Abstract

Keywords:

1. Introduction

In this study we show how life history relationships can be used to

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The adoption of the Precautionary Approach to fisheries management (**?**) requires a formal consideration of uncertainty so that risk (e.g. of stock collapse) does not increase as the as the level of information decreases (**?**). The definition of the level of infomation is commonly made on the availablity of catch and effort data and hence the type of stock assessment model that can be applied e.g. **?**. The Precautionary Approach has also meant that more stocks, those by caught as well as targeted have to be assessed and managed, e,g, **?**

The Precautionary Approach requires stock status to be assessed relative to limits and targets, to predict outcomes of management alternatives for reaching the targets and avoiding the limits, and to characterise uncertainty and associated risks. However, stock assessment data sets alone may contain insufficient information to estimate key parameters that determine the productivity of populations or their susceptibility to overfishing. This to uncertainty about biological and ecological processes such as natural mortality, recruitment and population structure. However, even when data are limited, empirical studies have shown that life history parameters, such as age at first reproduction, natural mortality, and growth rate are correlated (**????**).

Life history relationships have been used to derive population parameters, see (**?**Simon et al., 2012), such as population growth rate (r) and the steepness (τ, Francis (1992)) of the stock recruitment relationship, i.e. the relative reduction in recruitment as pawning stock biomass declines (S), Although **?** found that some biological reference points were insensitive to the choice of life history parameters they were sensitive to steepness. However, subsequently (?Simon et al., 2012) showed that steepness itself is a function of life history parameters. This shows the importance of considering life history relationships within a common framework that explicitly considers the relationships between them.

Application of the precautionary approach to fishery management depends on the amount, type and reliability of information about the fishery and stocks and is applicable even with very limited information (?). A key question for fisheries management is therefore how can research be prioritised so that the impact of biological uncertainty on achieving management objectives can be reduced? In other words, how can we provide advice that is robust to uncertainty? Answering this requires an evaluation of the relative importance of the biological assumptions with respect to management measures of interest. For example, does uncertainty about the stock recruitment relationship have a relatively bigger effect on yield and sustainability than uncertainty about natural mortality?

In case of limitations of scientific knowledge a variety of qualitative, semi-quantitative and quantitative modelling methods can be used (EFSA, 2013). Important approaches in fisheries have been the Management Strategy Evaluation (MSE e.g. (????) and Bayesian analysis e.g. (????). However, such studies can be time consuming and difficult to conduct and simpler approaches such as senstivity analyses can be used to evaluate the effect of changes in parameters and assumptions on management measures (i.e. system outputs). For example when there are unquantified uncertainties a thorough sensitivity analysis should be performed to account for the known uncertainty and variability in all other parameter estimates ?. This will allow the potential impact of the unquantified uncertaintoes on the outcome of a stock assessment to be evaluated, i.e. how different the true risk might be and how likely that is.

Another approach commonly used in financial, economic and conservation management but not fisheries is elasticity anlaysis ?. Elasticity analysis measures how changing one variable affects another. The approach can also be used within fisheries management to identify the stock assumptions that have the greatest impact on management measures and therefore where the impact of uncertainty may have the greatest effect on achieving managment objectives.

Elasticity measures the relative while sensitivity measures the absolute change. An elasticity analysis will tell you how if the assumptions about the steepness of the stock recruitment relationship is more important than those about M when estimating a biological reference point such as the maximum sustainable yield (MSY). Sensitivity analyses will tell you by how much the total allowable catch (TAC) would change. Elasticity analysis has proven to be a useful tool in a number of areas of population and conservation biology, for example relating changes in vital rates to changes in the population life history **?** and to quantities of importance in management such as population viability **?**. Previously, elasticity anaysis has focused on terrestrial ecology **???** with limited application to marine populations **??**. The applicability of this approach to resource management has therefore been demonstrated and here it is used to evaluate the relative importance of the biological assumptions made in fishery stock assessments which are too seldom questioned.

2. Material and Methods

2.1. Life History

Even when data are limited empirical studies have shown that in teleosts there is significant correlation between the life history parameters such as age at first reproduction, natural mortality, and growth rate **?**. This may mean that from something that is easily observable like the maximum size it is possible to infer other life history parameters, such as natural mortality that are less easy to observe. The biologically plausible parameter space is also restricted since size-spectrum theory and multispecies models suggest that natural mortality scales with body size **?**, **?** and **?**.

Kell et al (submitted) showed how life history relationships e.g. **?** can be used to help develop simulation tools for use in stock assessment. We extend this approach to pelagic sharks using the life history parameters for the three main shark species (Shortfin mako, Blue and Porbeagle) caught in Atlantic tuna fisheries.

Life history relationships were used to parameterise an age-structured equilibrium model, where SSB-per-recruit, yield-per-recruit and stockrecruitment analyses are combined, using fishing mortality (F), natural mortality (M), proportion mature (Q) and mass (W) -at-age with a stockrecruitment relationship.

SSB-per-recruit (S/R) is then given by

$$S/R = \sum_{a=r}^{n-1} e^{\sum_{i=r}^{a-1} -F_i - M_i} W_a Q_a + e^{\sum_{i=r}^{n-1} -F_n - M_n} \frac{W_n Q_n}{1 - e_{-F_n - M_n}} \tag{1}$$

where a is age, n is the oldest age, and r the age at recruitment. The second term is the plus-group (i.e. the summation of all ages from the last age to infinity).

Similarily for yield per recruit (Y/R)

$$Y/R = \sum_{a=r}^{n-1} e^{\sum_{i=r}^{a-1} -F_i - M_i} W_a \frac{F_a}{F_a + M_a} \left(1 - e^{-F_i - M_i}\right) + e^{\sum_{i=r}^{n-1} -F_n - M_n} W_n \frac{F_n}{F_n + M_n} \tag{2}$$

The stock recruitment relationship can then be reparameterised so that recruitment R is a function of S/R

e.g. for a **?**

$$S/R = (b + S)/a \tag{3}$$

S can then be derived from F by combining equation 3 or 4 with equation 1.

There are various models to describe growth, maturation and natural mortality and the relationships between them.

Here we model growth by applying (**?**)

$$L_t = L_\infty - L_\infty exp(-kt) \tag{4}$$

where L_∞ is the asymptotic length attainable, K is the rate at which the rate of growth in length declines as length approaches L_∞, and t_0 is the time at which an individual is of zero length.

Mass-at-age can be derived from length using a scaling exponent (a) and the condition factor (b).

$$W_t = a \times W_t^b \tag{5}$$

Natural mortality (M) at-age can then be derived from the life history relationship **?**.

$$log(M) = a - b \times log(L_\infty) + c \times log(L) + d \times log(k) - \frac{e}{T} \tag{6}$$

where L is the average length of the fish (in cm) for which the M estimate applies.

While maturity (Q) can be derived as in **?** from the theoretical relationship between M, K, and age at maturity a_Q based on the dimensionless ratio of length at maturity to asymptotic length (**?**).

$$a_Q = a \times L_\infty - b \tag{7}$$

2.2. Stock Recruitment Relationships

Stock recruitment relationships are needed to formulate management advice, e.g. when estimating reference points such as MSY and F_{crash} and making stock projections. Often stock recruitment relationships are reparameterised in terms of steepness and virgin biomass, where steepness is the ratio of recruitment at 40% of virgin biomass to recruitment at virgin biomass. However, steepness is difficult to estimate from stock assessment data sets: there is often insufficient range in biomass levels to allow the estimation of steepness **?**.

We use a Beverton and Holt stock recruitment relationship reformulated in terms of steepness (h), virgin biomass (v) and $S/R_{F=0}$.

Where steepness is the proportion of the expected recruitment produced at 20% of virgin biomass relative to virgin recruitment (R_0). For the Beverton & Holt stock-recruit formulation, this equals

$$R = \frac{0.8 \times R_0 \times h \times S}{0.2 \times S/R_{F=0} \times R_0(1-h) + (h-0.2)S} \tag{8}$$

For future studies however, it may be more appropraite to alter the stock recruitment relationship used here. For some species, particularly those with low fecundity, a more appropriate stockrecruitment relationship may be one that is expressed in terms of offspring survival rather than recruitment. Unlike fish producing millions of eggs, species with low fecundity (e.g. sharks), produce few offspring per litter and exhibit relatively little variability in litter size among spawn- ers. This suggests both low productivity in general and a more direct connection between spawning output (which is commonly expressed in numbers of eggs or embryos) and recruitment than for many species. The commonly used BevertonHolt and Ricker models can be stated in terms of pre-recruit survival, with two parameters controlling the shape of the function. Both models, however, would result in survival decreasing fastest at low stock size (concave decreasing survival) even though it is reasonable to expect that for low fecundity species, offspring survival would instead decrease faster due to competition when the population approaches carrying capacity (convex decreasing survival). New methods such as the a , flexible three-parameter stockrecruitment model (MaunderTaylor-Methot stock recruitment model), based on pre-recruit survival should be investigated. This new model enables the description of a wider range of pre-recruit survival curves than either BevertonHolt or Ricker, including those that correspond to shapes ranging from convex to concave **?**.

2.3. Observer Programmes

2.4. Power Analysis

A power analysis is conducted to determine the ability to detect trends in abundance for different life histories, population distributions and sampling levels. . The power analysis is conducted for a range of survey CVs based on different observer sampling levels and evaluates the number of years required before an given change in the population can be detected. The power of a change abundance being detected is calculated using linear regression given i) estimates of survey variability (CV), ii) the number of annual surveys, iii) the relationship between CV and population density and iv) the percent rate of change (see Gerrodette, 1987 and 1991).

Conducting a power analysis requires choosing appropriate power and significance levels. The power of a statistical test is the probability of correctly rejecting a null hypothesis (H_0) when the hypothese is false (in this case the H_0 is that there has been no increase in the population). As the power increases, the chances of a Type II error (i.e. a false negative) occurring decrease (Greene 2000). Conventionally a test with power greater than 0.8 level (or $\beta <= .2$) is considered statistically powerful.

The statistical power determines the ability of a test to detect an effect, if the effect actually exists (High 2000). The significance level is chosen depending on the acceptable risk of drawing the wrong conclusion. Smaller levels of α increase confidence in the determination of significance, but run an increased risk of failing to reject a false null hypothesis (a Type II error, or "false negative"), and so have less statistical power. The selection of the level α thus inevitably involves a compromise between significance and power, and consequently between the Type I error and the Type II error.

It was also assumed i) that the survey CV was independent of population size (i.e. consistent with the stock assessment assumptions) and ii) that the population increase was linear (since the stock is recovering to B_{MSY} and so density dependence will limit population increase).

Table X show the the population increase required to detect a significant upward trend (at the 95% level) with a power of 80%, while figure Y shows the spawning stock biomass (SSB) for the six projection trajectories used to provide management advice to the Commission by the SCRS (values are relative to the 2012 level). While table Z summaries the CVs by area for the different survey designs.

These table and figures allow important questions to be answered for example e.g. If stock is a single stock what CV will be required to detect a doubling of the population within 10yrs?

Table X shows that if the CV is 25% then it will take 11 years whilst if the CV is 20% it will take 6 years, so the answer would be a CV of 20-25%. The next question would be what survey design would provide a CV of between 20

The CV of the survey is a factor that can be controlled to some extent by the design of and the funding for a survey. The population increase is determined by the biology of a stock and managment. Even with perfect managment as assumed by the Commission and the SCRS there is however considereable uncertainty about the response of the stock to managment, i.e. the SCRS projections predict that stock may increase between 50

All modelling was conducted in R using the /pkgfishmodels and /pkgFLR packages

3. Discussion

A fuller consideration of uncertainty within fisheries advice frameworks can be performed used Bayesian approaches or Management Strategy Evaluation (MSE). MSE is commonly used to evaluate the impact of different management measures, given a broad range of uncertainty. However, performing an MSE is a costly process in terms of human resources and can take several years. Therefore, tools such as elasticity analysis, which is comparatively less demanding to carry out, are important to help identify and focus research and management efforts. For example, is it more important to reduce uncertainty about the stock recruitment relationship or natural mortality or to develop harvest control rules that are robust to such uncertainty? Elasticity analyses can be used to answer such questions and prioritise research effort. It can also shift the current focus from defining populations either as data poor or rich defined solely on fishery catch and effort towards a better understanding of biological processes. Here we demonstrate the use of elasticity analysis for prioritising research effort with a study of the population dynamics of a fish population based on life history theory. As such the study is not modelled on one species of fish. First we simulate a population based on life history relationships [REF] and then by projecting the population from an unfished to an over-exploited state. We then calculate elasticities to allow us to evaluate the relative importance of the different system or biological parameters when assessing the population relative to system characteristics defined by biological reference points. This allows us to address two important questions: what is the relative importance of the different biological processes in providing advice and and how robust is advice based on the common biological reference points?

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