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Multi-annual TACs and minimum biological levels

Paul Marchal and Joseph Horwood

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ICES has focused attention on minimum biologically acceptable levels (MBALs) as a basis for ensuring the safety of stocks and providing advice for management. Simultaneously the European Commission has proposed the use of multi-annual management strategies. This study models the effect of TACs, set constant for different periods of years, on the levels and variability of spawning stock biomass (SSB) and yield. The Celtic Sea cod is used as an example. It is shown that, even with annual updating of TACs, target SSBs have to be substantially greater, possibly more than seven times the MBAL, to avoid the risk of stocks falling below the critical level. Even if the stock is allowed to fall below the MBAL for 5% of the time, the target stock sizes need to be 3–10 times the MBAL if TACs are updated at 2–10 year intervals. As the period of stable catches is increased the problems of safeguarding the stock from falling below the MBAL also increase, and stability has to be paid for by lower target fishing mortalities. Specifically for the Celtic Sea cod, a balance of high yield and safety could be achieved with average catches of 7900 t and a target spawning stock biomass of 30 000 t.

Key words: fisheries management, multi-annual management strategies, MBAL, spawning stock biomass, TACs, modelling, simulations, Celtic Sea cod.

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Introduction

The basic Regulation on the policy of management and conservation of fishery resources in European Community waters (Anon., 1983) required the Commission of the European Union to report on the fisheries sector before 1992. This mid-term review concluded that the stocks managed under the European Common Fisheries Policy were in danger because of excessive fishing mortalities (Anon., 1991). The Commission proposed amendments to structural and conservation policy to improve profitability and stability of the industry, whilst ensuring the sustainability of the stocks.

The Commission recognised the importance of biological and technical interactions, amongst species and fleets, that exist in most fisheries, and the difficulties that these interactions pose in setting appropriate annual total allowable catches (TACs) for single stocks. It advocated the introduction of multi-annual, and perhaps multi-species, TACs. The use of multi-annual TACs and multi-annual decisions were reviewed by the EU Scientific and Technical Committee for Fisheries (Anon., 1992a). The Commission eventually proposed specific management measures (Anon., 1993a, b).

The International Council for Exploration of the Sea (ICES) vests authority for management advice in its Advisory Committee on Fishery Management (ACFM). Concurrent with the Commission developing its management proposals, ACFM altered the nature of the advice it provided. In 1991, it introduced the concept of a ''minimum biologically acceptable level'' or MBAL. This is defined as a stock size below which data indicate an increased probability of reduced recruitments (Anon., 1992b; Grainger and Serchuk, 1992; Serchuk and Grainger, 1992). There are many technical problems associated with providing a MBAL for a stock, such as the use of an absolute value rather than, say, an equivalent fishing rate. Notwithstanding the scientific problems other greater concerns have been expressed.

If a stock is below MBAL, or destined to go below MBAL, ACFM recommend management action to safeguard the stock. If a stock is considered safe then no recommendation is made and catch options are presented. The idea is that, if a stock is deemed to be safe from recruitment failure, then managers can decide on catch levels, taking account of socio-economic considerations not available to ACFM. Two concerns follow. First, that the traditional advice, based on biologically

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Table 1. Parameters used in the model of the Celtic Sea cod based on data in Anon. (1994).

Age	Selectivity (q)	Weight in catch (kg)	Weight in stock (kg)	Proportion mature	CV of stock estimates
1	0.175	0.882	0.647	0.00	0.26
2	0.995	2.092	1.565	0.05	0.3
3	0.969	4.815	4.547	1.00	0.31
4	1.000	7.123	6.883	1.00	0.35
5	0.806	9.371	9.220	1.00	0.31
6	0.825	11.515	11.161	1.00	0.3
7+	0.825	15.060	14.400	1.00	0.3
M (y^{-1})	0.20				
R (millions)	3.109				
σ	0.813				

and economically sensible fishing reference points (F_{max}, $F_{0.1}$ etc.) is neglected. Second, that with an absence of encouragement to reach such reference levels, short term pressures on managers will tend to cause all stocks to slowly drift towards their MBALs. These arguments were developed by Corten (1993). Events quickly showed that the concerns were justified. In Holland, national fisheries administrators appeared to conclude that management of fisheries just above MBALs was acceptable (Anon., 1993c).

This study examined some of the implications for management of the combination of the two concepts introduced above: that of multi-annual TACs in relation to MBALs. Other fisheries studies have considered management strategies and their effects on stability and stock size (e.g. Horwood, 1991; Pelletier and Laurec, 1991, 1992; Butterworth and Bergh, 1993; Francis, 1993; Punt, 1993). Here, we considered one specific realisation of the concepts: the fixing of a constant catch for a number of years, and the restrictions that this must impose on the size and duration of such catches in order to maintain stocks above an MBAL with some prior probability. A single stock fishery was modelled, based upon the biology and exploitation of cod in the Celtic Sea (ICES divisions VIIf+g). Random variations in recruitment and in estimated numbers at age were incorporated into the model. A specific stock-recruitment relationship was not necessary for the study. Two different ways of estimating the fixed catches were developed. The study demonstrates that, in order to maintain the spawning stock biomass above an MBAL, target stock sizes may have to be considerably greater than the MBAL.

Methods

Biological and observational models

An age-structured biological model of the Celtic Sea cod, and its fishery, was developed to calculate the "true" state of the stock. Observations, or stock assessments, are imperfect and an observational model was constructed; decisions were based on observed values. The biological and observational models are given in Appendix A. The algorithms for setting the multi-annual TACs, and the implementation of the simulations are described below.

Biological parameters values were taken or calculated from Anon. (1994) and are given in Table 1. Values for the coefficient of variance, of estimates of numbers at age (CV_i), were obtained from repeating the ICES analysis (Anon., 1994), but using the expanded output from the Extended Survivors Analysis (Shepherd, 1992; Darby and Flatman, 1994). No significant covariance of the stock estimates could be detected. For all ages the standard errors of the log-numbers were about 0.3, and measurement error was approximated by setting all CV_i at 0.3. No recruit indices are available for this stock and so no advance estimate of future recruitments could be utilised. The population is represented by six true age-classes with the last "age" a plus-group.

A stock-recruitment relationship has not been utilised, and a variable, but density independent recruitment has been assumed. No specific parameterisation of a stock-recruitment model could be justified for this, or many other, stocks. The conclusions will be seen to be robust to the assumption, since management at high stock sizes is concluded and the use of any stock-recruitment model implies a similar or more conservative management.

Catch algorithms and MBAL

It has not been possible for ICES to determine explicitly the MBAL for the Celtic Sea cod but current fishing mortality rates are high, at about 1.0 y^{-1}, and minimum spawning stock biomasses (SSB) have been about 3000 t, calculated at spawning time. This is equivalent to about 4000 t calculated on 1 January. For this study, the MBAL was taken as 4000 t on 1 January.

Catches were calculated so that the expected SSB, at chosen intervals of years (SSB_c), was equal to some multiple, Θ, of the MBAL, i.e. $SSB_c = \Theta \times MBAL$. The effect of the magnitude of Θ on the probability of the stock falling below MBAL is examined. This was done from 200 independent dynamic runs each of 200 years within which the same management procedure was implemented. The choice of 200 years allows a long-term appreciation of the management procedures. It might be seen as a long time, both in management time scales and in requiring the SSB never to fall below the MBAL over that time. In the latter respect, it is a demanding criterion, but one that might realistically be demanded. However, the time period also allows calculation of the frequency of the times that the stock is likely to be below MBAL in the long term. A ''run'' is considered as a single 200 year dynamic realisation and a ''simulation'' comprises the series of 200 runs. We define terms associated with probabilities (π_1, π_2) of different ''failures'' (α_1, α_2):

An α_1-type failure is identified when, for any one run, $SSB_x(t) < MBAL$ at least once within the 200 years. For a simulation the maximum frequency of α_1 is 200. The probability that an α_1-type failure will occur with the Θ-specific management procedure is π_1. If π_1 is 5% then the SSB will always have been above the MBAL threshold in 190 runs and, in 10 runs, the stock will have fallen below the MBAL at least once in the 200 years.

An α_2-type failure is identified at any time within a run that $SSB_x(t) < MBAL$. Within 200 simulations, the maximum frequency of α_2 is 40 000. The probability that α_2 will occur is π_2. If π_2 is 5% for a Θ-specific management procedure, then over 200 years it can be expected that the stock will be below the MBAL in 10 years. To ensure that the stock will never be below the MBAL, π_2 must be zero. It can be anticipated that examination of the (α_2, π_2) statistics is likely to be more realistic for management purposes.

The management procedures involve a catch set at a constant value for a period of Φ years; the period is varied in the study. At the beginning of each period a new catch is set, so that the expected SSB will be equal to SSB_c. Two different methods are examined, achieving SSB_c at either the end of the first or at the end of the last years of the period:

Method I: every Φ years the TAC is altered so that the expected SSB, at the end of that particular year, is equal to SSB_c. That TAC is then held constant over the next Φ years, and so on. Formally:

If $t = k\Phi$ (k integer ≥ 0) the catch C(t) is calculated so that the expected SSB in the following year ($SSB_e(t+1)$), based on observations Y(t), is equal to SSB_c. The real exploitation rate $E_x(t)$, applied to the actual stock X(t), is then calculated. If $t \neq k\Phi$, C(t) is set to $C(t-1)$. From C(t), $E_x(t)$ and $E_y(t)$ are calculated, based on the true and estimated stock sizes, for all t.

Method II: every Φ years a constant TAC is calculated for the next Φ years that gives the expected SSB, at the end of that period equal to SSB_c. Formally:

If $t = k\Phi$ (k integer ≥ 0) the equal catches C(t), C(t+1), . . ., $C(t+\Phi-1)$ are calculated so that $SSB_e(t+\Phi)$, based on observations Y(t), is equal to SSB_c. As above, $E_x(t)$ and $E_y(t)$ are calculated based on the true and estimated stock sizes.

In both methods a zero catch is set if SSB_c cannot be attained. A maximum exploitation rate of $3.0\ y^{-1}$ is assumed, so at extremely high or low stock sizes the catch will not be held constant over the Φ-year period.

The value of Φ is chosen within the set (1, 2, 3, 4, 5, 10 years), and Θ is varied between $\Theta = 1.0$ ($SSB_c = MBAL$) and $\Theta = 20$. Each simulation is for one pair (Φ, Θ) and all simulations involve the same 40 000 sets of random numbers, so that comparisons between simulations may be more realistic.

Implementation

The algorithms have been programmed in FORTRAN and have included some mathematical routines of minimization provided by the NAG library.

Initialization: for each run, the initial age compositions (X(0)) were established from the arithmetic mean recruitment and the deterministic fishing mortality rates that gave the expected $SSB_x(0) = SSB_c$. Variability was introduced independently at each age, to reflect the natural variability in recruitment. *iter* is a counter which can be increased from 1 to Φ. It is initially set to Φ.

Execution: consider year t where X(t), Y(t), $SSB_x(t)$ and $SSB_y(t)$ are known.

Method I: when $iter = \Phi$ (i.e. $t = k\Phi$), $SSB_e(t+1)$, and hence $E_y(t)$, have to be calculated. If the stock is so low that SSB_c cannot be attained then $E_y(t)$ is set to zero. Conversely, if $SSB_y(t)$ is very large, then an unrealistically high level of $E_y(t)$ may be required to reach SSB_c, and in this case $E_y(t)$ is restricted to a maximum of $3.0\ y^{-1}$. In both cases SSB_c is not attained and values of $SSB_y(t+1)$ are derived from equations (3), with $\Psi = 1$, and (8) with these constraints (see Appendix A). Normally, $E_y(t)$ is calculated from equations (3) ($\Psi = 1$) and (8) with NAG minimisation routines, and C(t) is calculated from equation (5). *iter* is then set to 1. When $iter \neq \Phi$, $E_y(t)$ is calculated from equation (5) so that $C(t) = C(t-1)$. However, if the stock is low then $E_y(t)$ may be large and again $E_y(t)$ is restricted to a maximum of $3.0\ y^{-1}$. *iter* is then incremented. In both cases $E_x(t)$, X(t+1), Y(t+1), $SSB_x(t+1)$, $SSB_y(t+1)$ are calculated from equations (4), (1), (2), (6), and (7), respectively. At the end of each year, t is incremented.

Method II: when *iter* $=\Phi$ (i.e. $t=k\Phi$), $SSB_e(t+\Phi)$, and hence $E_y(t)$, $E_y(t+1)$, ..., $E_y(t+\Phi-1)$, have to be calculated subject to the conditions:

$$\begin{cases} C(t)=C(t+1) \\ \dots \\ C(t+\Phi-2)=C(t+\Phi-1) \\ SSB_e\,(t+\Phi)=SSB_c \end{cases} \tag{9}$$

Solutions of this system, based on Φ transcendental equations and Φ variables are found, with a NAG minimisation routine, using equations (3), (5), (8), and (9) with Ψ from 1 to Φ. *iter* is then set to 1. When *iter* $\neq\Phi$, $E_x(t)$ is calculated from equation (4). In this case, $X(t+1)$, $Y(t+1)$, $SSB_x(t+1)$, $SSB_y(t+1)$ are calculated from equations (1), (2), (6), and (7), respectively. At the end of each year, *iter* and t are incremented.

As with method I, the above conditions cannot always be satisfied because the estimated stock size is either too big or too small to allow SSB_c to be achieved during the Φ years. When the stock is too small $E_y(t)$, ..., $E_y(t+\Phi-1)$ are set to zero (catches zero) and, for use later, this type of ''failure'' is termed β_1. When the stock is too large, some E_y may have to be set to the maximum value of $3.0\,y^{-1}$ and catches will then not be held constant over the period; this type of ''failure'' is termed β_3. These two failures are based on estimated stock sizes. However, although the estimated values may allow a solution, in fact the stock size may be too small to permit the estimated catches. In this case a catch based on $E_x=3.0\,y^{-1}$ is calculated for that year; this is termed a type β_2 failure.

Outputs: the outputs from both methods were: $\pi_1(\Phi, \Theta)$, $\pi_2(\Phi, \Theta)$, $\overline{SSB}_x(\Phi, \Theta)$, $\overline{C}(\Phi, \Theta)$, $\sigma_c(\Phi, \Theta)$, $\nu_1(\Phi, \Theta)$, $\nu_2(\Phi, \Theta)$, where $\overline{SSB}_x(\Phi, \Theta)$, $\overline{C}(\Phi, \Theta)$, are the means of SSB_x and C, and where σ_c is the standard deviation of C, from one simulation, (Φ, Θ). The probabilities of failures α_1, α_2, β_1, β_2 are given by π_1, π_2, ν_1, and ν_2, respectively.

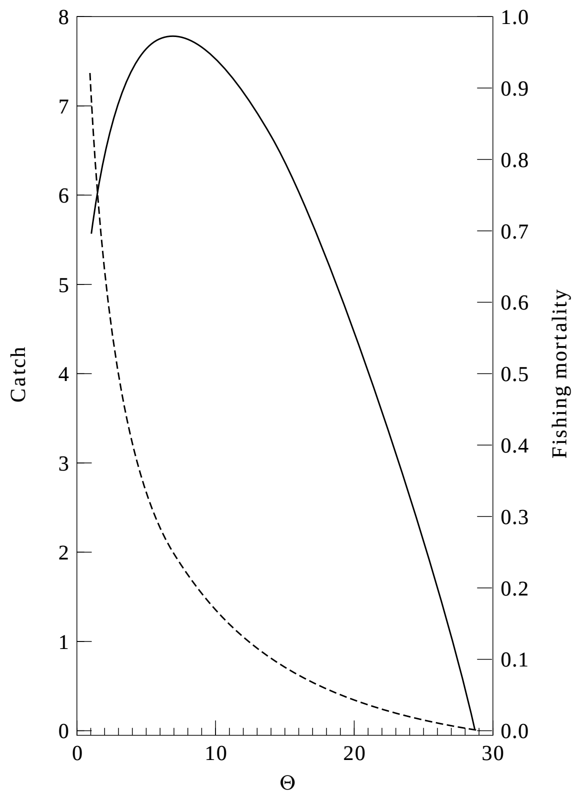

Figure 1. The equilibrium catch (kt) (solid line) and instantaneous fishing mortality rate (year^{-1}), averaged over ages 1–7 years (broken line), against Θ, where the target SSB is Θ*MBAL and MBAL is 4 kt.

Results

The deterministic equilibria are illustrated in Figure 1, based on the arithmetic mean recruitment over 1971–1992 (R). For $\Theta=1.0$, the SSB is at 4000 t, with $\overline{F}=0.93\,y^{-1}$ giving a catch of 5577 t. As Θ increases $\overline{F}$ necessarily declines. Catches reach a maximum of 7834 t at $\Theta=7.2$ and $\overline{F}=0.25\,y^{-1}$. The maximum SSB is 117 000 t ($\Theta=29.3$, $\overline{F}=0$). For the stochastic model, the results have been presented for $\Theta \in (1,20)$, however, more details are presented from the lower part of the range, as this is likely to be of more interest to managers.

Application of control method I

One 200 year simulation of the effect of control method I is illustrated in Figure 2(a, b, c) for $\Theta=10$ and $\Phi=5$ years; that is, the target SSB_c of 40 000 t is ten times the MBAL and the catch is updated every five years. It can be seen immediately that the performance is disappointing, with the SSB_x frequently falling below the MBAL and with catches fluctuating wildly. Above average recruitments boost the SSB_x and a high catch is needed to reduce this to the target SSB_x in one year. This high catch level cannot be sustained, resulting in a crash of the population below SSB_x. It can be recognised that such an approach fails both to maintain safe levels of stock biomass and to maintain a stability of catches; consequently no further work was undertaken with this control method.

Application of control method II

A similar run is illustrated in Figure 2(d, e, f) for control method II. Although a considerable variability is apparent, it is clear that the method is more successful in maintaining the stock above MBAL and that catches have been maintained at more constant levels for the five year periods. These plots of the basic simulations serve

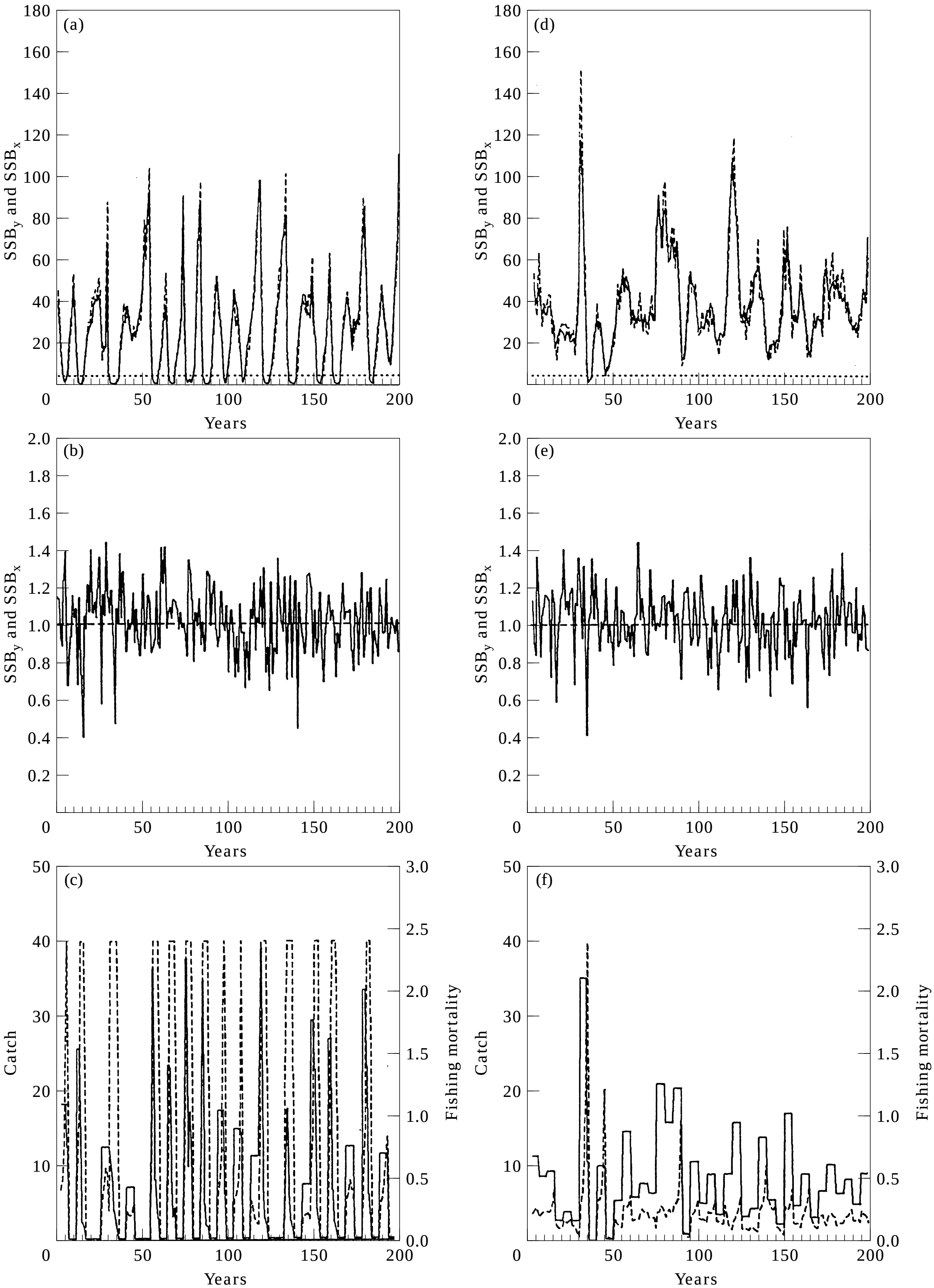

Figure 2. One 200 year run for $\Theta = 10$ and $\Phi = 5$ years for control method I (a, b, c) and method II (d, e, f): (a) and (d) bold line is $SSB_x(t)$, in kt, and broken line is $SSB_y(t)$, in kt, the MBAL is also plotted; (b) and (e) bold line is $SSB_y(t)/SSB_x(t)$ (cv = 0.183 in (b), and 0.166 in (e); (c) and (f) bold line is the catch (kt) and broken line is F (year^{-1}), averaged over ages 1–7 years.

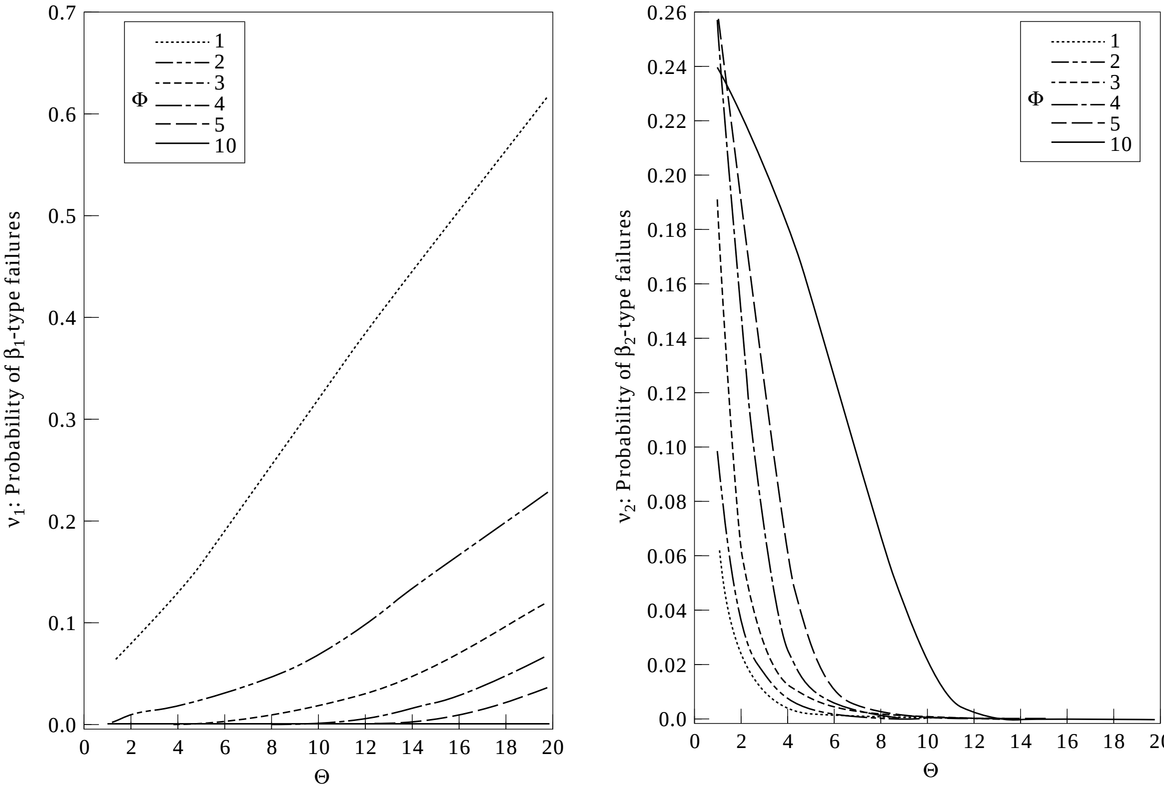

Figure 3. (a) Probability ν_1 of β_1-type failures (occurring when the exploitation rate has to be set to zero) plotted against Θ for values of Φ of 1–5 and 10 years, over 200 independent runs of 200 years each. (b) Probability ν_2 of β_2-type failures (occurring when the exploitation rate has to be set to its maximum value) plotted against Θ for values of Φ of 1–5 and 10 years, over 200 independent runs of 200 years each.

also as a reminder of the very dynamic character of the fish stocks we are attempting to regulate.

Figure 3(a, b) gives the probabilities ν_1 and ν_2 of the failures of β_1 and β_2 in terms of Φ (1–5, 10) and Θ. Failure β_3 occurred rarely. The frequency of type β_1 failures (F set to zero) increases with Φ and Θ, due to the ability of random variation to take the stock further below SSB_c, at high values of SSB_c, and because the stock is unable to recover in a short period (low Φ). Conversely, β_2 failures (F set to $3.0\ y^{-1}$ as the stock is too low to allow the predicted catch) increased as Φ and Θ decreased.

Figure 4(a, b) show the risks π_1 and π_2 against Θ for values of Φ of 1–5 and 10 years and illustrate the main finding of the study. Figure 4a shows that, even if the catch is updated every year ($\Phi=1$), the SSB is almost certain to fall below the MBAL over 200 years unless the target SSB is over three times the MBAL. As Φ is increased to 5 and then 10 years, the target SSB has to be above six and seven times the MBAL, respectively, to avoid certain failure. If the 50% failure point is considered, Θ ranges from 4 to 11 as Φ is increased from 1 to 10 years.

If the 5% failure point is considered, Θ ranges from 7 to about 14 as Φ is increased from 1 to 10 years. Clearly, with this control mechanism to maintain stable catches, target SSB levels have to be set well above MBAL levels to avoid the stock falling below that level.

Figure 4(b) shows the probability, π_2, of the stock being below the MBAL in any one year. In the extreme case where the SSB target is set to SSB_c ($\Theta=1$), the SSB is predicted to be below the MBAL 35–55% of the time for $\Phi \in [1,10]$. If it was deemed acceptable that the stock could be below the MBAL for no more than 5% of the time then it can be seen that the target SSB must increase as the period of fixed catches increases: values of Θ are 2 (for $\Phi=1$), 6 (for $\Phi=5$) and 10 (for $\Phi=10$). The probability, π_2, generally increases as Θ decreases, and as Φ increases, but this begins to reverse at low Θ and high Φ. This arises from the need to constrain the maximum effort and the stock builds up over the larger time periods.

Figure 5 shows the relationship between the ratio ($\overline{SSB}_x/SSB_c$) and (Φ, Θ). A significant deviation from the deterministic straight line at unity is observed when Θ is small and Φ is large, and conversely where Θ is large and Φ is small. These deviations are due to the imposition of

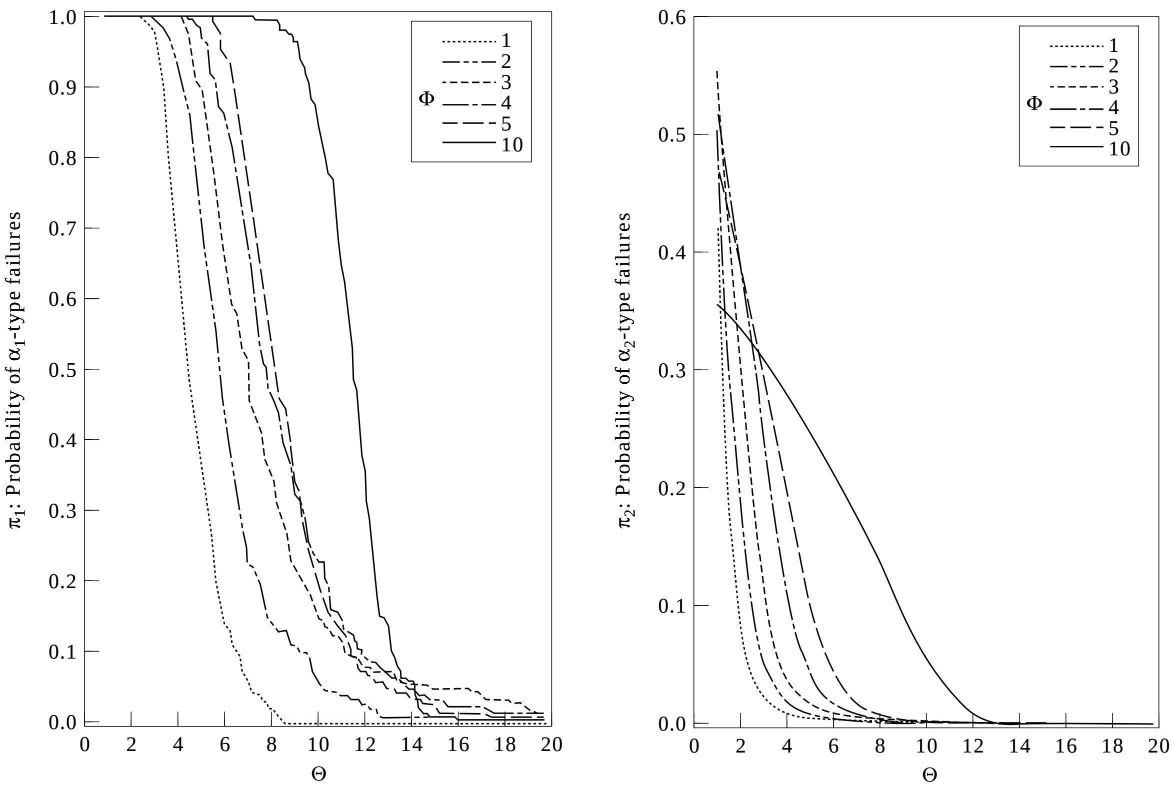

Figure 4. (a) Probability π_1 of α_1-type failures (the SSB fell below the MBAL at least once within 200 years over 200 runs) plotted against Θ for values of Φ of 1–5 and 10 years. (b) Probability π_2 of α_2-type failures (the SSB fell below the MBAL at any time over 200 runs of 200 years each) plotted against Θ for values of Φ of 1–5 and 10 years.

the constraints and the different ‘‘failures’’ described above.

Figure 6 depicts the relationship between average catch and (Φ, Θ). The parabolic shape as Θ increases is anticipated from Figure 1; however, the relationship is sensitive to the value of Φ. At small values of Φ the average catch is relatively low and, for $\Phi=1$, it reaches a maximum of 7480 t at $\Theta=7$. The average catch is also depressed for large values of Φ and, for $\Phi=10$, the maximum of 7340 t is reached at $\Theta=9.6$. Eventually, the extremum of 7857 t is achieved at intermediate values of $\Phi=5$ and $\Theta=7.5$. It can be appreciated that this result is also due to the frequency of occurrence of β_1 and β_2-type failures.

Figure 7 plots the standard deviation of the catches against (Φ, Θ). As intended by the management strategy, generally the deviations decrease significantly as the time between updates (Φ) increases. For example, at $\Theta=10$, the standard deviation for $\Phi=10$ is about a quarter than for $\Phi=1$. However, at small values of Θ, the distinction is less clear, again due to the β_2-type failures. The overall shape of the standard deviation as a function of Θ is due to the basic dynamics of the population and the underlying parabolic yield versus effort relationship.

Discussion

The results remind us of the very dynamic behaviour of the stocks and catches irrespective of the management strategies. The current results have immediate implications for the management of all stocks in waters managed by the European Community. If we want to ensure that stocks remain above MBALs, and even if there is an annual updating of TACs, then stocks cannot be managed at levels, or with corresponding catches or fishing mortality levels, that are near to the MBAL. Even with annual updating of TACs, the target SSBs have to be substantially greater, possibly greater than seven times the MBAL, to avoid the risk of stocks falling below the critical level.

It may be considered too severe a criterion to insist that stocks remain always above MBAL and we do not debate that issue here. If a weaker criterion be adopted of requiring that, on average, the stock is below the MBAL for no more than 5% of the time, then it can be seen that even with annual updating of TACs the target stock size needs to be above twice the MBAL. If we have multi-annual strategies that update over 2–10 years then the target stock size needs to be 3–10 times the MBAL.

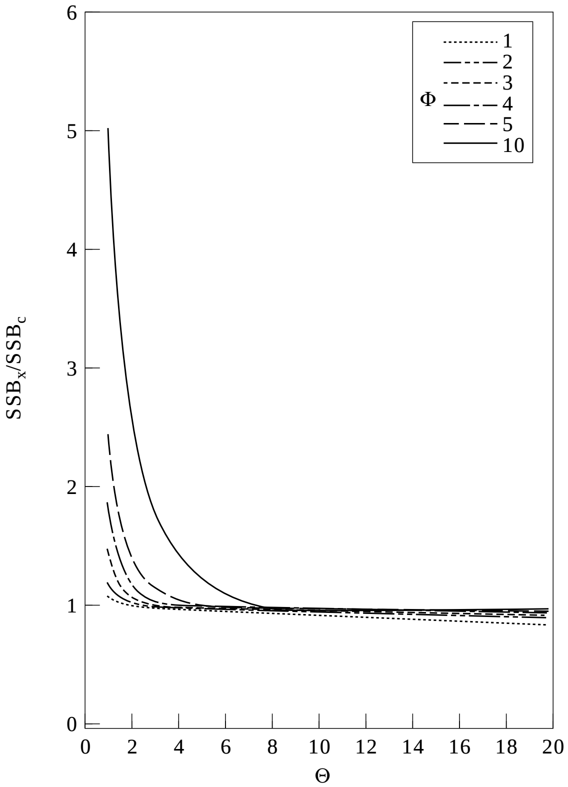

Figure 5. Ratio between the true spawning stock biomass, SSB_x (kt), averaged over 200 independent runs of 200 years, and the SSB target, SSB_c, plotted against Θ for values of Φ of 1–5 and 10 years.

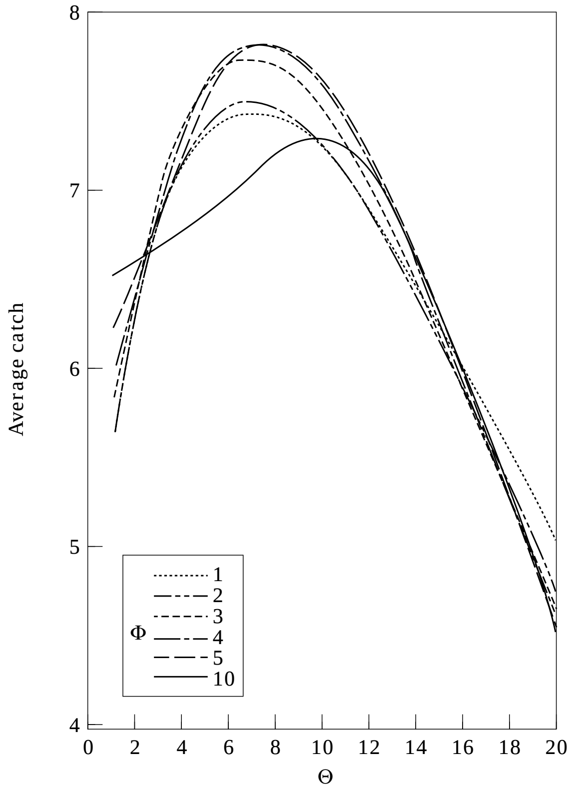

Figure 6. Catches in weight, $\overline{C}$ (kt), averaged over 200 independent runs of 200 years, plotted against Θ for values of Φ of 1–10 years.

Without seriously neglecting the concerns about MBALs it can be seen that, under any reasonable criterion, the stocks have to be managed well above the MBAL.

Greater stability for fishermen, producers, and administrators would be welcome. However, the above study illustrates that the underlying biological system is very variable, and it has frequently been demonstrated that this variability is significantly increased as the stocks are subject to higher fishing rates (e.g. Horwood, 1983; Horwood *et al.*, 1990). Any multi-annual stability of catches must make this underlying variability appear elsewhere, i.e. in variability of the stock. Consequently, as the period of stable catches is increased the problems of safeguarding the stock from falling below the MBAL also increases. Stability has to be paid for by lower target fishing mortalities.

The above results are based upon a realistic model of the Celtic Sea cod. The situation may be a little better for other stocks for two reasons. First, no pre-recruitment information is available for the Celtic Sea cod, and some other stocks may be managed in a more stable manner if information on recruits one or two years ahead can be provided. Second, the natural variability of this stock of cod is high compared with some other flatfish and pelagic stocks. However, the situation may also be worse for three reasons. It is assumed that the stock is estimated in the year that it is caught, and the one year time-lag, inherent in the ICES/EC assessment and management, was not explicitly modelled. Further, only variability in the ''standard'' assessment parameters has been modelled, and variability in, for example, natural mortality has been neglected, as has any possible stock-recruitment relationship. Autocorrelation in recruitments was not found in this stock but may be present in others. Last, the stock-recruitment relationship has not been modelled. Whilst this is not a concern if stocks are managed well above the MBAL, the results presented here will be unreasonably optimistic for management decisions that permit the stock to fall below MBAL for significant periods.

In considering the particular management strategies modelled above, as a mechanism to provide both safety and stability, we have to consider the significance of choosing management parameters (Φ, Θ). Thus, the plots of the frequency that the SSB is below the MBAL, and the relationship of the SSB against Φ and Θ,

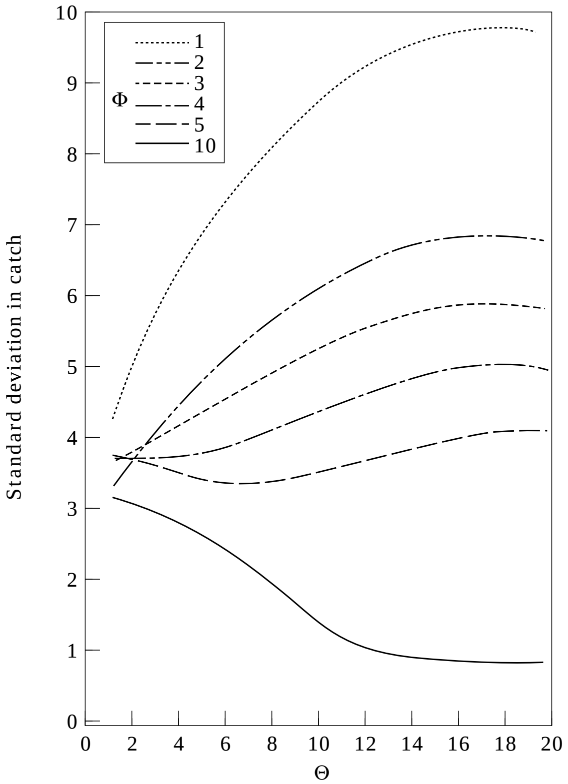

Figure 7. Standard deviation of the catches (kt), calculated over 200 independent runs of 200 years, plotted against Θ for values of Φ of 1–10 years.

represent the management of the stock, whereas the relationship of the catches and their variability, against Φ and Θ, illustrate socio-economic consequences. Is it possible to satisfy all desirable aspects? Is it possible to achieve high SSB, low frequencies of failures during which SSB<MBAL, high catches and low variations in catches? First, consider the effect of Θ. Obviously, high values of Θ are preserving the stock at a high level so that the probability that the stock is below the MBAL is small or even null. For a certain range of Θ (between 7.0 and 9.0), the average SSB is very close to the deterministic value irrespective to Φ; this may be important to the manager. Further, there is an optimum value of Θ (Θ=7.5, included in the range 7–9) which maximizes the catches. Consider Φ. Even when we have, on average, high SSB, high values of Φ cause high variability and the SSB often falls below MBAL; the catches are the best when Φ=5 and their variability is average. Assuming Φ=5, a compromise risk of π_2=5% is achieved, when the SSB target is about 6 times the MBAL.

Considering all of the above, and with this very specific management strategy, a balance of stability, level of yield and safety for the stock could be achieved with Φ≃5 and with Θ in the range 6–9. This gives target stock sizes of 24–36 000 t and fishing mortality rates of about 0.20–0.25 y^{-1} (Fig. 1). This is at a much lower fishing rate than currently generated by the fishery and this study does not address the important question of transitional management.

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Appendix A: biological and observational model used for the multi-annual management strategies

Define the following:
p is the number of age classes,
Φ is the period within which catches are set equal,
MBAL is the minimum biologically acceptable level in tonnes,
SSB_c is the critical (or target) spawning stock biomass, in tonnes,
Θ is a proportional factor relating MBAL and SSB_c,
N is the number of years upon which fishing data are simulated,
$X_i(t)$ is the numbers of fish at age i, in thousands, at the start of year t,
X(t) is the stock, in thousands, at the start of year t,
$Y_i(t)$ is the estimated numbers of fish at age i, in thousands, at the start of year t,
Y(t) is the estimated stock, in thousands, at the start of year t,
${}_t\hat{Y}_i(t+\Psi)$ is the numbers at age i, in thousands, at the start of year $t+\Psi$, as forecast in year t,
${}_t\hat{Y}(t+\Psi)$ is the forecast stock, in thousands,
$SSB_x(t)$ is the spawning stock biomass, in tonnes, at the start of year t,
$SSB_y(t)$ is the estimated spawning stock biomass, in tonnes, at the start of year t,
$SSB_e(t)$ is the expected spawning stock biomass, in tonnes, at the start of year t,
$F_{x,i}(t)$ is the instantaneous rate of fishing mortality, for age class i, in year t,
$F_{y,i}(t)$ is the estimated instantaneous rate of fishing mortality, for age class i, in year t,
M_i is the constant instantaneous natural mortality rate, for age class i,
q_i is the age-specific catchability, relative to the maximum value at age, obtained at age 4,
$E_x(t)$ is the exploitation rate in year t, that is the instantaneous rate of fishing mortality at age 4,
$E_y(t)$ is the estimated exploitation rate in year t, that is the estimated instantaneous rate of fishing mortality at age 4,
$Z_{x,i}(t)$ is the instantaneous total mortality, for age class i, in year t,
$Z_{y,i}(t)$ is the estimated instantaneous total mortality, for age class i, in year t,
C(t) is the catch in weight, in tonnes,
wc_i is the weight in catch by fish, in kg, for age class i,
ws_i is the weight in stock by fish, in kg, for age class i,
pm_i is the proportion of fish sexually mature, for age class i,
R is the arithmetic mean recruitment in thousand at age one,
$\varepsilon(t)$ is an uncorrelated random variable distributed as $N[0,\sigma]$, depicting variability in recruitment,
σ is the standard deviation of the natural logarithm of the recruitment,
$\eta_i(t)$ is an uncorrelated random variable distributed as N[0,1], depicting variability in estimation of stock, for age class i,
$\eta(t)$ is a p-vector, the elements of which are $\eta_i(t)$ ($i \in [1,p]$),
cv_i is the coefficient of variation of the stock estimates, for age class i.

Biological and observational methods

The biological model can be summarized as:

$$\begin{cases} X_1(t+1) = R \cdot \exp[\varepsilon(t)] \cdot \exp[-\sigma^2/2] \\ \ldots \\ X_i(t+1) = X_{i-1}(t) \cdot \exp[-Z_{x,i-1}(t)] \\ \qquad\qquad\qquad \text{for } i \in [2,p-1] \\ \ldots \\ X_p(t+1) = X_{p-1}(t) \cdot \exp[-Z_{x,p-1}(t)] + \\ \qquad\qquad X_p(t) \cdot \exp[-Z_{x,p}(t)] \end{cases} \tag{1}$$

The above model represents the assumed "true" state but we can only estimate the stock sizes and so an observation model is required. This is taken of the form:

$$Y_i(t) = X_i(t) + \eta_i(t) \cdot cv_i \cdot X_i(t) \text{ for } i \in [1,p] \tag{2}$$

The model below represents the way the manager will forecast the stock size for year $t+\Psi$, with $\Psi>0$, based upon the estimates of the stock at year t.

$$\begin{cases} {}_t\hat{Y}_1(t+\Psi) = R \\ \ldots \\ {}_t\hat{Y}_i(t+\Psi) = {}_t\hat{Y}_{i-1}(t+\Psi-1) \cdot \exp[-Z_{y,i-1}(t+\Psi-1)] \text{ for } i \in [2,p-1] \\ \ldots \\ {}_t\hat{Y}_p(t+\Psi) = {}_t\hat{Y}_{p-1}(t+\Psi-1) \cdot \exp[-Z_{y,p-1}(t+\Psi-1)] + {}_t\hat{Y}_p(t+\Psi-1) \cdot \exp[-Z_{y,p}(t+\Psi-1)] \end{cases} \quad (3)$$

and:

${}_t\hat{Y}_i(t) = Y_i(t)$ for $i \in [1,p]$.

Eventually, the expressions for the catch and SSB, for the actual and estimated stocks, will be given by:

$$C(t) = \sum_{i=1}^{p} \frac{F_{x,i}(t)}{Z_{x,i}(t)} [1 - \exp(-Z_{x,i}(t))] wc_i \cdot X_i(t) \quad \text{(for the actual stock)} \quad (4)$$

$$C(t) = \sum_{i=1}^{p} \frac{F_{y,i}(t)}{Z_{y,i}(t)} [1 - \exp(-Z_{y,i}(t))] wc_i \cdot Y_i(t) \quad \text{(for the estimated stock)} \quad (5)$$

and

$$SSB_x(t) = \sum_{i=1}^{p} pm_i \cdot ws_i \cdot X_i(t) \text{ (actual SSB)} \quad (6)$$

$$SSB_y(t) = \sum_{i=1}^{p} pm_i \cdot ws_i \cdot Y_i(t) \text{ (estimated SSB)} \quad (7)$$

$$SSB_e(t) = \sum_{i=1}^{p} pm_i \cdot ws_i \cdot {}_{t-1}\hat{Y}_i(t) \text{ (expected SSB)} \quad (8)$$

with:

$$Z_{x,i}(t) = M_i + F_{x,i}(t)$$
$$F_{x,i}(t) = q_i \cdot E_x(t)$$
$$Z_{y,i}(t) = M_i + F_{y,i}(t)$$
$$F_{y,i}(t) = q_i \cdot E_y(t)$$

The target SSB is set to be proportional to the MBAL so that:

$SSB_c = \Theta \cdot MBAL.$