

# Fisheries for small pelagic species: an empirical approach to management targets

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## Introduction

Fisheries management in its pure form consists of applying a set of fishery control measures in order to bring some measured parameter of a fish stock towards a specific target, with the objective of optimizing some specified aspect of the fishery. Here I review briefly some of the more commonly used objectives and targets with particular reference to small pelagic fish stocks, and propose a new target for managing a fishery towards a stable spawning stock biomass in situations where few data are available.

## Management objectives and targets in current use

The best-known objective for managing fisheries is maximum sustainable yield (MSY). This is the maximization of long-term sustainable yield by the management of effort and selection in a fishery. Its use involves a number of disadvantages, which have been reviewed by Larkin (1977) and Gulland (1977, 1978). These include the problem that a fishery managed for MSY will tend to be poorly profitable and will be vulnerable to collapse where environmental fluctuations affect the managed stock (Beddington and May, 1977).

MSY management targets can be calculated from surplus-production or from age-structured models. Examples of the former include the  $f_{\max}$  and the estimated MSY catch.

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Using age-structured models, targets such as the  $F_{0.1}$ ,  $F_{max}$ , and MSY catch can be defined. These are described in more detail below. A list of mathematical symbols used in this review appears in Appendix 1.

#### SURPLUS PRODUCTION MODELS

A large family of surplus-production models now exists, but these are essentially rather similar. The models of Schaefer (1957) and Fox (1970) are well known, but other useful models include those of Pella and Tomlinson (1969), Shepherd (1982, 1987) and Caddy and Csirke (1983). Traditional parameter estimation procedures were based on the assumption of equilibrium catch and effort data, but such methods have been shown to be strongly biased (Hilborn and Walters, 1992). Discrete dynamic time-series models are now preferred (e.g. Butterworth and Andrew, 1984). Such models are simple, require few data for fitting, and have the advantage of implicitly including a stock-recruitment relationship.

One of the targets that can be calculated from these surplus-production models is the fishing effort for maximum sustainable yield ( $f_{max}$ ). This is not always useful as a management tool because of short-term changes in catchability and on account of progressive improvements in fleet catchability. On occasion, the estimated MSY itself has been used as a management target. More generally, surplus-production models can be used to manage the stock size to a target biomass,  $B^*$ , according to a number of different strategies, which have been reviewed by Punt (1991). A summary of his review is given below. Management strategies based on surplus-production models include a straightforward constant effort strategy, where the total allowable catch (TAC) for the following year,  $TAC_{(n+1)}$ , is calculated as

$$B_n g(B^*)/B^*$$

where  $B_n$  is the stock biomass in year  $n$ , and  $g(B^*)$  is the equilibrium yield predicted by the surplus-production model for  $B^*$ . Using this strategy, effort will be stabilized and, depending on the amount of environmentally driven stochastic variation in the stock size, the stock size will be stabilized at  $B^*$ . An alternative strategy (Clark, 1976; Walters, 1986) is to attempt to bring the stock size to  $B^*$  as rapidly as possible, by setting the total allowable catch in the following year,  $TAC_{(n+1)}$ , to zero if the projected biomass for the next year is lower than  $B^*$ , but otherwise setting the TAC to the estimated surplus production above  $B^*$ , i.e.

$$TAC_{(n+1)} = B_n + g(B_n) - B^* \quad \text{if } B_n + g(B_n) > B^* \quad \text{otherwise } 0$$

This strategy, as Punt (1991) notes, is likely to be unacceptable to industry on account of the large inter-year fluctuations in TAC. However, a constant-catch strategy is highly risky except in cases where the target biomass is a very high proportion of the unexploited stock size, because environmental fluctuations will tend to drive the stock to extinction in cases where a constant catch is taken each year (Beddington and May, 1977).

The maximum allowable catch (MAC) strategy of Butterworth (1987) is a rather conservative strategy in which the estimated surplus production at the target population size is taken when current stock size equals or exceeds this target population size, but a reduced proportion of this yield is taken at lower stock sizes, i.e.

$$TAC_{(n+1)} = g(B^*) \cdot B_n / B^* \quad \text{if } B_n < B^* \quad \text{otherwise } g(B^*)$$

This procedure has advantages in terms of both catch stability and yield, and is likely to result in cautious management.

A further target is management to  $f_{0.1}$ , a parameter which is a measure comparable to  $F_{0.1}$  but based on effort in the surplus-production model rather than fishing mortality in the age-structured model. Details of the calculation of  $F_{0.1}$  are given below:  $f_{0.1}$  is calculated analogously. Arguments for the use of  $f_{0.1}$  rather than  $f_{\max}$  depend on expected economic benefits and more conservative biomass maintenance rather than avoidance of stock-recruit dependency.

#### AGE-STRUCTURED MODELS

MSY targets can also be calculated using age-structured models. If a possible decline in recruitment at lower stock sizes is ignored, fishing at maximum yield per recruit approximates to fishing at MSY. Stock-recruitment effects can be included if there is sufficient information about such a relationship. This target is the fishing mortality for maximum yield per recruit ( $F_{\max}$ ), which can be calculated using Thompson and Bell's (1934) age-structured forecast model, or the Beverton and Holt (1957) model, which is an integration that assumes knife-edge selection. Using  $F_{\max}$  involves assuming that stock-recruit effects are unimportant, which may be unrealistic.

Expansion of the model to take account of the dependence of recruitment on stock size explicitly is a rather complex task and one that is rarely attempted. However, a management target which attempts to include a consideration of declines in recruitment is the  $F_{0.1}$  target (Gulland, 1984). This is usually estimated by first plotting projected yield per recruit on fishing mortality  $F$ .  $F_{0.1}$  is the fishing mortality corresponding to 10% of the maximum rate of yield per recruit increase with respect to  $F$ . It is obtained by solving numerically for  $F_{0.1}$  in

$$\frac{dY}{dF_{0.1}} = 0.1 \times \frac{dY}{dF_0}$$

where  $Y$  is the yield and  $F_0$  is a fishing mortality approaching zero.

An additional argument for using the  $F_{0.1}$  target is that it is presumed to yield economic benefits even where stock-recruit considerations are unimportant.

#### TARGETS FOR SMALL PELAGIC SPECIES

These targets are not necessarily useful in the management of small pelagic shoaling species however. Using MSY as a management objective in a constant-catch strategy is likely to lead to stock collapses (Beddington and May, 1977). The use of yield-per-recruit targets for long-term management of pelagic fisheries has been specifically discouraged (Anonymous, 1983), largely because  $F_{\max}$  mortalities can lead to stock sizes that are so low that declines in recruitment are likely to occur. This is a consequence of the fast growth and high natural mortality in these stocks. In addition, there is little evidence that  $F_{0.1}$  fishing leads to stock sizes that are safe from stock-recruitment declines.

One appropriate management strategy to avoid such an occurrence is to manage effort to maintain a stable spawning stock biomass (SSB) (Saville, 1980). As well as avoiding problems of recruitment failure, this strategy also has benefits in that catch variability between years is reduced. Often in pelagic fisheries, environmental variability has strong effects on recruitment and even sometimes on adult mortality. Such effects provoke

considerable natural variability in even unexploited pelagic fish stocks, but it is nevertheless a legitimate management objective to avoid exacerbating environmentally driven stock declines by poorly directed fishing activity. Consequently, the preferred objective for managing a stock of shoaling fish is the avoidance of a stock-recruit collapse by maintaining a stable spawning stock biomass above a determined critical level.

The critical biomass level may be determined as a level some 20% to 40% of the unexploited stock size (Goodyear, 1989), simply as the lowest historical stock size at which no negative effects on recruitment have been observed, or as the level at which in historical analyses a larval survival rate in the highest decile was required in order to achieve recruitment in the highest decile of historical values (Serebryakov, 1990). Serebryakov also defines a 'safe' level, which is the stock biomass at which a median survival rate allowed recruitment in the highest decile.

There has been a perceived need, therefore, to define fishing mortality targets that can be used to manage a fishery towards a stable stock biomass. Such targets are the  $F_{low}$ ,  $F_{med}$ , and  $F_{high}$  reference points (Anonymous, 1983). These are the fishing mortalities at which historical data on recruitment suggest that the stock has respectively an over 90%, a 50%, or a worse than 10% chance of maintaining its spawning stock biomass. The targets are calculated by plotting by eye lines of SSB per recruit that pass through the origin of an SSB/recruit scatterplot and dividing the points into 10%, 50% and 90% sectors. The three values of SSB per recruit are then located on an SSB per recruit projection plot for different values of  $F$ , and the three critical values of  $F$  can usually be identified, although they are not always all defined for all stocks. Yield per recruit is usually plotted on the same graph, such plots now typically being included in most recent ICES stock assessments. An example is given in Fig. 1, and a fuller description and critique of the method is given in Sissenwine and Cohen (1991). Sissenwine and Shepherd (1987) criticize this methodology in that it makes no explicit assumption about the form of the stock-recruit relationship. In the absence of an explicit relationship, they argue, inclusion of stock-recruit information is inappropriate and may be misleading. However, the assumption that such a relationship exists is more likely to lead to cautious resource management.

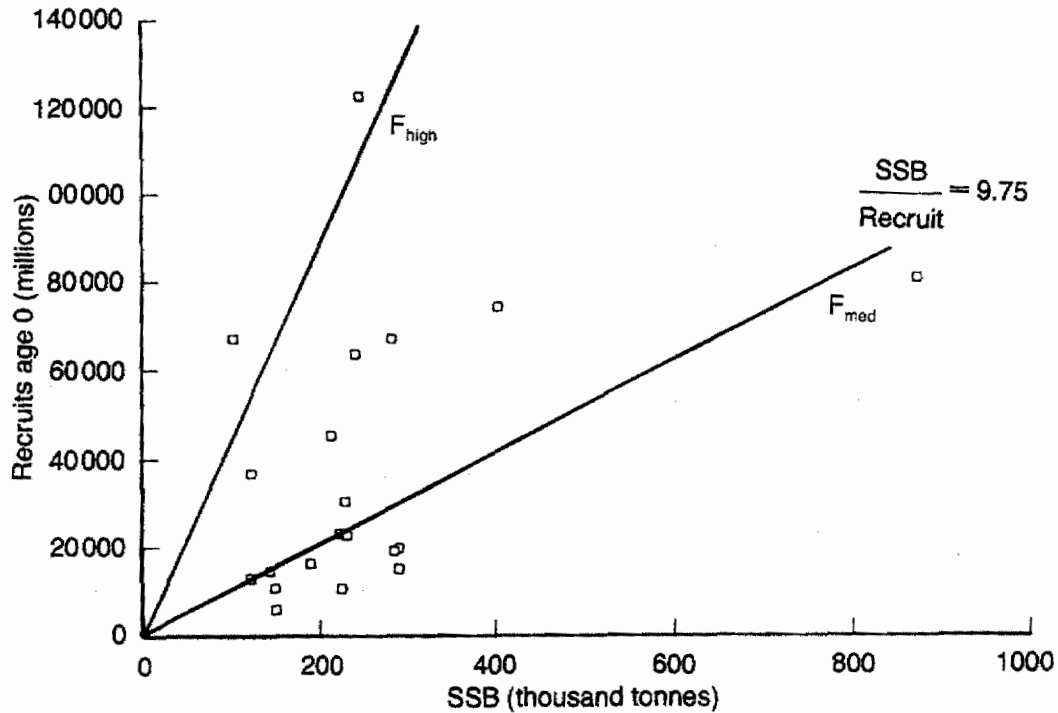
Pelagic stocks, especially in areas of upwelling, are notoriously affected by environmental fluctuation, so that even in the absence of exploitation, stock sizes will fluctuate considerably (Lluch-Belda *et al.*, 1989). However it remains a valid management objective to attempt to avoid stock declines that are driven principally by exploitation.

A summary of current management targets and corresponding management measures for some exploited small pelagic fish stocks is given in Table 1. This shows that in most stocks of small pelagic fish, the management target is the maintenance of spawning stock biomass, either explicitly or by management to a target such as  $F_{med}$ .

#### AN EMPIRICAL APPROACH

Walters (1986) argues that modelling the response of marine ecosystems to exploitation can often be more effective if no attempt is made to model in detail the many and complex processes that are occurring simultaneously. Instead, he proposes that better predictive models can be built by investigating the real responses of exploited ecosystems as observed under a variety of conditions, hence developing simple models that model these responses. Here I propose an approach which is closer to Walters' philosophy than to management methods in current use.

(a)



(b)

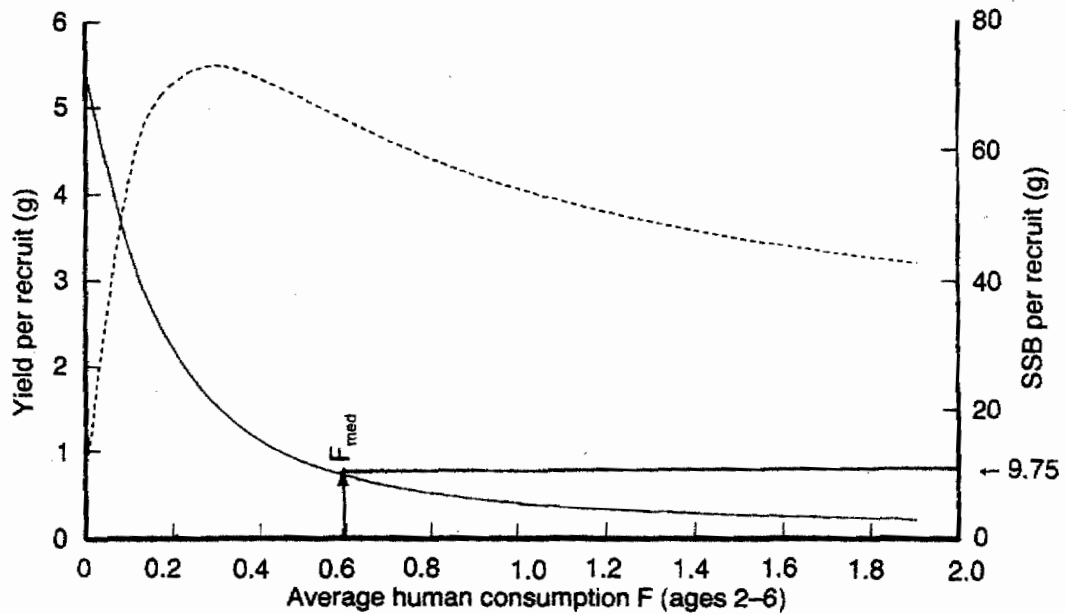


Fig. 1. An example of the calculation of the  $F_{med}$  and  $F_{high}$  target fishing mortalities, for haddock, *Melanogrammus aeglefinus*, in the North Sea (reproduced with permission from Anonymous, 1991). (a) Stock-recruit scatterplot on which the median survivorship line is drawn by eye, and the slope of this line is estimated. (b) Yield (broken curve) and spawning stock biomass (solid curve) per recruit, calculated from an age-structured projection for various values of fishing mortality, used to identify the fishing mortality corresponding to the median historical survivorship.

**Table 1.** Some examples of targets used in the management of small pelagic fish, together with the management measures used in controlling the fisheries.

Species	Area	Target*	Management measure*	Reference
<b>Clupeidae</b>				
<i>Sardina pilchardus</i>	Biscay	$F_{med}$	TAC	Anonymous (1989a)
<i>Sardinops sagax</i>	California	MSY catch	TAC (collapsed)	MacCall (1979)
<i>Clupea harengus</i>	Norway	SSM	TAC	Anonymous (1989f)
	North Sea	SSM	TAC	Anonymous (1989b)
	Clyde	SSM	TAC	Anonymous (1989b)
	Celtic Sea	SSM	Closed area	Anonymous (1989b)
	Irish Sea	SSM	TAC and closed area	Anonymous (1989b)
	NW Atlantic	$F_{0.1}$	TAC	Anonymous (1988)
	<i>Hilsa kelee</i>	India	Max YPR	None
<i>Hilsa kelee</i>	Mozambique	Max YPR	Mesh size regulation suggested	Sousa (1988)
<b>Scombridae</b>				
<i>Scomber japonicus</i>	California	SSM	TAC	Parrish and MacCall (1978)
<i>Scomber scombrus</i>	North Sea	SSM	TAC and closed area	Anonymous (1989c)
<b>Carangidae</b>				
<i>Trachurus trachurus</i>	NE Atlantic	SSM	TAC	Anonymous (1989a)
<b>Osmeridae</b>				
<i>Mallotus villosus</i>	Barents Sea	SSM	TAC	Anonymous (1989f)
	Iceland	SSM	TAC	Anonymous (1989f)
	NW Atlantic	SSM	TAC	Anonymous (1988)
<b>Various</b>				
Small pelagics	Philippines	MSY, MEY	None	Dalzell (1988)

\*Abbreviations: MEY, maximum economic yield; MSY, maximum sustainable yield; SSM, spawning stock maintenance; TAC, total allowable catch; YPR, yield per recruit.

This empirical methodology is less demanding of data than the traditional methods, and so may be of particular interest in developing countries, where it is unlikely that  $F_{med}$  or even the spawning stock maintenance targets can be used. Substantial time-series of data are required for their estimation, and both targets depend on the use of reasonably long series of stock and recruitment data, which typically are not available in situations where only a short time-series of data may be available. There is a perceived need, therefore, for some simple target that would help in managing a pelagic fishery to stabilize the stock biomass. This note describes a possible empirical approach. Instead of detailed models for single stocks, a simple general model is proposed which relates the response of pelagic stock biomasses to exploitation, based on available historical data from a variety of stocks.

To assess the likely consequence of various exploitation intensities on spawning stock biomass in fisheries for small pelagic fish, a brief review of available literature was made, and the medium-term effect of various levels of exploitation on the stock biomass was investigated. Time intervals of around 10 years were used, although shorter periods were included if unavoidable. No period shorter than 5 years was used. Where available, spawning stock biomass was used, but in certain cases only total biomass was available and this was used. Also as available, the mean fishing mortality on exploited age groups weighted by population size was used, although in many cases an unweighted  $F$  only was available. As comparisons were to be made across species and stocks, measures of change in stock size and of exploitation that were independent of both species and stocks were needed. The chosen measure of rate of change in stock size (usually spawning stock biomass, SSB) was  $\ln(B_i/B_j)/t$ , where  $B_i$  and  $B_j$  are stock biomasses at the start and finish of time period  $t$ . This provides a measure of change in stock size independent of absolute size. To account for species differences in natural mortality  $M$ , the fishing intensity measure used was the exploitation rate ( $E=F/Z$ ). The estimates of  $M$  used in the stock assessments were used to calculate yearly exploitation rates. Means of these values over the time period  $t$  were used as measures of fishing intensity.

Only results from conventional age-based virtual population analysis (VPA) was used, these being considered more reliable. Inevitably, a large part of the data used was from exploited fisheries in the ICES and North American areas. However, data from subtropical areas in the southern USA and in south-west Africa have also been included. Data are from herring and sardine stocks (Clupeidae), mackerel (Scombridae), scad (Carangidae) and two pelagic gadoids, Norway pout, (*Trisopterus esmarkii*), and blue whiting, (*Micromesistius poutassou*).

The stocks used for this analysis are given in Table 2, and the data from them are summarized in Table 3. A scatterplot of data is given as Fig. 2, together with a fitted GM (Ricker, 1973) regression line (Table 4). A GM (geometric mean) regression was used because there is likely to be as much variation in estimates of  $E$  as in the estimates of biomass change.

As might be expected, Fig. 2 shows increasingly negative rates of change of biomass with increasing  $E$ . The fitted regression crosses the 'change in biomass' axis at zero for  $E =$  approximately 0.4, suggesting that exploitation rates above 0.4 ( $F = 2/3 M$ ) have been associated with stock declines whilst below this level the tendency has been towards stock recovery. There is a wide scatter of points in the central region around  $E = 0.3$  to  $E = 0.5$ , suggesting that a stock is as likely to increase as to decrease. Above 0.5 ( $F = M$ ), very few stocks have been able to sustain themselves and a decline in SSB seems to have been inevitable. Exploitation below 0.3 ( $F \approx 1/2 M$ ) has allowed stocks to increase in size.

From Fig. 2 some immediate and obvious implications arise. Over 10-year periods, mean exploitation rates in excess of 0.5 have consistently caused stock biomasses to decline. Any stock that has a mean long-term exploitation rate (calculated in the way described above) of over 0.5, based on past experience is likely to suffer a decline in stock size. Conversely, reduction of the exploitation rate in an exploited fishery to below 0.3 is likely to allow a stock to recover. At intermediate exploitation rates, stock may either decline or increase.

This advice may be quantified somewhat. Using the fitted GM model (which has a normal distribution of residuals,  $p < 0.70$ ) one may calculate the probability that an

**Table 2.** Stocks used in the model. Areas in Roman numerals are ICES fishing areas; those in Arabic numerals refer to Baltic Sea divisions. Biomass is either total (T) or spawning stock biomass (SSB) and is in thousand tonnes, except where marked (+) in which biomass is in tonnes. Mean fishing mortality  $F$  is across the stated range of ages and is either weighted (W) or unweighted (U) by population size at age. Natural mortality  $M$  is as used by the author except where marked (\*), in which a mean  $M$  was calculated from a variable  $M$  at age.

Stock no.	Species	Area	Biomass	$F$	$M$	Reference
<b>Mackerals Scomber spp. (Scombridae)</b>						
1	<i>S. japonicus</i>	California	SSB	$F_{4+,U}$	0.5	Parrish and MacCall (1978)
2	<i>S. scombrus</i>	E Atlantic	SSB	$F_{4-8,W}$	0.15	Anonymous (1989c)
3	<i>S. scombrus</i>	NW Atlantic	SSB	Mean $F, W$	0.3	Anderson and Paciorkowski (1980)
4	<i>S. japonicus</i>	South Africa	T	Mean $F, W$	0.5	Newman and Crawford (1980)
<b>Herrings Clupea and Etrumeus; sprats Sprattus (Clupeidae)</b>						
5	<i>C. harengus</i>	N North Sea	SSB	$F_{2-6,U}$	0.15*	Anonymous (1989b)
6	<i>C. harengus</i>	North Sea IV	SSB	$F_{2-6,U}$	0.15*	Anonymous (1989b)
7	<i>C. harengus</i>	ICES VIIG-J	SSB	$F_{2-6,U}$	0.15*	Anonymous (1989b)
8	<i>C. harengus</i>	Clyde	SSB+	$F_{2-6,U}$	0.15*	Anonymous (1989b)
9	<i>C. harengus</i>	Ireland	SSB+	$F_{2-7,U}$	0.15*	Anonymous (1989b)
10	<i>C. harengus</i>	N Irish Sea	SSB	$F_{2-7,U}$	0.15*	Anonymous (1989b)
11	<i>C. harengus</i>	Norway	SSB	$F_{4-16,W}$	0.13	Anonymous (1989f)
12	<i>C. harengus</i>	Finland Gulf	SSB	$F_{2-5,U}$	0.15	Anonymous (1989g)
13	<i>C. harengus</i>	Iceland spring-spawning	SSB+	$F_{4-15,W}$	0.1	Jakobsson (1980)
14	<i>C. harengus</i>	Iceland summer-spawning	SSB	$F_{3-10,W}$	0.1	Jakobsson (1980)
15	<i>C. harengus</i>	Georges Bank	T	$F_{4+,U}$	0.2	Anthony and Waring (1980)
16	<i>S. sprattus</i>	Baltic [22-25]	SSB	$F_{1-5,U}$	0.40	Anonymous (1989g)
17	<i>S. sprattus</i>	Baltic [26-28]	SSB	$F_{2-6,W}$	0.50	Anonymous (1989g)
18	<i>S. sprattus</i>	Baltic [27, 29-32]	SSB	$F_{2-8,W}$	0.3	Anonymous (1989g)
19	<i>S. sprattus</i>	Baltic [22-32]	SSB	$F_{2-6,W}$	0.4	Anonymous (1989g)
20	<i>E. teres</i>	South Africa	T	$F, W$	0.5	Newman and Crawford (1980)



Sardines <i>Sardinops</i> (Clupeidae)							
21	<i>S. sagax</i>	California	T	$F_{4+,U}$	0.4	MacCall (1979)	
22	<i>S. ocellata</i>	South Africa	T	$F_5, W$	0.5	Newman and Crawford (1980)	
Sardines <i>Sardina</i> (Clupeidae)							
23	<i>S. pilchardus</i>	ICES VIII, IXA	SSB	$F_{2-6,U}$	0.4	Anonymous (1989a)	
Scad <i>Trachurus</i> sp. (Carangidae)							
24	<i>T. trachurus</i>	ICES VI, VII	SSB	$F_{5-11,U}$	0.15	Anonymous (1989a)	
25	<i>T. trachurus</i>	ICES VIII, IX and IX	SSB+	$F_{1-7,U}$	0.20	Anonymous (1989a)	
Norway pout <i>Trisopterus</i> sp.; blue whiting <i>Micromesistius</i> sp. (Gadidae)							
26	<i>T. esmarkii</i>	North Sea	SSB	$F_{1-3,U}$	1.6	Anonymous (1989d)	
27	<i>M. poutassou</i>	N Atlantic	SSB	$F_{4-8,U}$	0.2	Anonymous (1989e)	
28	<i>M. poutassou</i>	NE Atlantic	SSB	$F_{4-7,U}$	0.2	Anonymous (1989e)	

**Table 3.** Data used to fit the model. Stock numbers refer to Table 2. Biomasses are given in thousands of tonnes (except in tonnes, where marked (+) in Table 2). See text and Table 2 for the manner of calculating mean exploitation rate.

Stock no.	Years, 1900+		Biomass		Mean exploitation rate, <i>E</i>
	start	end	start	end	
1	29	39	248	150	0.36
1	40	49	150	96	0.67
1	50	59	96	80	0.65
1	60	67	80	3	0.63
2	72	79	3529	2071	0.23
2	80	87	2071	1713	0.32
3	62	69	1501	6655	0.20
3	70	77	6655	1194	0.57
4	68	75	286	228	0.41
5	72	79	273	153	0.45
5	80	85	153	796	0.25
6	47	57	4451	1406	0.37
6	58	67	1406	439	0.47
6	68	77	439	79	0.68
6	78	85	79	927	0.32
7	70	80	90	30	0.50
7	81	85	30	107	0.47
8	70	79	10165	8713	0.47
8	80	85	8713	16625	0.32
9	70	79	145	108	0.34
9	80	85	108	51	0.42
10	72	79	34	6	0.58
10	80	85	6	25	0.39
11	78	86	403	491	0.17
12	70	79	110	106	0.43
12	80	87	106	159	0.40
13	47	56	126	119	0.41
13	57	66	119	10	0.74
13	67	72	10	0.3	0.90
14	47	56	136	156	0.66
14	57	66	166	81	0.74
14	67	77	81	107	0.63
15	61	69	304	602	0.57
15	70	77	602	270	0.76
16	70	79	404	19	0.36
16	80	87	19	41	0.36
17	79	87	76	229	0.31
18	70	79	578	79	0.34
18	80	87	79	91	0.24
19	74	80	891	137	0.41
19	81	87	137	641	0.22
20	64	75	22	33	0.43
21	45	55	720	108	0.55

Table 3. continued.

Stock no.	Years, 1900+		Biomass		Mean exploitation rate, <i>E</i>
	start	end	start	end	
21	56	64	108	3	0.65
22	50	59	947	1940	0.10
22	60	69	1940	222	0.39
22	70	75	222	529	0.39
23	76	87	170	608	0.35
24	82	87	511	827	0.24
25	81	87	205	205	0.29
26	76	87	472	145	0.63
27	78	86	6038	4248	0.30
28	81	86	39	26	0.66

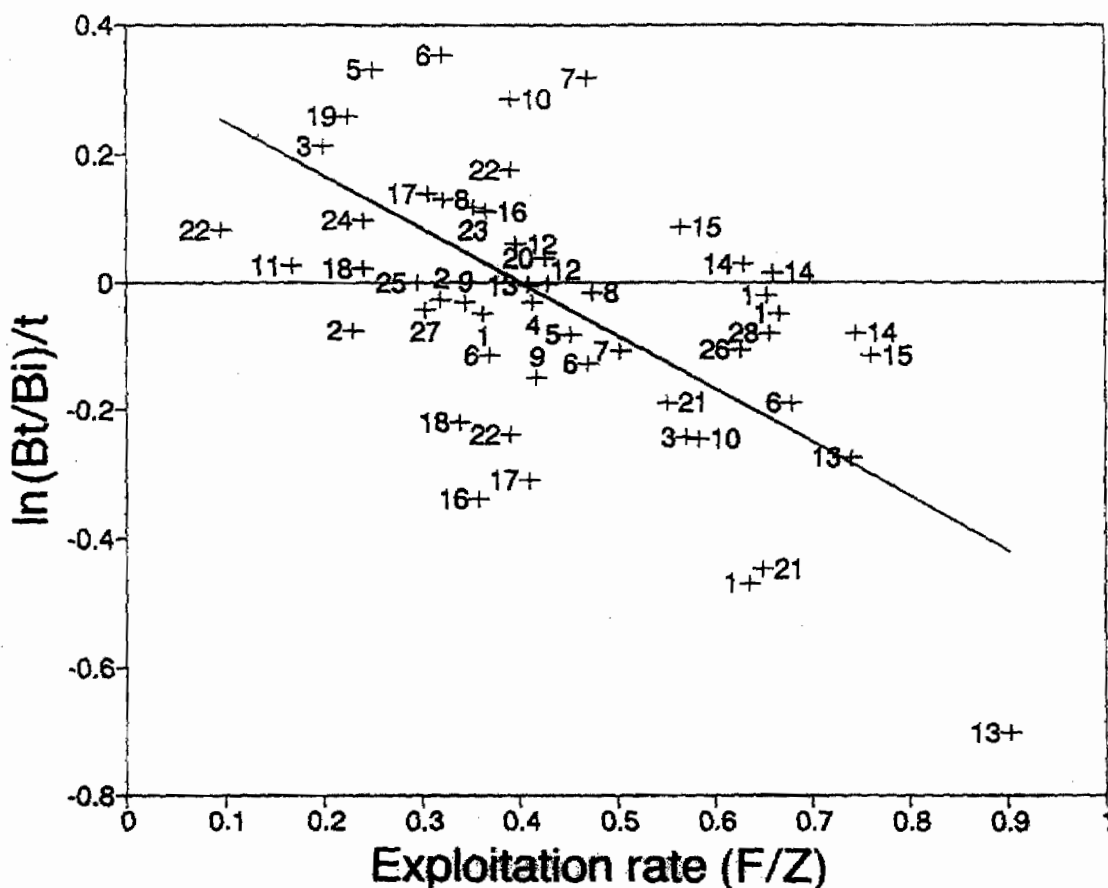


Fig. 2. Scatterplot of an index of the rate of change of biomass (as  $\ln(B_t/B_{t-1})/\text{year}$ ) of various stocks and species of small pelagic fish in periods of 5 to 10 years, plotted against the mean exploitation rate in the corresponding period. A geometric mean regression line (Table 3) is also shown.  $B_t$  and  $B_{t-1}$  are the biomasses at the start and finish of the time periods. Numbers next to the points refer to stock numbers in Table 1. Data plotted are calculated from data in Table 2.

Table 4. Fitted regression to data in Table 2

	SS	d.f.	MS	F	P(F)
Total	1.6112	52			
Model	0.5022	1	0.502	23.1 [1,50]	<0.001
Residual	1.1090	51	0.022		
$r^2 : 0.45$					
	AM Regression*		GM Regression*		
Slope	-0.5616	-0.8346			
Intercept	0.2110	0.3331			
$p(\text{normal distribution of residuals}) = 0.76$ (Shapiro and Francis $W'$ test); $> 0.20$ ( $\chi^2$ test)					

\* AM, arithmetic mean; GM, geometric mean.

additional observation of rate of change in biomass for a given  $E$  will lie below a certain value  $V$ . This was done by using the standard error of a predicted yield  $Y$  in a regression to estimate the  $p$  confidence interval for the  $\ln(B_t/B_i)/t$  interval =  $\pm V$  at given  $E$ . According to Ricker (1973), the use of ordinary confidence limits for a GM regression is a reasonable approximation and will rarely lead to incorrect conclusions. The  $p$  values so calculated are the probabilities that for a given new stock and 10-year time period that conform to the same model, the rate of change in stock biomass will equal  $V$ . Curves of  $p$  against  $E$  have been plotted for levels of  $V$  corresponding to any stock decrease (i.e.  $V < 0$ ), and for  $V$  corresponding to a 50% decrease in SSB over a 10-year period. The results are plotted in Fig. 3.

If it is assumed that a new stock will behave according to the same model, Fig. 3 can be used to predict the behaviour of the SSB of the stock over the forthcoming medium-term period. Thus, exploitation at  $E = 0.4$  is as likely to cause a stock decrease as a stock increase ( $p = 0.5$ ), whilst for example exploitation at  $E = 0.6$  has a probability of about 0.85 of causing some stock decline, and a 0.73 probability of a stock decline exceeding 50% of the starting value over 10 years.

Use of this simple model depends on two principal assumptions. One concerns the starting conditions of the stock: the data used are all from fairly mature fisheries, and would not be applicable to newly exploited stocks. Therefore one would expect a virgin stock to experience a decrease in biomass even at low values of  $E$ . In such conditions, however, a decrease in SSB is unlikely to be immediately harmful. The other assumption is discussed in the next section.

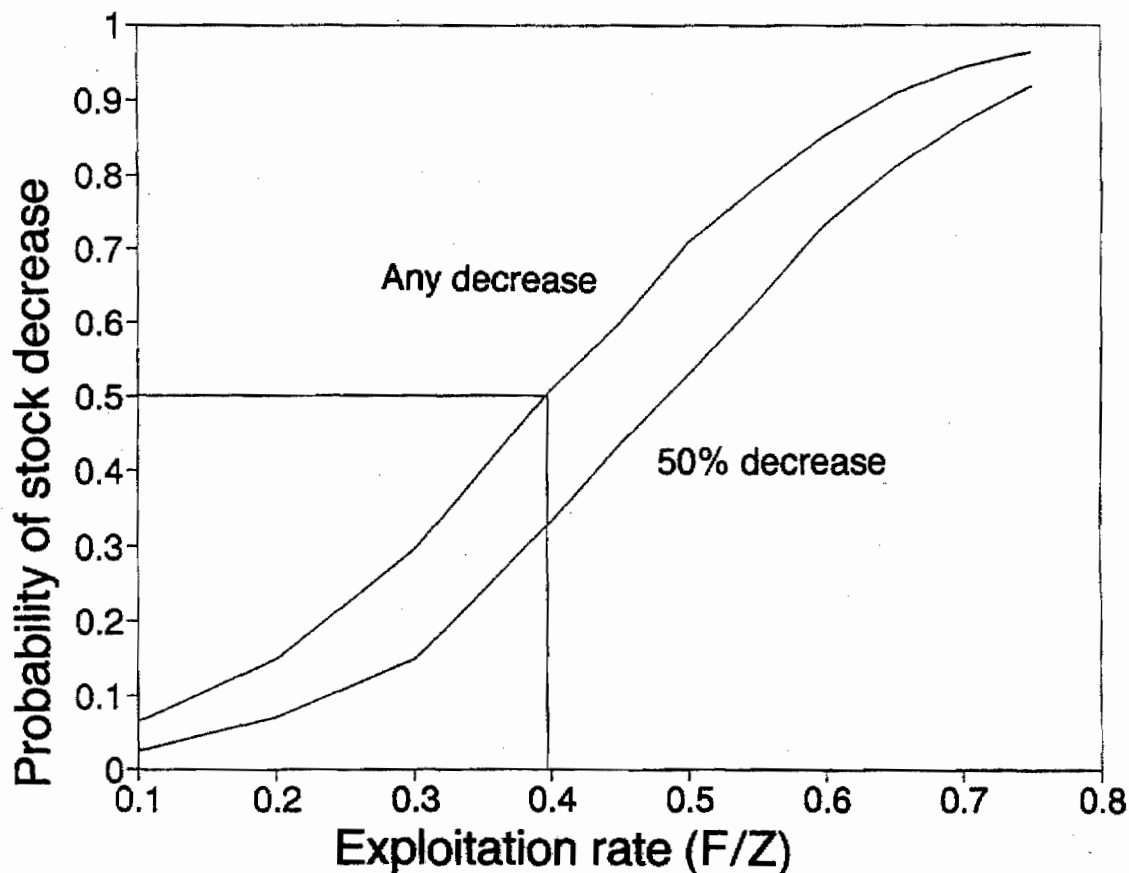


Fig. 3. Probability of decreases in stock at various levels of exploitation rate. Probability ogives of any stock decrease and of a 50% stock decrease at the end of a 10-year time period are given. Values are calculated from the GM regression fitted to data in Table 2. Note that 50% probability of stock decline corresponds approximately to  $E = 0.4$ .

#### Comparison of subtropical and temperate stocks

An important assumption of the model is that all small pelagic stocks show the same behaviour. One concern is that tropical stocks may behave differently from the temperate and subtropical stocks on which this model is based. In Fig. 1, there is little evident tendency for the data to segregate by taxonomic group, and indeed species effects were not found to be significant when included in the model ( $p(F)$  in analysis of covariance  $> 0.5$ ). A further analysis of covariance was attempted, grouping subtropical species (*Scomber japonicus*, *Sardinops* spp., *Etrumeus teres*) and temperate species separately. This effect was also insignificant to the model ( $p(F) > 0.5$ ), showing no evidence that a different trend is exhibited by the warmer-water species. This finding provides some reassurance as to the general applicability of this model. Eventually it would be preferable to include data from tropical stocks in this model; however, few reliable age-based stock assessments for tropical pelagic fish are available. The author would be most interested to receive such information for inclusion in this model.

The result of calculating  $F$  for  $E = 0.4$  can be compared with estimates of  $F_{high}$ ,  $F_{med}$

**Table 5.** Comparison of target fishing mortality  $F$  for exploitation rate  $E = 0.4$  and  $E = 0.5$  with some calculated values of the  $F_{\text{med}}$  and  $F_{\text{high}}$  targets

Fishing mortality for $F_{0.1}$		$F_{\text{med}}$	$F_{\text{high}}$	Species	Reference
$E = 0.4$	$E = 0.5$				
0.10	0.3	0.19	0.12	0.43	<i>Scomber scombrus</i> Anonymous (1989c)
0.10	0.3	0.21			<i>Clupea harengus</i> Anonymous (1989c)
0.10	0.3	0.22			<i>Clupea harengus</i> Anonymous (1989c)
0.10	0.3	0.16			<i>Clupea harengus</i> Anonymous (1989c)
0.20	0.8	0.09			<i>Sprattus sprattus</i> Anonymous (1989g)
0.33	0.5	0.51			<i>Sprattus sprattus</i> Anonymous (1989g)
0.27	0.6	0.48			<i>Sprattus sprattus</i> Anonymous (1989g)
0.27	0.8	0.49	0.87		<i>Sardina pilchardus</i> Anonymous (1989g)
0.13	0.4	0.15	0.24		<i>Trachurus trachurus</i> Anonymous (1989a)
0.10	0.3	0.17	0.18		<i>Trachurus trachurus</i> Anonymous (1989a)
0.13	0.4	0.19	0.05		<i>Micromesistius poutassou</i> Anonymous (1989e)

and  $F_{0.1}$  (Table 5). This shows that  $E = 0.4$  is a rather conservative measure, especially for herring, *Clupea harengus*, in which  $F = 0.2$  to  $0.3$ , corresponding to  $E = 0.5$  to  $0.6$ , are generally considered 'safe' limits (Anonymous, 1989b) although such levels of exploitation do not, from Fig. 2, appear to have been sustainable in the past.

In applying results from this analysis it must be understood that the use of a medium-term mean  $E$  does not imply that short-term management is unnecessary: a brief period of very high exploitation can of course deplete a stock considerably, although the medium-term  $E$  may be reasonably low. In fact, it is generally desirable to fish at fairly constant fishing mortality (Shepherd, 1981).

#### Comparison with previous $F/M$ -based methods

Gulland (1970) derived from the Schaefer (1954) surplus-production model a proposal that a fish stock should be exploited at  $E = 0.5$  ( $F = M$ ) for maximum sustainable yield, and this expression has been widely used in assessing the potential yields of fish stocks in developing countries. Maximum sustainable yield from the Schaefer (1954) model is estimated as being taken from the stock when it is at half its unexploited stock size. This implies a mortality rate twice the unexploited mortality rate, i.e. that  $(F+M) = Z \approx 2M$ , and  $E \approx 0.5$ , which is more usually written as  $F = M$  (Gulland, 1970). This target fishing mortality for the exploitation of a stock for which few data are available has been widely used in fishery-development situations. However, the above analysis indicates that pelagic fish stocks when exploited at this rate tend to decline in stock size: the target appears distinctly incautious.

A similar conclusion was reached by Beddington and Cooke (1983). Using a variety of simulation models they showed that the relationship between MSY and unexploited stock size was dependent on both natural mortality and the von Bertalanffy growth parameter  $K$ , but that MSY lay more typically in the region of  $0.3 M B_0$ . Similarly, Alverson and

Pereyra (1969) concluded that yields were better approximated by  $0.4 M B_0$ . The present result that  $E = 0.5$  is a risky exploitation strategy, is consistent with these findings.

The analysis presented here may be used as an approximate indication of a 'safe' medium-term level for the exploitation of pelagic stocks in cases where the prime concern is the maintenance of spawning stock biomass and the prevention of stock collapse. It shows that prolonged periods of high levels of exploitation are likely to cause stock collapse, and gives a guide to the risk of stock collapse associated with different levels of exploitation.

### Summary

Long-term management targets based on MSY,  $F_{\max}$  or  $F_{0.1}$  are inappropriate for small pelagic fish because of the possibility of stock collapse owing to a stock–recruit relationship at low biomasses. Better reference points such as  $F_{\text{med}}$  and  $F_{\text{high}}$  that take account of stock and recruit data cannot be used in developing fishery situations because they are too demanding of data. A simple model was fitted to medium-term (about 10 year) periods in exploited small pelagic fisheries, relating change in stock biomass to exploitation rate. Data from 28 stocks and 11 species were used. The fitted model was used to estimate likelihood of stock decrease at different exploitation rates. The pelagic stocks included in the model appeared to be in equilibrium for an exploitation rate  $F/Z = 0.4$ , which may be used as a guideline for the appropriate exploitation of pelagic stocks.

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### APPENDIX 1

Mathematical symbols used in this review.

$B^*$	Target biomass
$B_n$	Stock biomass in year $n$
$E$	Exploitation rate, $F/Z$
$f$	Fishing effort
$f_{\max}$	Fishing effort for maximum sustainable yield
$f_{0.1}$	Fishing effort for 10% marginal yield
$F$	Variance-ratio test parameter
$F$	Fishing mortality
$F_{\text{low}}, F_{\text{med}}, F_{\text{high}}$	Biological reference points for $F$
$F_{\max}$	Fishing mortality for maximum yield per recruit
$F_{0.1}$	Fishing mortality for 10% marginal yield per recruit
$g(B)$	Surplus-production function
$M$	Natural mortality
$p$	Probability in statistical tests
$r^2$	Coefficient of determination
$TAC(n+1)$	Total allowable catch for year $(n+1)$

V	Predicted rate of change of biomass from the model
W'	Shapiro–Francis test parameter
Y	Predicted yield
Z	Total mortality

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