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Towards Monitoring the World's Fishery Resources Using Viability Indices

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Abstract

This paper develops an easy to use and cost efficient index for the assessment of stock viability in fisheries management and bioeconomic analysis. The index is predicated on biological and economic theory, and can be applied to different bioeconomic frameworks including different behavioural assumptions. Available time series data for the Canadian Atlantic cod, Danish North Sea cod and Norwegian cod fisheries are then assimilated into the model dynamics in order to estimate the index. To buttress the utility of this index, a jackknife technique is used to provide standard errors of estimation. It is found that for all the three fisheries, the imputed indices are low and consistent with observational data.

Introduction

In an April 2003 conference organised by EcoFish in Dakar-Senegal, scientists from a variety of backgrounds were invited to discuss an important issue in fisheries management and bioeconomic analysis (http://filaman.uni-kiel.de/ecofish/reports/). The scientists were asked to each propose a sustainability index or an indicator that could be used to monitor the state of world fishery stocks. Sumaila (2003) proposed an approach with poverty consideration while others proposed, for example, supply and demand or ecosystems approaches (EcoFish, 2003). Such efforts underscore the need for measures of performance both with regard to profitability and, more importantly, stock viability.

This paper proposes a simple, easy to use and cost efficient but broad index that is predicated on bioeconomic theory. The index can be used in the analysis of many fisheries around the world. It is broad because it is not normative and does not hinge on any particular goal. Dynamic models of optimal approach strategies and the behavioural models of commercial fishing have been the mainstay of this line of bioeconomic analysis. In this paper, the behavioural model is used because the analysis is positive (descriptive) rather than normative (see Clark, 1990). Also, we point out that this model can be applied to a sole owner fishery where the profit function is assumed to be linear in the output or harvest. The objective is to use these model dynamics to estimate an index that is based on the revealed long-run biomass level, i.e., the biomass that will result as a consequence of the policy or set of polices being pursued by the management authorities.

The objective of the index is broad and aims at providing a measure that informs management and fishermen about the level of the biomass that their policy will yield in the long run. This indicator can be useful in both static and dynamic evaluation of the stock biomass. We will use both scenarios to illustrate the potential usefulness of the index.

In fisheries management, each policy or set of policies has an explicit or implicit long-run biomass level which may be revealed by the analysis of historical data. For example, a policy that is not biologically and/or economically sustainable will at least in the long-run lead to a biomass level that is below the minimum biological acceptable level (MBAL) (Bjorndal *et al*., 2004), while good and plausible actions on the part of management or fishermen should lead to a higher standing biomass level. In an optimally managed fishery, the optimal approach path will result in a revealed long-run biomass that is economically viable; other policies may result in a steady state biomass that is biologically viable. Research has documented that this leads to economic and biological overfishing (see Clark, 1990). It is also shown that a sole owner who neglects the future productivity of the stock reaches the same level of biomass that the open access fishery reaches (Scott, 1955; Clark, 1990).

The proposed index is tested using data from the Canadian Atlantic cod, Danish North Sea cod and Norwegian cod (a.k.a North East Arctic cod) fisheries. These data have been previously used in the economic analysis of the optimal strategies for these fisheries and are hence appropriate for conducting rigorous testing and evaluation of the method in this paper. Not only will the indicator be tested on different data sets but also different estimators will be used to examine its robustness and variability.

Also, a nonparametric technique is employed to provide the standard errors for the indicator (Efron and Tibshirani, 1993). The technique is a resampling method called the jackknife. The importance of this is that it allows for the construction of confidence intervals and hypothesis testing (Pindyck and Rubinfeld, 1998).

The rest of the paper is structured as follows. First, we briefly present the bioeconomic model and conduct an equilibrium analysis. Second, the proposed index is discussed and interpreted. We then introduce and define the jackknife technique for estimating the standard errors of the index. A historical background of the fisheries is given with a qualitative review of the data. Third, the estimation procedures are presented followed by a discussion of the results. Fourth, the paper is summarised and concluded.

The Bioeconomic Model

The model dynamics in this paper are developed and discussed in detail by Ussif *et al.* (2002). As a result, we will only present a cursory discussion of the model dynamics. This model is a variant of the original behavioural model developed by Smith (1969); see Bjørndal and Conrad (1987) for an empirical application to the North Sea herring fishery. Ussif *et al*. (2002) extended the model and applied it to the Norwegian cod fishery. The model posits a reaction between the harvest rates and economic rent, i.e., fishermen are assumed to vary harvest rates (efforts) in proportion to economic rent. In this case, managers use the marginal profit as an index of profitability based upon which they either invest or disinvest in the stock by varying their harvest rates (efforts). Firms enter or leave the fishery depending on the size of the profitability index. In other words, they increase or decrease capital investment in the fishery according to whether the profitability index is positive or negative. Flåm (1993) provided an algorithm based on this approach, which has been applied in Sumaila (1997).

We begin by restating the population dynamics equation assuming again that the logistic growth model reasonably approximates the natural growth of the species. Thus, population dynamics are given by

$$\frac{dx}{dt} = rx(1 - x/K) - h \qquad (1)$$

where r is the intrinsic growth rate and K is the environmental carrying capacity (Clark, 1990). To model the dynamics of the commercial fishing industry, the following equation is formulated

$$\frac{dh}{dt} = \gamma(p - c/x)h \qquad (2)$$

where p is the unit price, c is the unit cost, γ is a proportionality constant which reflects the speed with which capital is being added to or removed from the industry and $p - c/x$ is, in this case, the average or marginal profit which we define as the profitability index. Thus, the economic interpretation of equation (2) is that the output growth rate ($\dot{h}/h$) varies in proportion to the profitability index.

We note that, in this model, data on p and c are not necessary in order to fit the dynamics. The assumption of constant price may be quite restrictive but for some fisheries, this is a reasonable approximation. For the Danish North Sea cod fishery it was found that the data do not support the assumption of downward sloping demand and hence, a constant price assumption was used (Arnason et al., 2004). Whence, we redefine the following products $\alpha = p\gamma$ and $\beta = c\gamma$, which then leads to

$$\frac{dh}{dt} = (\alpha - \beta / x) h \qquad (3)$$

This leaves us with two parameters, α and β, to be estimated, thus, obviating the need for precise data on prices and costs. It may not be unreasonable to think that price and cost information is embedded in the harvest and stock data. This is because, for example, cost efficiency may induce higher harvest rates which will affect supply.

An important thing to note is that in an optimal control framework, a model with a linear in harvest objective function leads to a bang-bang control, while a non-linear model may lead to a gradual approach to the steady state (Clark, 1990).

Equilibrium Analysis

To derive the relevant equations for the empirical analysis we first consider the equilibrium behaviour of these dynamics. In equilibrium, we have

$$\frac{dx}{dt} = 0 \text{ and } \frac{dh}{dt} = 0$$

which result in the equations

$$h^* = rx^* \left(1 - x^* / K\right) \qquad (4)$$

$$x^* = \beta / \alpha \qquad (5)$$

Thus, the steady state biomass is a function of the economic parameters, i.e., the unit cost and unit price of the output. Also, the equilibrium harvest rate can be expressed as a function of the biological and economic parameters. Note that this point corresponds to the open access biomass (Bjørndal and Conrad, 1987).

To lay the platform for the ensuing empirical analysis, these equations are formulated as econometric models given by

$$h = rx(1 - x/K) + \varepsilon_h \qquad (6)$$

$$x = \bar{x} + \varepsilon_x \qquad (7)$$

where the asterisks are suppressed since there is no ambiguity, ε is a random error term and $\bar{x} = \beta/\alpha$. This quantity coincides with the equilibrium referred to as the open access equilibrium biomass. Hence one approach is to estimate the parameters of this set of equations and then use them to compute the indicator that will be defined shortly.

This approach of estimating the parameters of a surplus production model has been referred to as the "equilibrium estimators" (Polacheck *et al.*, 1993). Note that the equations can easily be estimated using Ordinary Least Squares (OLS). In fact, estimation of the parameter in equation (7) is trivial because the OLS estimator is the sample mean. Alternatively, the dynamics in equations (1-2) can be fitted to data and the estimated parameters can then be used to compute the index. These estimators will be denoted as the "dynamic estimators" for the purposes of nomenclature. We will explore both approaches in this analysis and compare the results. Again, we express these model dynamics in econometric form as

$$\frac{dx}{dt} = rx(1 - x/K) - h + \varepsilon_{xt} \qquad (8)$$

$$\frac{dh}{dt} = (\alpha - \beta/x)h + \varepsilon_{ht} \qquad (9)$$

where ε_{xt} and ε_{ht} denote random error terms which are assumed to be uncorrelated. These equations may be fitted to the available time series data using a continuous/discrete time dynamic systems estimation capability available in SAS software. However, this will not be done here; instead, an equation by equation method will be used. This may be considered as a form of limited information estimation (see Greene, 1997). Estimates of the parameters can then be used to compute the indices of viability and profitability. Hence, for convenience of estimation and analysis, we transform equations (8-9) as

$$\dot{x} + h = r(1 - x/K) + \upsilon_{xt} \qquad (10)$$

$$\frac{\dot{h}}{h} = \alpha - \beta/x + \upsilon_{ht} \qquad (11)$$

where $\dot{x}$ denotes the time derivative of the stock variable and υ is the transformed random error term. This reduces the problem to regression equations which are easy to perform. Here we use the nonlinear regression equations capabilities for single equations in SPSS.

Index Theory and Definition

Index number theory is commonly used in national income accounting calculations (Wachtel, 1997). We present a unit free number that can be used to compare the viability of different fish stocks around the world. Note that this indicator can be used in the analysis of many fisheries that follow the hypothesis of the aggregated model (Clark, 1990; Smith, 1969; Arnason *et al.*, 2003). Again, we emphasise the fact that every policy or set of policies drives the stock biomass towards a certain long-run level. This level of stock when compared to a reference point, herein the carrying capacity, can provide information about the viability of the stock.

The index is defined as

$$\theta = \frac{x^*}{K} \qquad (12)$$

where x^* is the revealed long-run biomass level and K is the environmental carrying capacity. We emphasise that x^* can be an open access or an optimal dynamic long-run biomass level or a steady state for a fishery where regulators use very high discount rates. If an optimal policy drives a stock to the maximum economic yield biomass then the index is expected to be high and the stock may be highly viable. Note that the inclusion of stock effects in profit function tends to shift the equilibrium biomass towards the right of the MSY biomass (Sandal and Steinshamn, 2001). Intuitively, the index says that the long-run viability or sustainability of a stock can be measured by the ratio of the revealed level of biomass to the environmental carrying capacity. That is, this raises the question, how are existing policies ultimately going to impact future biomass level? This indicator has most of the desirable properties that are often mentioned in the literature. For example, ease of computation, interpretability and cost effectiveness are crucial in judging the usefulness of the index.[1]

Another important advantage of this indicator is that it is a unitised quantity, i.e., it lies between zero and one, making it easy and convenient to compare the computed values across fisheries. Remember that low values of this index may indicate that a fishery is in danger of being overfished or depleted, thus, warranting a review of current policies. Research has shown that many fisheries are in distress and in a risk of collapsing (Pauly et al., 2002). While this is defined in terms of equilibrium

[1] Note the similarity between this index and some of the financial ratios employed in the analysis of solvency of corporations or firms in the financial markets (Brealey and Myers 2000).

quantities, it can be used as an annual time varying index with slight modification, e.g., the ratio of the current stock to the carrying capacity.

Using the model in this paper as an example, we see that the index is defined as

$$\hat{\theta} = \frac{\hat{\beta} / \hat{\alpha}}{\hat{K}} \qquad (13)$$

where the numerator $\hat{\beta} / \hat{\alpha}$ (the cost-price ratio) is the ratio of the unit cost to the unit price for the fishery. Note that the hat sign implies the quantity is estimated and will be suppressed whenever there is no possibility of confusion. It can be seen that if the cost-price ratio is high, the index is also high due to low profitability in the fishery. However, technological improvement may eventually lead to overfishing.

Using algebraic manipulation, it can be shown that equation (13) can be simplified as

$$\theta = \frac{c / p}{K} \qquad (14)$$

which again implies that the index is the ratio of the cost-price factor to the carrying capacity. The assumption of constant unit price and unit cost, when relaxed, can lead to a varying index. Furthermore, a comparative static analysis shows that a unit increase in harvesting cost tends to improve the index ($d\theta / dc > 0$), while a unit increase in price has a negative impact ($d\theta / dp < 0$). In general, the parameters of (14) vary over time and may also be random. However, if the economic parameters are time dependent but are such that they change according to the relations $p(t) = \kappa(t)\, p$ and $c(t) = \kappa(t)\, c$, then we will still have a constant index as in equation (14).

The Jackknife Technique

To provide estimates of the standard error for the proposed index, we use a resampling method known as the jackknife (Efron and Tibshirani, 1993). This method focuses on the samples that leave out one observation at a time, i.e., for some $i=1,2,....n$, $\bar{x}_{(i)}=(x_1,x_2,....x_{i-1},x_{i+1},x_n)$ is called the bootstrap sample. The regression is then run and in each step one set of observations is left out and the parameters are again re-estimated. This process is repeated a number of times, and the collection of estimates is then used to calculate the variance of the index. The resulting standard errors can then be used to construct confidence intervals and also to conduct hypothesis testing.

Historical Background of the Fisheries

The three fisheries under consideration – the Norwegian cod fishery, the Danish North Sea cod fishery and the Canadian Atlantic cod fishery – all have a history of supporting their respective coastal populations for many centuries. Figures 1-3 are respectively the stock biomass and harvest each normalized by their maximum observed values and the ratio of the harvest rate to the estimated stock biomass for each fishery. The ratio tells us in relative terms which years represent the highest harvest to stock factor.

The graphs show that for the Canadian Atlantic cod and Norwegian cod fisheries, the stock size was largest in the first year of the available data. It has since declined for the Canadian Atlantic cod stock until the late 1970s, while the Norwegian cod stock declined until early 1960s. The persistent decline in the case of the Canadian Atlantic cod fishery led to a moratorium in the early 1990s. The Norwegian cod fishery has been in serious troubles experiencing its lowest stock level in 1984 and appearing to turn around in mid 1990s. The Danish North Sea cod fishery, however, appears to follow a different path. The stock was at a low level in 1964, it grew to a maximum level in 1971, then declined for a few years followed by another few years of growth. The stock then declined and continued the decline back to about its 1964-level.

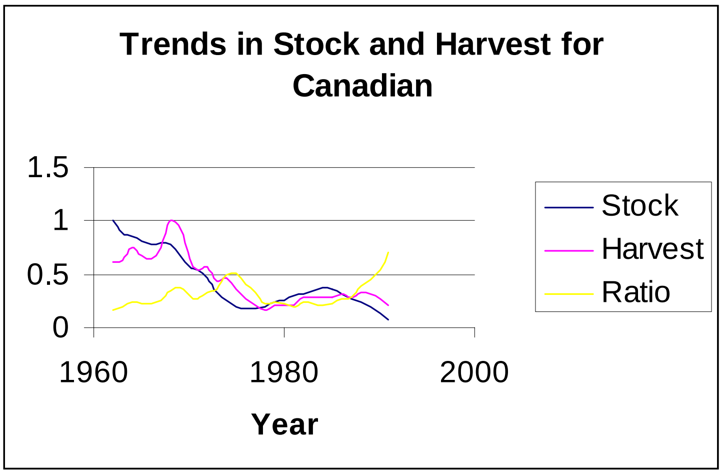

Figure 1: Normalised stock and harvest (1962-1991) using the maximum value in each series, and the ratio of harvest to stock biomass. Ratio denotes the ratio of harvest to stock. Source: secondary data from Table 2 of Grafton et al. (2000).

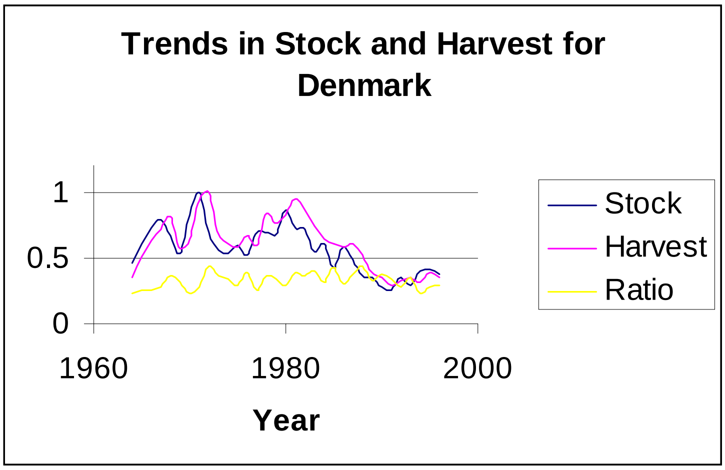

Figure 2: Normalised stock and harvest (1964-1996) using the maximum value in each series, and the ratio of harvest to stock biomass. Ratio denotes the ratio of harvest to stock.Denmark Statistics (1996).

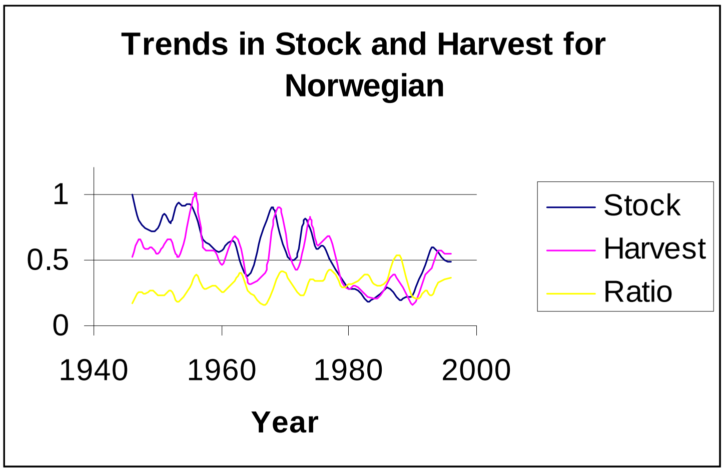

Figure 3: Normalised stock and harvest (1946-1996) using the maximum value in each series, and the ratio of harvest to stock biomass. Ratio denotes the ratio of harvest to stock. Directorate of Fisheries Norway (2001).

Discussion of Results

This section presents the results of the analysis. For each of the fisheries, we provide estimates of the coefficient for the equilibrium and dynamic estimators. In Table 1, the estimates are generally all statistically significant with reasonably good fit to the data (r-squares greater than 63%). The Norwegian cod fishery seems to have the largest intrinsic growth rate followed by the Danish North Sea cod and the Canadian Atlantic cod fishery. The estimated carrying capacities appear to be too high in the case of the equilibrium estimators despite the statistically significant t-values. The assumption of equilibrium seems to overestimate the carrying capacity and underestimate the intrinsic growth rate. To back this observation, we conducted a simple simulation experiment using the model dynamics in this paper and some known parameters in Arnason *et al.* (2004) for cost and price parameters together with a chosen value of the $\eta = 0.001$ to test the to estimators. We found that the dynamic estimator appears to be much better than the equilibrium estimator[2].

In Table 2, the dynamic estimators are presented. The results are in general very good and are within reasonable range based on recent available estimates (Grafton *et al.*, 2000; Ussif *et al.*, 2003, Arnason *et al*., 2004). The intrinsic growth rates are within reasonable limits and the carrying capacities are also generally good. It can be seen that the Danish North Sea and Norwegian cod fisheries have larger intrinsic growth rates than the Canadian Atlantic cod fisheries. Note that the low r-square values in Table 2 reflect the fact that we are fitting the transformed equations (10-11).

As stated earlier, the estimates of the parameters in Tables 1-2 are used to impute the viability indices for the fisheries. These estimates are reported in Table 3 and the corresponding standard errors using the jackknife technique are given in parentheses. Note that the estimates using the so-called dynamic approach are more plausible and are used in this discussion. The measures indicate that the policy that existed for the most part of the period of available data will in the long-run drive the Danish North Sea cod fishery to about 37% of the carrying capacity, while Norwegian cod fishery will end up at 20% and the Canadian Atlantic cod fishery at 21% of the carrying capacity. These numbers are quite reasonable and do reflect the history of the stock. The Norwegian cod fishery has been described by scientists as being in a serious condition, while the Canadian Atlantic cod fishery off the coast of Newfoundland has been under a moratorium since the early 1990s.

[2] The exercise was performed using model equations 1-2 and the set of parameters {r=.65, K=1402, p=84.215 and c=6624}.

Table 1: Estimated coefficients using equilibrium estimators (t-values in parentheses).

	Canadian	Danish	Norwegian
r	0.3770(9.952)	0.392(9.757)	0.422(11.943)
K	6,647 (4.871)	4,143 (2.369)	8,747 (6.431)
$\bar{x}$	1,280 (8.818)	665 (17.833)	2,353 (17.473)
R^2	0.7483	0.6958	0.6279
N	30	33	51

Note: Estimation is performed using nonlinear least squares. K and x are measured in ‘000 tonnes.

Table 2: Estimated coefficient using dynamic estimators (t-values in parentheses).

	Canadian	Danish	Norwegian
r	0.2918 (6.4988)	0.7218 (4.9745)	0.5388 (7.1935)
K	5796 (3.9004)	1330 (7.1257)	5636 (7.8935)
α	0.0730 (1.127)	0.1150 (1.129)	.083 (1.038)
β	90.88 (1.679)	58.11 (1.011)	91.79 (0.685)
R^2	0.474	0.103	0.164
Rh^2	0.094	0.033	0.0096
N	30	33	51

Note: Estimation is performed using nonlinear least squares for each equation. Two r-square values are reported one for each equation. K is measured in ‘000 tonnes.

Table 3: Computed indices for the equilibrium and dynamic estimators with jackknife estimates of standard errors.

	Equilibrium	Dynamic
Canadian	0.1926 (0.0289)	0.2157 (0.0202)
Danish	0.1604 (0.0345)	0.3750 (0.0208)
Norwegian	0.269 (0.0163)	0.2098 (0.0283)

Conclusions

In this paper, an index of stock viability is proposed and estimated for three cod stock biomass. The measure has potential usefulness in monitoring and managing natural resource stocks around the world. Owing to the overwhelming evidence of the threat of depletion in many fisheries and the need to examine existing and future policies, the significance of this research is quite substantial. The estimated indices have been found to be too low in all the three fisheries, consistent with real world observations and earlier research. The stocks of these fisheries are in a precarious situation, and there is a need for more focused attention on long-term sustainable management of the world's fishery resources.

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