Sustainable exploitation of temperate fish stocks

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The theory of maximum sustainable yield (MSY) underpins many fishery management regimes and is applied principally as a single species concept. Using a simple dynamic biomass production model we show that MSY can be identified from a long time series of multi-stock data at a regional scale in the presence of species interactions and environmental change. It suggests that MSY is robust and calculable in a multispecies environment, offering a realistic reference point for fishery management. Furthermore, the demonstration of the existence of MSY shows that it is more than a purely theoretical concept. There has been an improvement in the status of stocks in the Northeast Atlantic, but our analysis suggests further reductions in fishing effort would improve long-term yields.

Keywords: maximum sustainable yield; marine; fisheries; multispecies

1. INTRODUCTION

The concept of maximum sustainable yield (MSY) in exploited fisheries has informed the management of fish stocks for many years (e.g. Punt & Smith 2001). Although initially used by managers to maximize food production, it is now recognized that achieving single species MSY can go a long way to meeting ecosystem objectives (Mace & Sissenwine 1993). In 2002, the World Summit on Sustainable Development (WSSD) made a commitment to restore the world's fisheries to MSY by 2015.

MSY corresponds to a maximum sustainable catch (yield) that represents a balance between the growth and death rate of a stock (Russell 1931). Calculation of MSY is generally done on a single stock basis and does not usually consider biological interactions between species. These may modify natural death and growth rates and hence change the position of MSY (Gislason 1999) or even question its existence as an optimum (Pope 1991). For this reason it is often dismissed by stakeholders as a theoretical concept with little practical value in fishery management (Anon. 2004).

In order to examine whether MSY can be identified in a multi-stock context we analysed stocks of five groundfish species: cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), plaice (*Pleuronectes platessa*) and sole (*Solea solea*) in the Northeast Atlantic. They are often taken together

in mixed trawl fisheries. In total, we considered 28 stocks of these species that account for approximately half of the total groundfish catch in the region (figure 1a). They are assessed annually by the International Council for the Exploration of the Sea (ICES), the organization that is recognized by regional fishery management bodies as the official source of scientific advice on fish stocks.

We fit a dynamic production model to the multi-species data and the results are discussed in the context of optimal harvest rates for the stocks. We see no reason to reject the MSY theory.

2. MATERIAL AND METHODS

We included stocks for which ICES regards the assessment as at least indicative of stock trends. Stock areas include the Arctic, Iceland, Faroe, Baltic, North Sea, Irish Sea, West of Scotland, Celtic Sea and English Channel. For each series, we rejected the estimates for the most recent two years, because these have a low precision owing to the 'convergence' feature of VPA (virtual population analysis) type models (Pope 1972). Yield data, which are complete for all years and all stocks are taken from the FAO/ICES FishStat Plus Database (www.ices.dk).

ICES provides estimates of yield, spawning stock biomass and fishing mortality from the middle of the twentieth century for the stocks considered (ICES 2007). However, data are not available for all years and stocks (table 1). To obtain aggregate estimates of spawning stock biomass for all years from 1950 we used a factor analysis procedure (Rosenberg *et al.* 1992) to fill in the missing years for stocks with incomplete data and then summed across stocks to obtain a total figure for biomass in the Northeast Atlantic. The fill-in procedure extracted a single factor from the data (i.e. the annual biomass) and then used the estimated factor scores to fill in the missing values iteratively until convergence was achieved (Little & Rubin 1987).

We used a similar process for filling in missing values of fishing mortality and then took a simple mean across stocks as a measure of total fishing effort in the region. A simple mean was preferred to, for example, a biomass weighted mean, as even small stocks contribute information to the general population dynamics. As all stocks had a rather similar development over time in fishing mortality and stock development, the method is not very sensitive to this alternative approach. The fill-in procedure will help correct for bias in the total estimates, but will not, of course, improve the precision of the estimates, which will remain low for the early years.

To obtain an analytical value for MSY we fitted a simple dynamic biomass production model (Fletcher 1978) to the time series of aggregate yield, spawning stock biomass and fishing effort. The model was fit to the time series of observed annual spawning stock biomass B_t , yield Y_t and fishing effort E_t . The model, where m and B_∞ are estimated parameters corresponding to MSY and spawning stock biomass in the absence of fishing, was the general Pella–Tomlinson model (Pella & Tomlinson 1969):

$$B_{t+1} = \left(1 + \frac{\gamma m}{B_\infty}\right) B_t - \frac{\gamma m}{B_\infty} B_t^n - Y_t$$

where n determines the shape of the yield curve and

$$\gamma = \frac{n^{n/(n-1)}}{n-1}$$

We assumed $Y_t = qE_tB_t$, where q is a catchability constant and t is an index for year. The model was fit by setting $n = 2$ for the Schaefer model (Schaefer 1954) and minimizing the sum of squares:

$$\sum \{w_B [w_B (\ln(B_t/\hat{B}_t))^2 + w_E \ln(E_t/\hat{E}_t)^2 + w_Y \ln(Y_t/\hat{Y}_t)^2]\}$$

where 'hatted' quantities are fitted values and w_i is an annual weight determined by the number, j , of stocks represented in the annual biomass estimate,

$$w_i = \frac{\sqrt{j_i}}{\sqrt{j_{\max}}}$$

The weights w_B , w_Y and w_E are relative weights given to the different data, with a default value of one.

In order to investigate uncertainty, we performed a sensitivity analysis that considered different data weighting regimes, examining two subsets of years, a different data fill-in procedure (see the electronic supplementary material) and alternative relationships between yield, biomass and effort.

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Figure 1. (a) Commercial catch of groundfish stocks included in the analysis (solid shading) in relation to the total stocks (unshaded). (b) Long-term trends in fishing effort (thin line), spawning stock biomass (broken line) and yield (heavy line). The trends have been smoothed using a 15-year running mean. (c) Observed annual values of spawning stock biomass plotted against fishing effort. The solid line shows the predicted equilibrium values derived from the Schaefer model. (d) Observed annual values of yield plotted against fishing effort. The solid line shows the predicted equilibrium values from the Schaefer model. MSY is indicated by a vertical line.

3. RESULTS

Figure 1b shows the 15-year running-mean trends in yield, spawning stock biomass and fishing effort from 1950 to 2003. Up to the early 1990s increasing fishing effort and decreasing spawning stock biomass can be observed, with yield showing a clear maximum in the early 1970s. These trends show the classic characteristics of a conventional equilibrium yield plot where, as fishing effort increases, equilibrium biomass declines and equilibrium yield shows a maximum at the trade-off between population growth and mortality due to fishing. If we assume that over the period of observation the annual changes in fishing mortality are small and approximate to local equilibria, then it follows that the observed yield curve in figure 1b would correspond to equilibrium yield. It implies that MSY was achieved when the total catch reached approximately 3 million tonnes and $E_{\text{MSY}} = 0.55$.

Figure 1c,d shows the estimated relationship between equilibrium biomass and yield derived from the model (solid line) with the annual observed values over-plotted. Although annual values will be displaced from the equilibrium, over time they should show a tendency to return towards the equilibrium. In figure 1c the annual estimates of biomass do tend to follow the predicted equilibrium downwards as effort increases and they track the equilibrium closely at the higher effort values. This would be consistent with the annual biomass values being near local equilibria. Figure 1d shows similar agreement between equilibrium yield and annually observed yield. The model predicts fishing effort at $E_{\text{MSY}} = 0.46$ and MSY at 2.6 million tonnes. These are similar to, although slightly lower than, the values derived from inspection of figure 1b.

Table 1. The number of stocks with biomass and fishing mortality data for each year. From 1982 to 2003 there are complete data for all 28 stocks.

year	number
1950	2
1951	2
1952	2
1953	2
1954	2
1955	3
1956	3
1957	6
1958	6
1959	6
1960	7
1961	8
1962	9
1963	11
1964	12
1965	12
1966	13
1967	14
1968	15
1969	16
1970	18
1971	21
1972	21
1973	21
1974	21
1975	21
1976	22
1977	23
1978	25
1979	26
1980	27
1981	27

Table 2. Results of sensitivity analysis. The base model run with $n = 4$ corresponds to a Pella–Tomlinson model (Pella & Tomlinson 1969) where the relationship between equilibrium yield and biomass is asymmetric in contrast to the parabolic Schaefer model. High weight to residuals was a factor of two compared to the base model weighting of one. The equilibrium fit is the Schaefer model assuming that the annual data represent equilibrium values.

model configuration	q	MSY	B_{∞}	E_{MSY}	coefficient of determination
base model, all years 1950–2003, $n = 2$	1.35	2.57	8.29	0.46	0.737
as base model but with different fill-in procedure	1.30	3.08	11.88	0.39	0.825
as base model but $n = 4$	1.37	2.60	5.74	0.53	0.764
no down-weighting of historical data	1.40	2.48	7.42	0.48	0.751
high weight to catch residuals	1.35	3.98	16.51	0.36	0.859
high weight to biomass residuals	1.36	2.54	8.11	0.46	0.872
high weight to effort residuals	1.36	2.52	7.88	0.47	0.757
fit to 1982–2003	1.19	2.27	7.84	0.49	0.948
fit to 1950–1981	1.56	2.84	5.57	0.65	0.874
equilibrium model fit	1.37	2.44	7.01	0.51	0.502
alternative relationship between yield and effort, $Y = (1 - e^{-qE})B$	2.65	3.57	14.62	0.25	0.731

Results of the sensitivity analysis are shown in table 2. These demonstrate that model estimates have greatest sensitivity to the catch data, the choice of year range in the analysis and the structural relationship between yield and biomass. They are relatively insensitive to alternative data weighting regimes. Examining the early period up to 1981 gives a much higher value of E_{MSY} , which is nevertheless inconsistent with the direct observation in figure 1b. The later period (1982–2003) gives values similar to the baseline model and corresponds to the period where there are no missing data. The similarity of the estimates obtained from this run, the baseline model run and direct observation in figure 1b, supports the view that the true values are likely to lie in the region estimated by these analyses. Nevertheless, the flatness of the yield curve and the sensitivity of the estimates to catch assumptions mean that the MSY values are somewhat uncertain.

4. DISCUSSION

The gradual increase in fishing mortality from 1950 to the present time offers a natural experiment to discover the value of MSY. This has happened against a background of environmental change, including periodic inflows of oceanic water to the Baltic (Matthäus & Franck 1992) and periods of cooling and warming (Clark *et al.* 2003). The ‘experiment’ also includes biological interactions between fish stocks. The species concerned are all predators, and some such as saithe and cod are known to be major predators both of themselves and of other species included in the analysis (ICES 1997). It is noteworthy that maximum yield is readily identifiable and that it is consistent with a simple production model that ignores species interactions and assumes constancy of the environment. Furthermore, the maximum observed yield obtained corresponds to the maximum sustainable yield predicted from an equilibrium model with specific simplifying assumptions.

It is possible that the observed trends could be explained by a corresponding covariate rather than the

MSY theory. A warming trend might explain decreasing cod biomass (Beaugrand *et al.* 2003; Clark *et al.* 2003). Both direct observation of the trends in figure 1b and the Schaefer model fit would be susceptible to this problem. However, in the most recent years, the long-term increase in fishing mortality has been reversed and is matched by a corresponding increase in spawning stock biomass (figure 1b). This observation is consistent with the MSY theory rather than with environmental forcing, because long-term external forcing would be expected to continue to determine the biomass trend, regardless of the change in fishing effort.

As many stocks, especially those in the Northeast Atlantic, are fished above E_{MSY} (ICES 2007) according to estimates using single species models, there is pressure from fishers to justify the concept as a valid basis for management (Schiermeier 2004). It is argued frequently that declining stocks are driven primarily by environmental change (Beaugrand *et al.* 2003; Clark *et al.* 2003; Anon. 2004), or that MSY based on single species models is not meaningful in the presence of biological interactions between stocks. Our analysis does not support that view. Both observation from historical stock trends and the application of an aggregate stock production model appear to provide consistent estimates of MSY. The most recent estimates of fishing effort are close to 0.60 compared to the model estimates of E_{MSY} of 0.46. Given that fishing effort, as measured by fishing mortality, is decreasing and spawning stock biomass is increasing, it would appear possible that at a regional scale MSY is an achievable target for fishery management by reducing exploitation to rates experienced in the late 1960s.

A corollary of our results is that the excessive amount of fishing effort currently being expended is wasting valuable cash for fishers and also taxing resources of fuel, fishing vessels and fishing gear.

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