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Bioeconomic target reference points for the Commonwealth Small Pelagics fishery

Report to the Australian Fisheries Management Authority (AFMA)

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Executive summary

Aim

The aim in this report is to provide information relevant for determining appropriate target reference points for the main target species of the Commonwealth small pelagics fishery. In particular, the report will focus on the appropriate target reference points for the Eastern Jack Mackerel component of the fishery.

Methods

Ideally, target reference points would be established using an integrated bioeconomic model of the fishery. While substantial progress has been made in the development of a biological operating model, there is insufficient economic information to turn this into a bioeconomic model.

The estimation of potential target reference points is undertaken using a theoretical model construct. The model can be solved analytically and numerically for a range of potential fisheries related conditions (economic and technical). The model utilises a Cobb-Douglas production function to link catch, effort and biomass. The model allows for the potential for hyperstability in the fishery, such that the relationship between catch per unit of effort and biomass is not assumed to be linear.

The models are estimated using two alternative assumptions about the population dynamics in the fishery, although both are solved as equilibrium models rather than dynamic models.

The models are solved for a range of economic and hyperstability assumptions. Estimates of biomass from the biological operating model are compared with observed catch per unit of effort data to derive the most appropriate hyperstability parameters for fishery.

Results

The results of the model analysis indicate that the economic target reference point is influenced by the hyperstability parameter as well as the cost structure of the fleet. At the extremes, a hyperstability parameter value of 1 (indicating a linear relationship between catch per unit of fishing effort (CPUE) and biomass) provides the standard bioeconomic reference points (as expected). In contrast, a hyperstability parameter value of 0 (indicating no relationship between cpue and biomass) results in the unique case that the economic target reference point is equivalent to the maximum sustainable yield (MSY) level of biomass (B_{MSY}).

The best estimated value of this parameter for the eastern jack mackerel fishery, using the estimates of biomass and observed CPUE, is zero. This suggests that B_{MSY} is an appropriate target reference point for the fishery irrespective of cost structure.

1 Introduction

The move to maximum economic yield (MEY) as a fisheries management target requires increased information not only on the fishery dynamics but also a range of economic parameters, and ideally an operational bioeconomic model to identify the optimal target reference points.

In many fisheries, such models do not exist. In Australia, there is increasing reliance on proxy bioeconomic reference points that have been derived more generically for many fisheries. These are usually derived from models that assume a linear relationship between catch per unit of effort and biomass.

Previous estimates of single species target reference points (Pascoe *et al.* 2014) suggest that an appropriate target for biomass in the fishery may be in the order of around $0.7B_0$ (or higher), where B_0 is the unfished level of biomass. This assumes that fishing in the fishery is a relatively high cost operation relative to revenue, although without economic information on the fishery this can not be verified.

However, the modelling work underlying this initial estimate of proxy target reference points assumed a linear relationship between catch and biomass. This relationship is invalid for many schooling species, particularly small pelagics. In some cases, catch rates may not decline at all despite declining stock size, while in other cases it decreases at a less than proportional rate – a process known as hyperstability.

The purpose in this short study is to assess the impact of hyperstability on potential bioeconomic reference points, and the likely relationship between catch and biomass for the eastern jack mackerel fishery. We examine the effects of the relationship using two common underlying biomass dynamic models – a logistic growth model (Schaefer 1954; Schaefer 1957) and Gompertz growth model (Fox 1970).

2 Methods

2.1 Fisheries production functions

In most biological and bioeconomic models, catch (C) per unit of fishing effort (E) is generally assumed to be linearly related to stock biomass (x), such that C/E =qx, where q is a constant known as the catchability coefficient. Given this, we can assume that catch can be given by C=qEx.

While this relationship holds for many species, it is a not a universal truth. For many small pelagic fisheries (e.g. anchovies, pilchards, sardines etc.) – some of the largest fisheries in the world in terms of quantity of catch – fishing takes place on schooling aggregations. In such cases, catch rates may remain relatively high as the total biomass declines, a process known as hyperstability (Hilborn and Walters 1992).

Hannesson (1983) suggested a more generalised fisheries production function based on the Cobb Douglas production function (Douglas 1976), given by $C = qx^{\alpha}E^{\beta}$ where α and β represent biomass and effort elasticity respectively. Hannesson (1983) found that the value of β was generally not significantly different to 1 for most fleets, a result also found in other more recent studies (e.g. Pascoe *et al.* 2012; Pascoe *et al.* 2017). In the case of hyperstability, $0 < \alpha < 1$.

2.2 Optimal biomass levels given hyperstability

The harvest strategy policy (DAFF 2007) identifies maximising the economic yield in the fishery as an appropriate objective for the Commonwealth fisheries. As a result, the biomass at maximum economic yield (B_{MEY}) is considered an appropriate target reference point.

We derive the equilibrium conditions given the Cobb-Douglas form of the production function for two different biomass dynamic models, namely the Schaefer (1954); Schaefer (1957) logistic form of the model, and the Gompertz form proposed by Fox (1970). These models are commonly employed in fisheries economic analysis.

The models are solved first analytically to determine the appropriate equilibrium conditions, and numerically for a range of potential economic parameters.

2.3 Relationship between catch rate and biomass

The biomass estimates from the Eastern Jack Mackerel assessment (Punt *et al.* 2016) were regressed against the catch as a log linear relationship given by $\ln C = \ln q + \alpha \ln x + \beta \ln E$. From this, the appropriate value of α for the fishery could be determined.

3 Results

3.1 Analytical results for the equilibrium models

We consider the relationship between catch, fishing effort and biomass to be given by $C = qEx^{\alpha}$, and two alternative population dynamics models; given by

$$x_{t+1} = x_t + rx_t(1 - x_t / k) - qEx_t^{\alpha} \quad (1)$$

$$x_{t+1} = x_t + x_t r \ln(k / x_t) - qEx_t^{\alpha} \quad (2)$$

where *r* is the instantaneous growth rate and *k* is the carrying capacity of the stock (also referred to as the unexploited biomass or x_0). These equations state that the stock next year (x_{t+1}) is equal to the stock in the previous year (x_t) plus the net natural growth (a function of the instantaneous growth rate that the stock size relative to the carrying capacity) less the catch. Equation (1) represents the Schaefer (1954); Schaefer (1957) logistic form of the model, while the Equation (2) is the Gompertz form proposed by Fox (1970). These models are commonly employed in fisheries economic analysis. In equilibrium, the stock sizes are equal (i.e. x_t=x_{t+1}), and the growth component is equal to the catch. The catch at this point is sustainable indefinitely.

The sustainable yield varies depending on the stock size. Similarly, the level of effort required to take the sustainable catch, which can be derived from Equations 1 and 2, also depends on the stock size

$$E = \frac{r}{q}\left[x^{1-\alpha} - \frac{1}{k}x^{2-\alpha}\right] \quad (3)$$

$$E = \frac{x^{1-\alpha} r}{q} \ln(k / x_t) \quad (4)$$

Fisheries profit is derived as revenue (price multiplied by catch, a function of fishing effort) less costs (cost per unit effort multiplied by total effort), which can also be expressed in terms of biomass by substituting in Equations 3 and 4 for the effort terms.[1]

$$\Pi = \frac{r}{q}\left(pqx^{\alpha} - c\right)\left[x^{1-\alpha} - \frac{1}{k}x^{2-\alpha}\right] \quad (5)$$

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[1] The full derivation of all of these relationships is given in the Appendix.

$$\Pi = \frac{x^{1-\alpha} r}{q} \ln(k/x)\left[pqx^{\alpha} - c \right] \tag{6}$$

Profits are maximised (i.e. MEY) when $d\Pi / dx = 0$. Solving this for each of the growth models (see Appendix) provides the relationships

$$\left(1 - \frac{c}{pqx^{\alpha}}\right)\left[(1-\alpha) - (2-\alpha)\frac{x}{k}\right] = \alpha\left[\frac{x}{k} - 1\right] \tag{7}$$

$$a = \left[1 - \frac{c}{pqx^{\alpha}}\right]\left[\frac{1}{\ln(k/x)} - (1-\alpha)\right] \tag{8}$$

Solving these for x is not trivial, but the special case of $\alpha = 0$ and $\alpha = 1$ can be derived relatively easily. Ion terms of $\alpha = 1$, the optimal level of biomass is given as

$$x = \frac{k}{2} + \frac{c}{2pq} \tag{9}$$

$$\ln(k/x) = \left[1 - \frac{c}{pqx}\right] \tag{10}$$

which are the standard definitions for MEY from the traditional Schaefer and Fox bioeconomic model respectively. In contrast, if $\alpha = 0$,

$$x = \frac{k}{2} \tag{11}$$

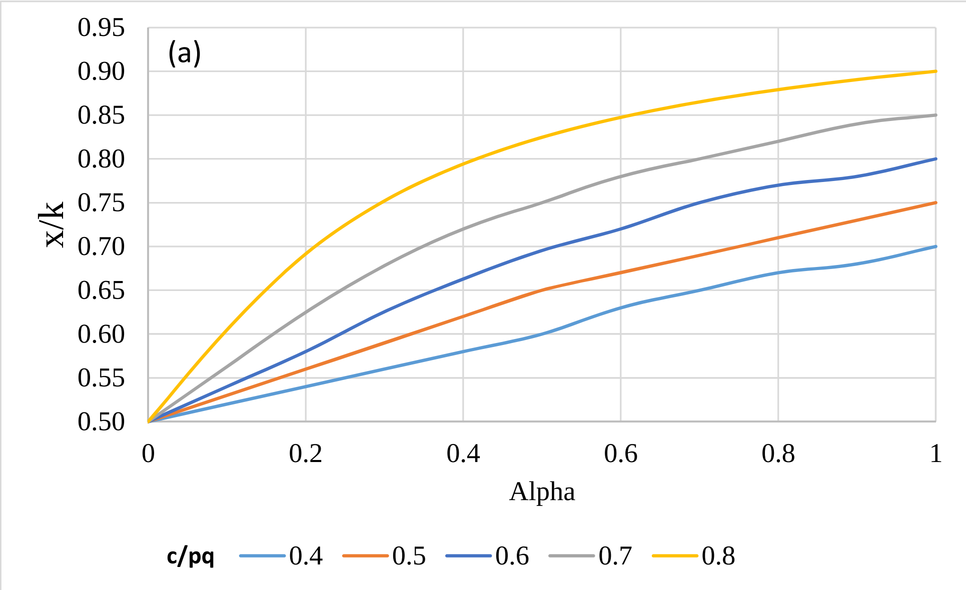
$$x = \frac{k}{\exp(1)} \tag{12}$$

which represent MSY for both models respectively. That is, if there is no relationship between catch rate and biomass ($\alpha = 0$), then MEY=MSY.

3.2 Numerical results (relative measures) where $0 < \alpha < 1$

Solving for values of x where $0 < \alpha < 1$ is more complex. Given the highly non-linear nature of the optimality conditions, a genetic algorithm was used to find a biomass level that satisfied Equations (7) and (8) for a range of different price and cost (*c/pq*) conditions. For simplicity, these were estimated with fixing *k=1*, such that the estimated value of *x* is essentially the biomass relative to the carrying capacity. The resultant relationships are provided in Figure 1, with the biomass at MEY expressed as a proportion of the unexploited biomass, and Figure 2 relative to biomass as MSY.

Figure 1. Relationship between x/k, alpha and c/pq (a) Schaefer model; (b) Fox model



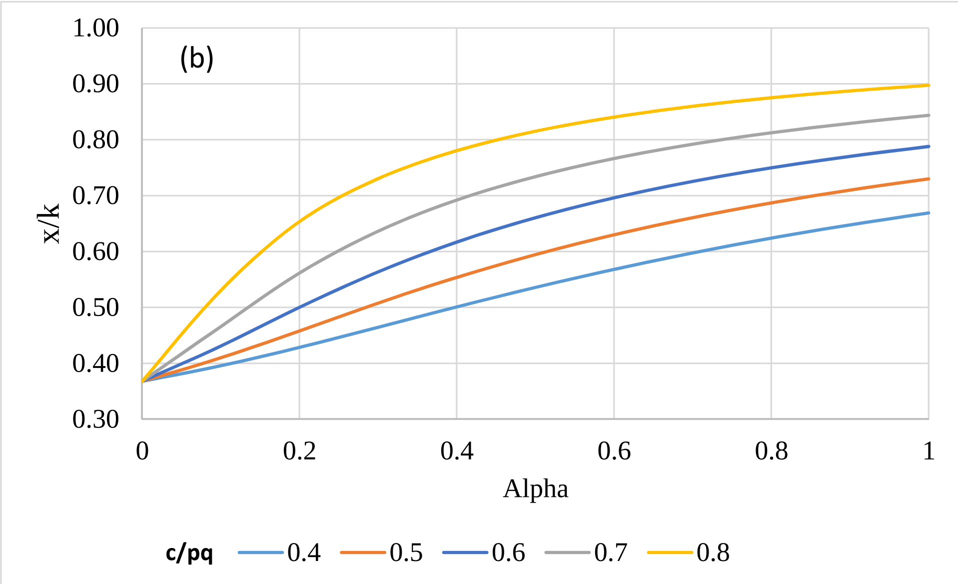
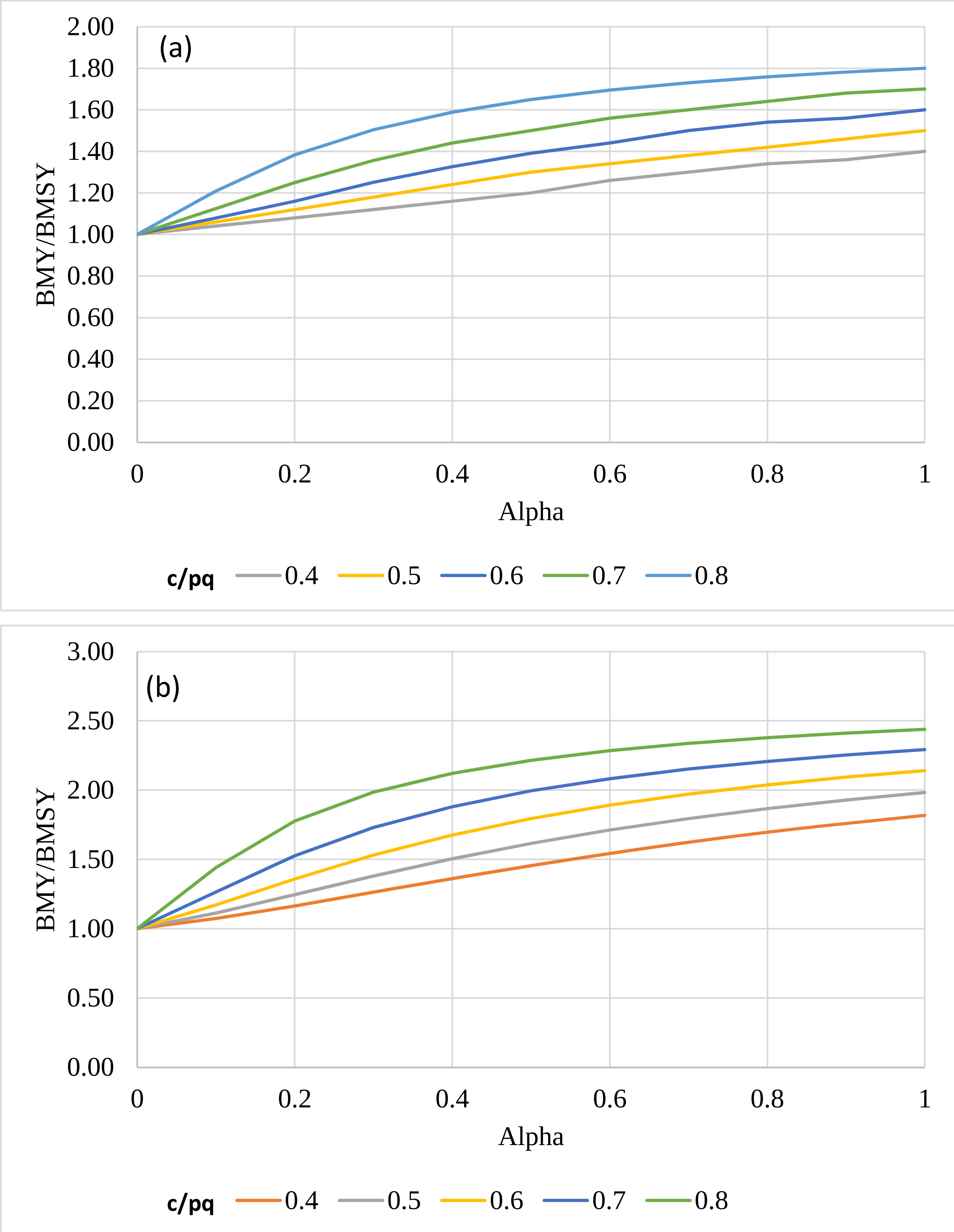


Figure 2. Relationship between BMEY/BMSY, alpha and c/pq (a) Schaefer model; (b) Fox model

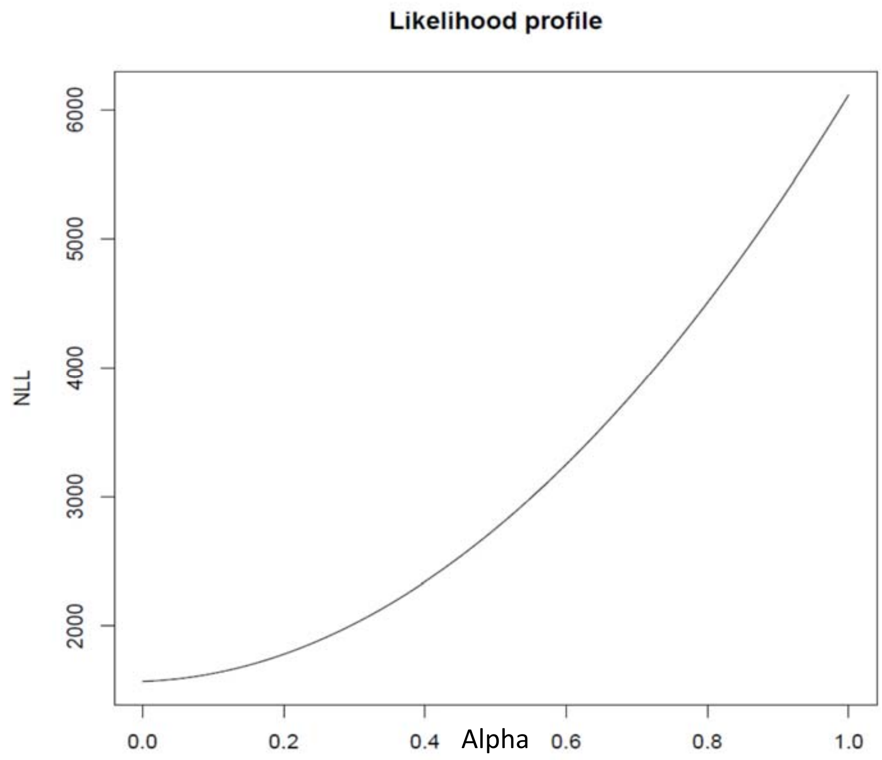


3.3 Relationship between catch rate and biomass

The regression model ($\ln C = \ln q + \alpha \ln x + \beta \ln E$) was run first with the parameter on the effort variable unrestricted. This parameter was found to be not significant different to 1, consistent with other studies cited earlier. This enabled the model to be respecified as $\ln(C/E) = \ln q + \alpha \ln x$.

The parameters for the revised model were estimated through minimising the log likelihood function. The likelihood profile for different levels of $0 < \alpha < 1$ is shown in Figure 3. From this, the most likely value is $\alpha = 1$, which suggests that the most appropriate target reference point from an economic perspective is $B_{MEY}=B_{MSY}$.

Figure 3. Likelihood profile for values of alpha



4 Discussion

The move to maximum economic yield (MEY) as a key management target for Australian Commonwealth fisheries has brought a range of challenged, for most of which has been the lack of fishery specific bioeconomic models. The Commonwealth harvest strategy policy (DAFF 2007) has suggested the used of proxy economic reference points, with a target biomass at MEY (B*MEY*) relative to that at maximum sustainable yield (MSY, B_{MSY}). The default proxy value is that BMEY=1.2B_{MSY}, although the policy allows for more appropriate proxy values if they are available. Ongoing research has identified a range of potential bioeconomic reference points for single species (Pascoe et al. 2014) and multispecies fisheries (Pascoe *et al.* 2015). These proxies, however, were based on models that assumed catch rates were linearly related to stock size, an assumption common to a wide range of stock assessment and bioeconomic models.

A range of fisheries in Australia, as elsewhere, are based on species that do not conform to the standard model structures commonly employed in bioeconomic models. In particular, schooling species such as many small pelagic species exhibit high catch rates even as stocks are depleted to low levels.

The results of this analysis indicate that as the relationship between catch rates and stock size deteriorates, then the influence of economic conditions on the optimal stock size decreases. With no relationship (i.e. ($\alpha = 0$), then MEY=MSY.

Ironically, Christensen (2010) earlier proposed that MEY=MSY, but for substantially different reasons to those considered in our study. This was subsequently rebuffed both theoretically and empirically (Sumaila and Hannesson 2010; Grafton *et al.* 2012). However, the results of this study have also come to the same conclusion, although for very different reasons than proposed by Christensen (2010) and also only under very specific conditions.

Relatively few studies have attempted to estimate the α parameter. In the study by Hannesson (1983) cited earlier, the values of α ranged from around 0.77 to 0.90 for the fleets examined. At these high values of α, the estimated optimal biomass at MEY is close to (but slightly lower than) the value where $\alpha = 1$ (the "standard" assumption when estimating MEY).

In contrast, our work on the Australian Eastern Jack Mackerel fishery found that $\alpha = 0$, and hence MSY was an appropriate proxy target for MEY also.

The results also illustrated the effects of cost relative to revenue on these relationships. High cost fisheries (i.e. low profit margins) required higher levels of biomass to achieve MEY than lower cost fisheries. While this is consistent with previous studies (Pascoe et al. 2014), the results in this study suggest that, for higher cost fisheries, stock levels greater than MSY are necessary for MEY even if the relationship between catch rate and biomass is low. Higher cost fisheries approach the biomass estimated by assuming a constant relationship ($\alpha = 0$) at a faster rate than low cost fisheries.

Deriving an appropriate proxy economic reference point is complex when so many factors may affect this relationship. Previous studies have demonstrated the effects of price, cost and growth assumptions on these proxy targets (Pascoe et al. 2014; Pascoe et al. 2015), while this study adds an additional level of complexity through also requiring an understanding of how catch rates change with stock size.

Appendix A Derivation of optimal biomass levels with each model

1. Logistic (Schaefer) growth model

Production function $C = qEx^{\alpha}$ (i)

Biomass dynamic relationship $x_{t+1} = x_t + rx_t(1 - x_t / k) - qEx_t^{\alpha}$ (ii)

Rearranging (i) and (ii) gives $qEx_t^{\alpha} = \left(x_t - x_{t+1}\right) + rx_t(1 - x_t / k)$ (iii)

From which we can derive sustainable effort as a function of biomass

$$E = \frac{r}{q}x^{1-\alpha}(1 - x/k) \text{ or } E = \frac{r}{q}x^{1-\alpha} - \frac{r}{qk}x^{2-\alpha} \quad \text{(iv)}$$

Given a profit function where profits is revenue (catch times price) less costs (cost per unit of effort times effort), $\Pi = pC(E) - cE$, we can express sustainable profit solely as a function of biomass, such that

$$\Pi = \left(pqx^{\alpha} - c\right)\left[\frac{r}{q}x^{1-\alpha} - \frac{r}{qk}x^{2-\alpha}\right] \text{ or } \Pi = \frac{r}{q}\left(pqx^{\alpha} - c\right)\left[x^{1-\alpha} - \frac{1}{k}x^{2-\alpha}\right] \quad \text{(v)}$$

Profits are maximised when the first derivative with respect to biomass is equal to zero. That is,

$$\frac{d\Pi}{dx} = \frac{r}{q}\left[\frac{d\left(pqx^{\alpha} - c\right)}{dx}\left[x^{1-\alpha} - \frac{1}{k}x^{2-\alpha}\right] + \left(pqx^{\alpha} - c\right)\frac{d\left[x^{1-\alpha} - \frac{1}{k}x^{2-\alpha}\right]}{dx}\right] = 0 \quad \text{(vi)}$$

This can be solved and rearranged through a series of sets

$$\frac{d\Pi}{dx} = \frac{r}{q}\left[\alpha pqx^{\alpha-1}\left[x^{1-\alpha} - \frac{1}{k}x^{2-\alpha}\right] + \left(pqx^{\alpha} - c\right)\left[(1-\alpha)x^{-\alpha} - (2-\alpha)\frac{1}{k}x^{1-\alpha}\right]\right] = 0$$

$$\left[\alpha x^{-1}\left[x^{1-\alpha} - \frac{1}{k}x^{2-\alpha}\right] + \left(1 - \frac{c}{pqx^{\alpha}}\right)\left[(1-\alpha)x^{-\alpha} - (2-\alpha)\frac{1}{k}x^{1-\alpha}\right]\right] = 0$$

$$\left[\alpha\left[x^{-\alpha} - \frac{1}{k}x^{1-\alpha}\right] + \left(1 - \frac{c}{pqx^{\alpha}}\right)\left[(1-\alpha)x^{-\alpha} - (2-\alpha)\frac{1}{k}x^{1-\alpha}\right]\right] = 0$$

$$\left[\alpha x^{-\alpha}\left[1 - \frac{1}{k}x\right] + \left(1 - \frac{c}{pqx^{\alpha}}\right)x^{-\alpha}\left[(1-\alpha) - (2-\alpha)\frac{1}{k}x\right]\right] = 0$$

$$\left[\alpha\left[1 - \frac{1}{k}x\right] + \left(1 - \frac{c}{pqx^{\alpha}}\right)\left[(1-\alpha) - (2-\alpha)\frac{1}{k}x\right]\right] = 0$$

To give the condition

$$\left(1 - \frac{c}{pqx^{\alpha}}\right)\left[(2-\alpha)\frac{x}{k} - (1-\alpha)\right] = \alpha\left[1 - \frac{x}{k}\right] \quad \text{(vii)}$$

This condition is complex to solve, except under certain limiting conditions. For example, when $\alpha = 1$

$$\left(1-\frac{c}{pqx}\right)\left[\frac{x}{k}\right]=\left[1-\frac{x}{k}\right]$$

$$\left(1-\frac{c}{pqx}\right)=\left[\frac{k}{x}-1\right]$$

$$\left(x-\frac{c}{pq}\right)=\left[k-x\right]$$

$$\left(2x-\frac{c}{pq}\right)=k$$

Which yields the optimal biomass level

$$x=\frac{1}{2}\left(k+\frac{c}{pq}\right) \qquad \text{(viii)}$$

This is the "traditional" value of biomass at MEY given the Schaefer growth model, and is half way between the carrying capacity (k) and the open access equilibrium (c/pq)).

Similarly, when $\alpha = 0$

$$\left(1-\frac{c}{pq}\right)\left[1-2\frac{x}{k}\right]=0$$

$$\left[1-2\frac{x}{k}\right]=0$$

Which yields the optimal biomass level

$$x=\frac{k}{2} \qquad \text{(ix)}$$

This is the value of MSY from the Schaefer model.

2. Gompertz (Fox) model

The Fox model has the same production function, $C = qEx^{\alpha}$, but a different biomass dynamic function due to the different growth assumptions

$$x_{t+1} = x_t + x_t r \ln(k/x_t) - qEx_t^{\alpha} \qquad \text{(x)}$$

Rearranging (x) gives $qEx_t^{\alpha} = (x_t - x_{t+1}) + x_t r \ln(k/x_t)$ (xi)

From which we can derive sustainable effort as a function of biomass

$$E = \frac{x^{1-\alpha} r}{q}\ln(k/x_t) \qquad \text{(xii)}$$

As before, the profit function is defined as revenue (catch times price) less costs (cost per unit of effort times effort), $\Pi = pC(E) - cE$. We can express sustainable profit solely as a function of biomass, such that

$$\Pi = pqx^{\alpha}\frac{x^{1-\alpha} r}{q}\ln(k/x) - c\frac{x^{1-\alpha} r}{q}\ln(k/x) \text{ or } \Pi = \frac{x^{1-\alpha} r}{q}\ln(k/x)\left[pqx^{\alpha} - c\right] \qquad \text{(xiii)}$$

Profits are maximised when the first derivative with respect to biomass is equal to zero. That is,

$$\frac{d\Pi}{dx}=\frac{r}{q}\left[\begin{array}{l}\frac{d(x^{1-\alpha})}{dx}\left[\ln(k/x)\left[pqx^{\alpha}-c\right]\right]+\\ \frac{d(\ln(k/x))}{dx}\left[x^{1-\alpha}\left[pqx^{\alpha}-c\right]\right]+\frac{d\left[pqx^{\alpha}-c\right]}{dx}\left[x^{1-\alpha}\ln(k/x)\right]\end{array}\right]=0 \qquad \text{(xiv)}$$

where

$\frac{d\ln(kx^{-1})}{dx}=\frac{1}{u}\frac{du}{dx}=\frac{1}{kx^{-1}}\left[-kx^{-2}\right]=-\frac{1}{k}kx^{-1}=-\frac{1}{x}$ where $u=kx^{-1}$

This can be solved and rearranged through a series of sets

$$0=(1-\alpha)x^{-\alpha}\left[\ln(k/x)\left[pqx^{\alpha}-c\right]\right]-x^{-1}\left[x^{1-\alpha}\left[pqx^{\alpha}-c\right]\right]+\alpha pqx^{\alpha-1}\left[x^{1-\alpha}\ln(k/x)\right]$$

$$0=(1-\alpha)x^{-\alpha}\left[\ln(k/x)\left[pqx^{\alpha}-c\right]\right]-\left[x^{-\alpha}\left[pqx^{\alpha}-c\right]\right]+\alpha pqx^{\alpha-1}\left[x^{1-\alpha}\ln(k/x)\right]$$

$$0=(1-\alpha)\left[\ln(k/x)\left[1-\frac{c}{pq}x^{-\alpha}\right]\right]-\left[\left[1-\frac{c}{pq}x^{-\alpha}\right]\right]+\alpha\left[\ln(k/x)\right]$$

$$0=\left[1-\frac{c}{pq}x^{-\alpha}\right]\left[(1-\alpha)\ln(k/x)-1\right]+\alpha\left[\ln(k/x)\right]$$

$$0=\left[1-\frac{c}{pq}x^{-\alpha}\right]\left[(1-\alpha)-\frac{1}{\ln(k/x)}\right]+\alpha$$

$$0=\left[1-\frac{c}{pq}x^{-\alpha}\right]\left[(1-\alpha)-\frac{1}{\ln(k/x)}\right]+\alpha$$

To give the condition

$$a=\left[1-\frac{c}{pqx^{\alpha}}\right]\left[\frac{1}{\ln(k/x)}-(1-\alpha)\right] \qquad \text{(xv)}$$

As with the Schaefer model, this condition is complex to solve, except under certain limiting conditions. For example, when $\alpha=1$

$$\ln(k/x)=\left[1-\frac{c}{pqx}\right] \text{ or } x=\frac{k}{e^{\left[1-\frac{c}{pqx}\right]}} \qquad \text{(xvi)}$$

This is the “traditional” condition for MEY given the Fox growth model. Similarly, when $\alpha=0$

$$0=\left[1-\frac{c}{pq}\right]\left[\frac{1}{\ln(k/x)}-1\right]$$

From which $\ln(k/x)=1$ and hence

$$x=\frac{k}{\exp(1)} \qquad \text{(xvii)}$$

This is the value of MSY from the Fox model.

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