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Management performance indicators based on year-class histories

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ABSTRACT

The stock assessment data provided by ICES's Arctic Fisheries Working Group represents a unique source of insight into the interplay between environmental factors, stock dynamics, fisheries and management decisions. This paper explores how the life history of year-classes constituting the Northeast Arctic cod stock could be used as performance measures for fisheries management. Five biological indicators are suggested for management evaluation, together with time series of environmental variables (ocean temperature and salinity). A brief evaluation of the indicator values indicates successful management of the cod stock, where most of the indicators develop in a positive direction, reflecting a sound stock situation in line with expressed management objectives.

1. Introduction

The idea of Virtual Population Analysis (VPA) is to estimate the stock history on the basis of catch profiles of the year-classes constituting the stock. Simple accounting systems of this type had developed before Gulland (1965) first published the first full-featured presentation of the method. VPA has since then been the core stock assessment component in most fisheries.

It is essential to have good information on the current stock status for fisheries management. Hence, the aim for assessments is to evaluate the current state of the stock and how this changes over time. The life history of each year-class will be a part of this, but the biomass profile of each year-class throughout its life span is seldom emphasised.

It seems to be a common understanding that without restricting access to a fishery or limiting the catches in other ways, the fish stock will be biologically overfished and eventually face extinction. This is not necessarily the case. Fishing activity even in a pure open access fishery is constrained by natural, technical and economic factors. Fishing will not be sustainable if costs are not covered by income. There will normally be a critical minimum size of the stock to sustain a fishery, even without regulations, since the cost of fishing typically increases with decreasing stock size. Fishing activities in the past have consequences for those utilising the stock now. Possible catch of one fisher now is not solely influenced by his previous catches, but by the fishing activity of all fishers in the past. Economists refer to this as a market failure (external cost), a failure that only can be corrected by controlling fishing activities.

A large amount of information is needed to regulate a fishery given management objectives. Implementing the regulations is another challenge. Surveillance and control are needed to ensure that the fishers comply with regulations. If the regulating authorities fail at one or more of these steps, the original market failure may remain and the cost of unsuccessful regulating effort adds to the cost of the market failure, leading to an even greater loss.

From a biological point of view, the regulation of a single species fishery aims to achieve two goals: (1) enhance biomass growth and recruitment of the stock and (2) improve the selection pattern of the fishery, to take advantage of the faster individual weight-growth of young, immature fish. This is usually believed to lead to economic benefits by reducing or removing the loss of resource rent found in unregulated fisheries.

This aim of this study is to utilise information on the life histories of year-classes, to evaluate how stock changes could be related to management activities. A number of year-class specific indicators are suggested that differ from the standard reference indicators, fishing mortality rate and spawning biomass, by being related to the life span of a single year-class, rather than representing an annual observation. The Northeast Arctic (NEA) cod fishery is used to exemplify the proposed indicators in relation to the two biological goals listed above. Data utilised are biological stock assessment data provided by the ICES's Arctic Fisheries Working Group (AFWG).

1.1. The Northeast Arctic cod fishery

The NEA cod fishery is often referred to as an example of successful regulations (Eide et al., 2013; Kjesbu et al., 2014). Gullestad et al.

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(2015) provides a through summary of the regulatory and political discussions during a critical management period around 1990, showing how an improved exploitation pattern was identified and implemented. Kjesbu et al. (2014) shows how the implementation of a harvest control rule (HCR) with moderate fishing mortality rates has contributed to a high spawning biomass and sustainable exploitation of the resource.

The NEA cod fishery has a long history and is among the most well-documented fisheries in the world. For example, time series of catch and effort data are available. Many scientific works discuss stock dynamics and fisheries issues related to the NEA cod stock. How to include existing knowledge into stock assessment and available management instruments also are complex questions under continuous debate. Kvamme and Bogstad (2007) discuss for example the effect of including length structures in the yield per recruit (YPR) calculations for NEA cod, showing how model sensitivity related to selection of model variables (in this case length or weight based calculations) also depends on exploitation pattern.

In addition to exploitation patterns, variation in the physical environment and ecosystem dynamics are important factors in explaining fluctuations in the NEA cod stock. Sundby (2000) demonstrates how ocean temperature affects the recruitment of cod directly and indirectly in complex ways, while Kjesbu et al. (2014) claim that even though environmental factors are crucial for the stock dynamics, fisheries management and implementation of HCRs are essential for the recent increase in population size. Rather than investigating the complex dynamics these factors lead to, the aim of this paper is to search for suitable, simple indicators, mapping stock development and environmental variation and reflecting management performance.

The AFWG annually conducts stock assessments for the most important exploited fish species in the Barents Sea and adjacent areas, utilizing all available information. VPA is a core component of this work, providing back-calculations of a number of individuals in each year-class. As a first step, last year's catches are structured in terms of number of individuals at different ages.

For the NEA cod stock, this work has essentially started in 1965, today analyzing all catches since 1946. The assessment methodology has been refined over time, and the computing and tuning methodology performed annually by the AFWG represents the state of the art in stock assessment.

Fig. 1 presents the cod stock history estimated by the AFWG in a condensed way as year-class layers, together constituting the total stock size in weight. The varying thickness of the layers illustrates varying year-class strength, emphasized in the figure by colours referring to the year-class strength while recruited to the fishable stock at age three years.

Quota advice is given by HCRs based on identified precautionary and critical levels of fishing mortality rates and the size of spawning biomass in the stock. Fig. 2 shows the development of fishing intensity and the spawning biomass over time from Tables 3.19 and 3.24a in Anon. (2015), both indicating successful management of the stock during the last decade. Precautionary (*pa*) and critical (*lim*) limits are given to the right, while the arrows indicate preferred directions. The data sets in Fig. 2 are presented as anomalies about critical levels, while solid black lines display the precautionary levels.

Fig. 3 compares the estimated numbers of recruits of a year-class (blue line) with the obtained catch (in thousand tonnes) of the same year-class throughout its life-span (red line). The comparison displays a striking correspondence between the two. This is not surprising, but in this case the correspondence is almost linear and about 95% of the variation in total life-span catches of a year-class is explained by the variation in recruitment to the fishable stock at the age of three years.

Sakuramoto (1995) shows how the close relationship between catch-at-age data and recruitment can be utilised to estimate relative recruitment using fuzzy logic theory. The idea of employing catch data as a recruitment measure is further developed by Mackinson et al. (1999). The recruitment measure employed below could have been calculated directly from the catch data in the way suggested by Sakuramoto (1995). In this study, however, outputs from the VPA runs have been used. Tests indicate that catch data and fuzzy rules, such as those presented by Sakuramoto (1995), are a sufficient source for calculating the suggested biological indicator values. This needs however, further investigation.

While the red line in Fig. 3 presents the total catch of each year-class from 1943 to 2001, Fig. 4 provides a more detailed description of the same, presenting the annual catches of each year-class by three panels. The lower panel presents the catches as year-class layers, corresponding to Fig. 1. The upper panel in Fig. 4 maps the age distribution in the catches, clearly indicating a rather stable peak in the catches around the age of six years.

During the period covered by Figs. 1–4, the fishery has moved from an unregulated pure open access fishery to a heavily regulated fishery, controlling both input to and output from the fishery. Is it possible to identify these substantial changes from the data obtained from the AFWG?

2. Suggested indicators of management performance

It is not straightforward to answer questions like the one above. In order to facilitate a discussion around the problem, we suggest a number of indicators believed to be useful for that purpose. The first five indicators are biological year-class indicators. Two additional environmental indicators are suggested for the special case of NEA cod.

2.1. Stock payload efficiency

The first indicator is directly linked to the observed strong correlation between year-class strength (in terms of number of recruits) and year-class catch (Fig. 3). The stock payload efficiency (*pe*) of year class *y* is the ratio between total life-span catch and the number of recruits of a year-class:

$$pe_y = \frac{\sum_{a=3}^{\infty} C_{y,a} W_{y,a}}{N_{y,3}} \quad (1)$$

when $C_{y,a}$ is the catch of year-class *y* at age *a* in individuals (in thousands, Table 3.6 in Anon, 2015), $N_{y,3}$ is the number of individuals of year-class *y* recruited at age three years (in thousands, Table 3.24a in Anon, 2015), and $W_{y,a}$ is the individual weight in kg at age *a* in year-class *y* (Table 3.8 in Anon, 2015).

2.2. Selection efficiency

The selection efficiency (*se*) is the ratio of the proportion of the catch (in weight) that is immature for year-class *y*:

$$se_y = \frac{\sum_{a=3}^{\infty} \left(1 - m_{y,a}\right) C_{y,a} W_{y,a})}{\sum_{a=3}^{\infty} C_{y,a} W_{y,a}} \quad (2)$$

when $m_{y,a}$ is the proportion of mature cod of year-class *y* at age *a* (Table 3.10 in Anon, 2015).

2.3. Average year-class weight in catch

Estimated individual weights in catch for different age groups are given in Table 3.7 in Anon. (2015). The weight indicator of each