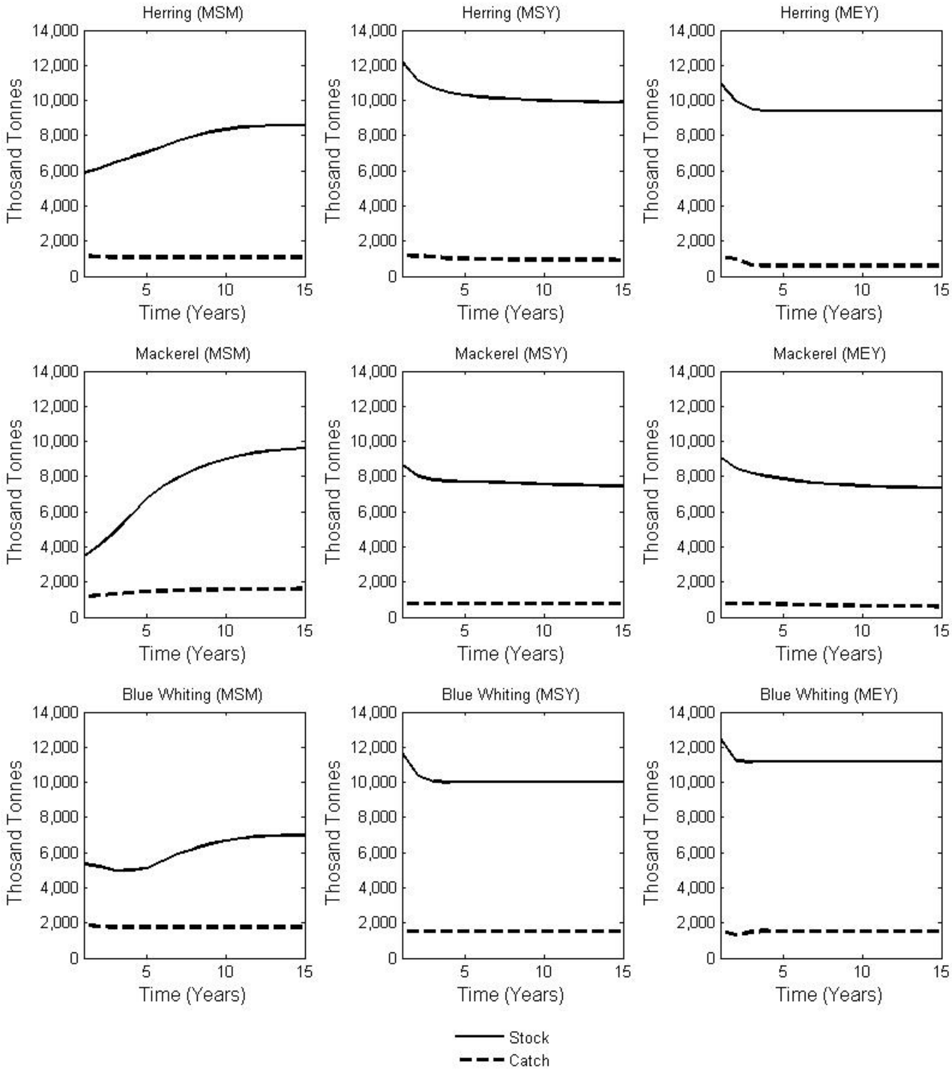

Figure 3: Stock sizes and catch levels over a 15 year period. From left to right, optimal multi-species management (MSM), MSY, and MEY, respectively

Table 4: Net present values (million NOK), comparing actual policy (and actual stock sizes, 1997-2011) with actual policy and modelled stocks, optimal policy (MSM), MSY, and MEY over 15 years

Stock	Actual policy and stocks	Actual policy	MSM	MSY	MEY
NSSH	30,031	30,189	30,636	30,885	25,965
Mackerel	54,783	56,504	79,010	62,492	58,850
Blue whiting	17,000	20,720	24,960	24,438	24,201
Total	101,814	107,413	134,606	117,815	109,016

However, if the optimal policy (iii) had been followed, the NPV would have been about NOK 134 billions, about 25% higher compared to the NPV of about NOK 107 billions obtained with the actual catch policy (ii). Further, we see that for the MEY policy (v) the NPV is approximately the same as the actual policy with modelled stocks (ii).

Summary and conclusions

The purpose of this article has been twofold. First, to develop an empirically based bioeconomic optimization model for herring, mackerel and blue whiting in the North East Atlantic that takes species interaction into account, and apply this model to give quota advice for the three species. Secondly, to use the model to estimate approximately how much is lost by sticking to single-species approaches for management and ignore species interaction. This is done by using three separate surplus growth models, one for each species, to determine optimal MEY and MSY and the corresponding stocks. The single species policies derived this way, are then used as constraints in the multi-species model in order to simulate what happens in the real world when species interaction is ignored.

The problem is looked upon from a sole-owner perspective, and the main objective has been to maximize discounted net revenue. The biological interaction in the model is mainly competition for food. It has been an aim to keep the number of parameters low. An important result from this exercise is that net revenue could have been increased by up to 24 percent by taking species interaction into account in a situation close to a steady state equilibrium. Further, the net revenue could have been increased by 26 percent compared with the revenue accruing from the actual harvest and stock levels in the period analyzed. In other words, the difference between the actual policy and optimal single-species management is not very large, only a few percentage, whereas the difference between actual management and the optimal multi-species approach to management is quite significant.

The relevance of the work is further emphasized by the ongoing conflict between EU and Norway on one side and Iceland and the Faroe Islands on the other side, over the size and allocation of mackerel quotas. An optimal approach to management, whether it is single- or multi-species based, is only possible under a regime of cooperation, and the results derived here emphasize the potential gain that can be achieved if all nations involved join in a concerted action to optimize regional management of the fisheries.

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Table A-1: Results from regressing total landings against deflated Norwegian first hand fish prices, 1998-2011

Species	Constant (p_i)	Slope (γ_i)	$\bar{R}^2$
NSSH	5.49	-.0017	.21
	(.000)[a]	(.054)	
Mackerel	10.61	-.0016	-.07
	(.015)	(.765)	
Blue whiting	2.46	-.00064	.34
	(.000)	(.017)	

[a] p-values in parentheses

Appendix

Equation 7 were fitted without a constant term, *i.e.*, regression through the origin, the reason for this is the assumption that without harvest there will be no variable costs, only fixed costs. What determines fishermen's behavior is variable costs, not fixed costs. Because of caveats applying to the interpretation of the R^2, this statistic is not reported in Table A-2.

Table A-2: Results from calibration of the cost function parameters in Equation 7

Species	Cost parameter β_i	Catch elasticity $1 - b_i$
NSSH and Mackerel	.00124	.826
	(.571)[a]	(.003)
Blue whiting	.00174	.705
	(.703)	(.050)
Other species (ω)	.0000284	
	(.827)	

[a] p-values in parentheses

Table A-3: Results from fitting a single species logistic growth model to stock and harvest data

Species	Growth rate (r_i)	Carrying capacity (K_i)
NSSH	.35	14,303
	(.082)[a]	(.088)
Mackerel	.42	7,327
	(.000)	(.000)
Blue whiting	.31	19,963
	(.096)	(.157)

[a] p-values in parentheses

Table A-4: Single species management objectives: MSY and MEY

Stock		MSY	MEY
NSSH	X_1	7,151	9,401
	H_1	1,250	1,127
Mackerel	X_2	3,663	2,256
	H_2	766	653
Blue whiting	X_3	9,982	11,161
	H_3	1,569	1,547

Optimal management of herring, mackerel and blue whiting in the North East Atlantic is analyzed. The main motivation is to quantify the potential gain from implementing multi-species management compared to traditional single-species management. The objective is to maximize discounted net revenue; in other words a sole-owner perspective. The results are derived from an empirically based surplus growth type of model with three species. The biological interaction in the model is mainly competition for food. An important result is that discounted net revenue could have been up to 30% higher if the stocks had been optimally managed from a multi-species perspective.

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