Are F_{max} and $F_{0.1}$ really illusive as fisheries reference points?

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Abstract

In many fisheries the management objectives are based on a recommended total allowable catch (TAC) which can be framed in terms of biological reference points such as MSY or by fisheries strategies such as F_{max} and $F_{0.1}$. One of the main problems in such strategies is to estimate the location of F_{max} and $F_{0.1}$ on the Y/R-curve. Here we demonstrate through the use of an individual based model that F_{max} and $F_{0.1}$ are located at lower F-values and give higher yield than using traditional methods for calculating the Y/R-curve. Furthermore F_{max} is much better defined as the Y/R-curve has a much better defined maxima from the model than when estimated using traditional methods.

Introduction

In the past, the main objective of fisheries management was the conservation of fish stocks. In modern fisheries management this objective has been expanded to also take into account economic, social and environmental objectives. It can therefore be said that the objectives of fisheries management are quite broad and may include the conservation of fisheries resources and their environment, the maximization of economic returns and even payment of fees to the community from profits made by the fishery. Encompassing these objectives is the need to ensure that the fisheries are harvested on an ecologically sustainable basis (Quinn & Deriso, 1999).

Fisheries management must often, as stated above, address social, political, legal, economic and biological factors. Because of this fisheries management will always involve compromise but the main aim must always be the long-term sustainability of fisheries resources. This of course involves preventing biological (growth and recruitment overfishing) and economic overfishing as well as minimizing disruption to the ecosystem (Hilborn & Walters, 1992; Quinn & Deriso, 1999).

When a policy has been defined for a particular fishery then a range of management strategies designed to achieve the objectives can be considered (King, 1995). In general a management plan should contain a description of:

- 1) Exploitation and development state of the fishery at present.
- 2) The policy aims, or objectives, for managing the fishery.
- 3) The strategies to achieve the objectives.
- 4) Set of regulations that apply to the fishery.

A management strategy should not be a set of annual regulations but a long term plan that is robust enough to the unpredictable biological variations that can be expected in the stock. That means a well defined strategy should not need modifications because of unusually good or bad recruitment. Nor should there be need to change it because of economic factors such as price changes in products from the fishery. On the other hand tactics used to implement the harvest strategy each year will normally need annual adjustments (Hilborn & Walters, 1992).s.

In the early stages of a fishery, that is in a previously unexploited one, each increase in fishing effort produces an increase in yield. At this stage, catch rate will be high and will lead to more entry into the fishery. As fishing effort increases (number of boats, size of boats), the resulting increases in yield will not be as great, and mean catch rates (CPUE) will decrease. Eventually the fishing effort reaches a level so that any further increase in fishing effort will not lead to increase in yield. This level of fishing effort (F_{MSY}) is the fishing effort which is required to secure maximum sustainable yield (MSY). MSY is defined as the maximum yield that can be taken from a stock without adversely affecting future reproduction and recruitment. Increasing fishing effort will eventually result in the cost of the fishing activity exceeding the revenue obtained from the yield (Russel, 1931; Hjort *et al.*, 1933; Graham, 1933). The point where this occurs is termed the "economic breakeven point" and the fishing effort subsequently referred to as F_{BE} (King, 1995) (Figure 1).

Maximum sustainable yield (MSY) as an objective in fisheries management has been criticized as it is very hard to estimate and can easily be exceeded (Larkin, 1977; Hilborn & Walters, 1992; Stefánsson, 1997; Cook *et al.*, 1997; Punt & Smith, 2001). In spite of this a long term goal in many fisheries is still MSY (Punt & Smith, 2001). There have similarly been attempts to replace MSY with concepts such as optimum sustainable yield (OSY). Estimation of OSY is illusive as it takes into account sociological, economical as well as biological factors (King, 1995). MSY is not a good objective in the long term as stock size varies with the strength of cohorts in the stock. Setting MSY to some mean value will likely lead to overexploitation in years of low recruitment (Hilborn & Walters, 1992; King, 1995; Stefánsson, 1997)

Maximum economic yield (MEY) is based on similar principle as MSY. In an economic sense excess fishing effort occurs when the revenue generated by a marginal increase in effort is less than cost of that increase. In figure 1 this point is where the difference between the revenue and cost curve is at its maxima. MEY is obtained at a lower fishing pressure than MSY so that $F_{MSY} > F_{MEY}$ (Hilborn & Walters, 1992;



Figure 1: A fishing revenue curve and fishing cost line for a commercial fishery. The plot shows the location of maximum sustainable yield (MSY) and maximum economic yield (MEY). The economic break even point is where the revenue curve and the cost line cross. The points F_{MSY} , F_{MEY} and F_{BE} represent the level of fishing effort which corresponds to these points respectively. Redrawn from King (1995)

King, 1995; Punt & Smith, 2001).

In many fisheries the management objectives are based on a recommended total allowable catch (TAC) which can be framed in terms of biological reference points such as MSY or economic reference points such as MEY. Many fisheries are managed by a strategy called $F_{0.1}$ (Hilborn & Walters, 1992). The $F_{0.1}$ is a so called Constant Exploitation Rate (CER) strategy where the fishing mortality (denoted $F_{0,1}$) is set equal to the value of F where the slope of the yield per recruit (Y/R) function is 0.1 times the initial slope (Deriso, 1987; Hilborn & Walters, 1992; King, 1995; Stefánsson, 1997). This is illustrated in figure 2. On the other hand a fishing mortality that maximizes Y/R is often denoted as F_{max} and occurs where the slope of the Y/R function is zero (Figure 2) and if fishing mortality is increased beyond F_{max} it is termed growth overfishing. $F_{0,1}$ is always lower than F_{max} and thus in general more economically efficient (Hilborn & Walters, 1992). It should be noted that $F_{max} \neq F_{MSY}$ and that the value of F_{max} changes if the selection pattern is changed and both F_{max} and $F_{0.1}$ are long term equilibrium points. F_{max} was used as a fisheries reference point by the majority of of the International Fisheries Commissions as a long term objective of management (1950-1970) (Cadima, 2003). The main problem with using F_{max} as a reference point is the fact that for many stocks the Y/R curve is asymptotic or flat-topped and therefore it is easy to exceed the value of F_{max} . Furthermore F_{max} does not consider other factors such as the level of spawning biomass.



Figure 2: Location of $F_{0.1}$ and F_{max} level of fishing mortality in yield-per-recruit analysis. Based on figure in Deriso (1987)

Fisheries policies based on the $F_{0.1}$ strategy are widely used (Hilborn & Walters, 1992; King, 1995). As Hilborn & Walters (1992) point out $F_{0.1}$ is totally *ad hoc*, that is it is not based on any theoretical reasons for optimization or maximization of a given fishery. However, it has been demonstrated that for a range of models of population dynamics that the $F_{0.1}$ policy does not seem to reduce SSB (Deriso, 1987). Furthermore according to Hilborn & Walters (1992) $F_{0.1}$ policies are probably the most significant changes in fisheries harvesting practice since the earlier acceptance of MSY.

The aim of this paper is to compare estimates of F_{max} and $F_{0.1}$ produced by a previously published individual growth model parameterized to Icelandic cod to those produced by conventional methods. It is demonstrated that conventional methods underestimate Y/R for both of these reference points and they are achieved at a lower value of F.

Materials and methods

The model

In this paper the model proposed by Kristiansen & Svåsand (1998) is used but reparameterized for Icelandic cod. The model is based on individuals, each with its own growth trajectory which go through their lifespan independently from each other. The model predicts the life of a fish in 90 day time steps (one quarter) and in each step the fish has a size-dependent probability of surviving to the next time step and growing according to a partly deterministic growth function. If the fish dies it is either fished or it perishes from other causes according to length-dependent probability functions. If the fish does not die the loop stops at a maximum age (11 years).

In the model the initial length for an individual cod is drawn from at random from a normal distribution. The expected mean and s.d. chosen were 130mm and 34mm for age 1 cod (Guðmundsson, 2005). According to Kristiansen & Svåsand (1998) model the expected mean length of the cohort in the following time step, if there is no mortality, is:

$$L_{t+\triangle t} = L_t + I_D(L_t)\triangle t$$

where $I_D(L_t)$ is a length-dependent function for the daily length increment and L_t is mean length at the previous time step. The individual length-dependent growth rates are furthermore taken to be normally distributed, $\sim N(I_D(L_t), \sigma)$. At release each cod is allocated a constant or inherited deviation, s(i) from the mean growth rate, which is drawn randomly from the distribution $\sim N(0, \sigma)$, but to avoid unrealistic fast or slow growth only growth deviations within the 90% confidence interval are accepted (±1.6 σ). Furthermore to make the length distribution more realistic the deviation in each growth step, $s_{i,t}$ was again drawn randomly from the 90% confidence interval of the normal distribution $\sim N(s_j, \sigma/4)$. the s.d. (σ) was chosen to be independent of fish length. The function describing individual growth trajectory is:

$$L_{i,t+\triangle t} = L_{i,t} + \left(I_D(L_{i,t}) + s_{i,t}\right) \triangle t$$

In the model fish is not allowed to decrease in length and maximum growth rate can not exceed $250 \frac{mm'}{\mu ear}$.

In their parametrization for Norwegian cod Kristiansen & Svåsand (1998) implemented mean length-dependent growth rate as constants within five length intervals: <250, 250-350, 350-450, 450-900 and >900mm and the same intervals are used here. Similarly they set maximum size at 1400mm which is also assumed here. Length (L, cm)is converted to weight (W, g) by the function:

$$W = \alpha + \beta L$$

where $\alpha = 0.01$ and $\beta = 3.0$.

In Kristiansen & Svåsand (1998) model the size dependent total rate of instantaneous mortality per year, $Z(L_i)$, is the sum of the fisheries induced mortality $F(L_i)$, and natural mortality $M(L_i)$.:

$$Z(L_i) = F(L_i) + M(L_i)$$

Size dependent predation mortality is implemented in the model by a linear function in which predation mortality decreases as prey size increases up to a maximum:

$$M(L_i) = 4.325 - 0.1375(L_i)$$
 when $L_i < 30 cm$, otherwise $M(L_i) = 0.2$

According to Kristiansen & Svåsand (1998) this function produces realistic values for Norwegian cod and for lack of estimates for Icelandic cod the function is adopted here. Size-dependent fishing mortality is modelled as an S-shaped logistic curve in which relative retention is:

$$R(L_i) = \frac{1}{1 + e^{-r(L_i - L_{50}))}}$$

$$r = \frac{2\ln 3}{L_{75} - L_{25}}$$
(1)

where L_{50} denotes the length where 50% of the fish is caught by the fishery. Fishing mortality is expressed as:

$$F(L_i) = F_{Asymp}R(L_i)$$

and F_{Asymp} is fishing mortality at 100% recruitment to the fishery or more precisely when $R(L_i) = 1.0$. The size dependent probability of survival through one time step (quarter), S is modelled as:

$$S(L_i) = \mathrm{e}^{-Z(L_i)/4}$$

when $Z(L_i)$ is expressed in instantaneous length-dependent mortality per year. In the model at the beginning of each time step a random number (R_1) is drawn from a uniform distribution [0, 1], and if the number is $\leq S(L_i)$ the fish survives the quarter. If the fish dies it is either fished or it perishes from some other causes. The conditional probability of being fished, given that the fish does not survive is:

$$P(\text{fished} \mid \text{dead}) = \frac{F(L_i)}{Z(L_i)}$$

To decide if the fish is caught by the fishery a second random number R_2 is drawn from a uniform distribution [0, 1], and if the number is $\leq P(\text{fished} \mid \text{dead})$ the fish is fished, otherwise it dies from natural causes.

The model was programmed in R (R Development Core Team, 2005). Random numbers were generated by the functions **rnorm** for normally distributed variables and **unif** for uniformly distributed ones.

Model parametrization and runs

In Kristiansen & Svåsand (1998) paper the model was parameterized based on backcalculation of otoliths from tagged Norwegian cod but there is no such data for Icelandic cod. Therefore as an approach to estimate true population growth the model was run assuming $\bar{F}_{5-10} = 0.65$ which is close to long term average fisheries induced mortality of Icelandic cod (Ref). Selection pattern was set as $L_{50} = 570mm$ and $L_{75} - L_{25} = 200mm$ which results in $F_{max} \simeq 0.8$. Daily growth rates for each length intervals were adjusted so that mean length in population was close to those values reported by Guðmundsson (2005) from annual groundfish spring surveys. Similarly σ is adjusted as well. For growth intervals 1-3, daily growth rates were set to $0.34 \frac{mm}{day}$, $0.34 \frac{mm}{day}$, $0.31 \frac{mm}{day}$. Growth interval 4 was set to 85% of interval 3 and $\sigma = 0.08$.

Traditional estimates of Y/R

The standard procedure in estimating Y/R is to use mean weight at age along with a set selection pattern and then to investigate the effects of changing F. Here we use mean length at age and then derive the selection pattern using equation 1.

Effects of increased fishing mortality on growth

According to the model, increasing fishing mortality results in decrease in growth (Figure 3). This applies both to length at age in the catch and in the population. When F is increased the growth curve bends, resulting in apparent decrease in growth in the older age groups. Growth in younger age groups is not affected even though the mean length at age in catches is considerably higher than in the stock. The reason is the low fisheries induced mortality being applied because of the shape of the selection pattern.



Figure 3: Effects of fishing effort on growth in population, p (solid line) and on length at age in catches, c (dotted line)

Estimates of F_{max} and $F_{0.1}$

There is considerable difference between the "true" Y/R-curve from the model and the one estimated by traditional methods (Figure 4). Not only is the shape different as it has a more distinctive maxima but the Y/R is considerably higher for \bar{F}_{5-10} less that 0.6. Another note is the location of the reference points $F_{0.1}$ and F_{max} . Both points

are achieved at lower fishing mortality than according to the traditional method and result in considerably higher yield. Most importantly F_{max} is much better defined on the "true" Y/R-curve and the relative gain of decreasing \bar{F}_{5-10} from 0.65 or so is much greater than according to the traditional Y/R-curve. That is approximately about 20% compared to 3-5%.



Figure 4: Y/R-curve from an individually based growth model (solid line), from traditional method, assuming growth fishing at $\bar{F}_{5-10} = 0.26$ (broken line) and at $\bar{F}_{5-10} = 0.65$ (dotted line). Blue circles are estimates from single runs of 10,000 individuals.

Discussion

The results from the model runs presented here are that both F_{max} and $F_{0.1}$ are achieved at a considerably lower F than predicted using conventional methods for estimating Y/R. Furthermore the relative gain from decreasing fisheries induced mortality from 0.65, as an example, is much larger according to the model than from conventional methods. This strongly indicates that conventional estimates of F_{max} and $F_{0.1}$ are to high and in the case of $F_{0.1}$ not as precautionary as previously assumed as it is located close to the "true" F_{max} .

It should be noted that this is a preliminary exercise and is at this stage based on some simplifications and assumptions. The most significant ones are that unlike in Kristiansen & Svåsand (1998) paper we do not have back-calculated length at age for Icelandic cod. Therefore the true growth rate in the population is not known. The approach adopted here is to calibrate the model so that length at age from surveys approximates true length at age in the stock when $\bar{F}_{5-10} = 0.65$ which is close to what the Icelandic cod stock has been subjected to in recent years. This results in close to linear growth in the absence of fishing. This is similar to what has been observed from back-calculation of length at age from Icelandic haddock otoliths (Thordarson, 2005). At the MRI a project has been started to address this for Icelandic cod.

The model does not account for the possible effects of density dependent growth and as estimates of F_{max} and $F_{0.1}$ are close to M density dependent growth could affect the predictions. Though the Icelandic cod stock is well below the high historical levels observed before the 1980's density dependent-like effects can and have been observed in the stock. Incorporating density dependence into the model is a relatively easy and a worthy exercise.

In terms of management, if the model predictions have any relevance to the true Y/Rcurve of the Icelandic cod stock, the case for decreasing catch levels is much stronger than previously assumed as the marginal gain in yield is much higher. Furthermore this exercise is a food for thought in how variability in individual growth affects yield and can be easily be extended both in terms of ecological interactions but also to explore the possible evolutionary effects of size selective harvesting.

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