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Paper Title: Economically optimal management strategies for the South Georgia Patagonian toothfish fishery

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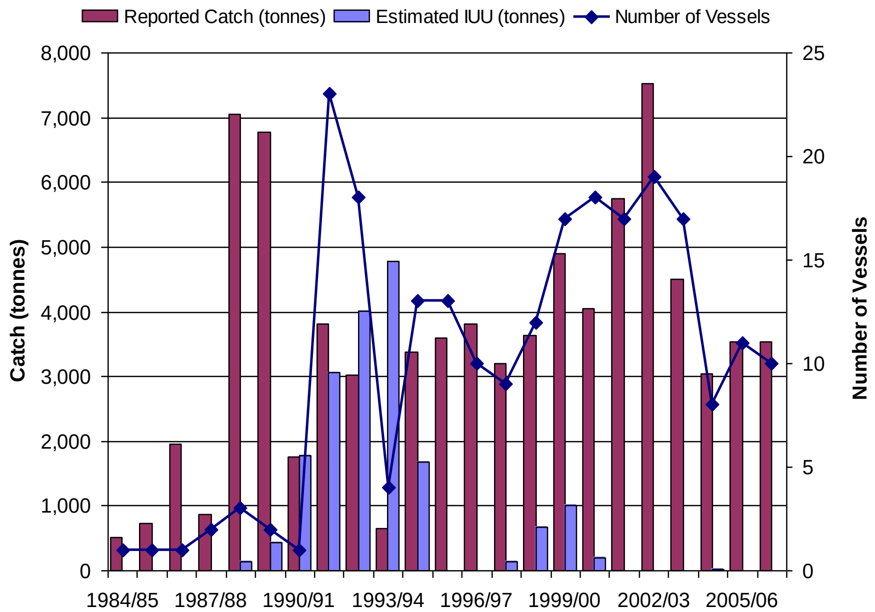
Abstract:

The fishery for Patagonian toothfish (*Dissostichus eleginoides)* around the island of South Georgia in the Southern Ocean is a profitable operation targeting a high-value, slow-growing species. We substituted the complex Bayesian age-structured model currently used for assessments with a Schaefer production model, which performs equally well as an operating model for management strategy evaluation. A number of potential effort reduction strategies are investigated, several of which would achieve better conservation objectives and higher future profits from the fishery than those predicted using the current management strategy. The article also discusses the applicability of this approach to the Australian sub-Antarctic fisheries targeting the stocks of *D. eleginoides.*

Introduction

Patagonian toothfish (*Dissostichus eleginoides)* is a large demersal, long-lived fish distributed widely in shelf and shelf-slope waters around Sub-Antarctic islands and both the east and west coasts of South America. There are assumed to be 5-6 stocks in the Antarctic (SC-CAMLR, 2007) and probably 2-3 on the east and west coasts of South America (Payne *et al.* 2005). Globally, toothfish stocks have experienced high levels of exploitation due to high international demand for what is considered to be luxury seafood in the USA, Japan, and the EU (Catarci 2004). The global catches of Patagonian toothfish peaked in mid-1990s, with declared catch of around 40,000 tonnes from 1994-1996, and an additional illegal, unreported, and unregulated (IUU) catch in Antarctic waters estimated to be between 30,000 and 40,000 tonnes (Agnew 2000; SC-CAMLR 2008). Catches of both regulated and IUU fishing have declined since then, and for 2008 they were estimated to be 24,000 tonnes (including about 1,000 tonnes of IUU catch). The stock of Patagonian toothfish around the island of South Georgia is managed by the Government of South Georgia and the South Sandwich Islands (GSGSSI), an Overseas Territory of the UK, which manages fishing and other activities within the South Georgia Maritime Zone (SGMZ). Along with other Antarctic fishery resources, this stock is subject to management advice from the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). A summary of historical toothfish catch and number of registered vessels in the region is given in Figure 1. For a more detailed exposition of the history of this fishery see Agnew (2004).



Source: SC-CAMLR (2007).

Figure 1. Historical Summary of Toothfish Fishery in South Georgia

CCAMLR has defined specific harvest control rules (HCRs) for toothfish species exploited in the convention zone. These harvest control rules are designed to avoid significant impacts on recruitment: the probability that spawning stock biomass will drop below 20% of

B_0 over a 35-year projection period is less than or equal to 10%; and that to ensure that removal of this top predator is consistent with obligations to maintain ecosystem functioning, the median biomass at the end of a 35-year projection period should be greater than or equal to 50% of virgin stock biomass (SC-CAMLR 2007). CCAMLR tends to consider the decision rule to represent an implicit limit reference point of spawning stock biomass at 20% of its median unexploited level, and target reference point of spawning stock biomass at 50% of its median unexploited level. Total allowable catches (TACs) are set within these bounds and divided between a number of licensed vessels. IUU fishing has been a problem in the past for the fisheries in the convention area. However, with the introduction of extensive patrolling of the SGMZ from 1998 onwards, the number of sightings of IUU vessels rapidly decreased in South Georgia and only one further incident of IUU has been recorded (Agnew and Kirkwood 2005). IUU catches of this toothfish stock are currently estimated to be zero (SC-CAMLR 2008).

Both GSGSSI and CCAMLR management objectives have focused heavily on biological/ecological sustainability, driven by both organisations' primary objective of ecosystem conservation. As a result, the current management target and reference points, as set out above, were set solely on the basis of biological perspectives. No consideration has yet been given to the long-term economic aspects of the fishery.

In this article an alternative set of potential management strategies with economic objectives are explored, and these strategies are compared with the current management objectives, based on both economic and biological performance criteria. This is the first attempt to apply bioeconomic modelling to the Patagonian toothfish fishery in South Georgia and to Antarctic resources. The applicability of this approach to the management of Patagonian toothfish stocks in Australian sub-Antarctic waters is discussed in the later section.

Methods

Constructing a Bioeconomic Operating Model

The current stock assessment method used for toothfish in South Georgia is a complex, Bayesian age-structured integrated assessment model (Hillary *et al.* 2006). To simplify the problem of estimating bioeconomic equilibrium, we reduce the age-structured population and fishery model to a more tractable surplus production/biomass dynamic operating model. We use the term operating model because not only are the biomass dynamic population model and the production function parameters used to estimate economically optimal harvesting conditions, we also subsequently use them as the basis for a full simulation model of the population and fishery (Kell *et al.* 2007; Rademeyer *et al.* 2007).

The model is the standard Schaefer model, dictating the change in biomass, B_t, over time:

$$B_{t+1} = B_t + rB_t\left(1 - B_t/K\right) - Y_t, \tag{1}$$

where r and K are the intrinsic rate of increase and carrying capacity parameters, respectively, and Y_t is the total harvest taken from the stock at period, t, by both legal and illegal fleets.

Estimating Intrinsic Growth Rate

Following the method detailed in Myers *et al.* (1997), the *r* parameter was estimated by solving the Euler-Lotka equation:

$$\sum_{j=0}^{\infty} e^{-rj} l_j m_j w_j a = 1, \qquad (2)$$

where l_j is the probability of surviving to age *j*, m_j is the maturity at age *j*, w_j is the weight at age *j*, and *a* is the recruits per unit of spawning stock biomass. The life-history parameters (age at maturity, natural mortality, and stock-recruit parameter) were obtained from the results from CCAMLR stock assessment (SC-CAMLR 2007). These life history parameters have distributions with known mean and variance. A Monte Carlo approach was used to obtain 1,000 sample values for *r* to account for uncertainty in this key parameter, given uncertainty in the life history parameters that define *r*. From these samples a median value (*r*=0.12) and 95% confidence interval of *r* of between 0.09 and 0.17 was obtained. The reasons for estimating *r* in this manner are as follows: Firstly, the stock of toothfish in South Georgia waters has experienced a gradual 'fish-down' dynamic, without any periods of decline followed by growth. This confounds the estimation of both *r* and *K* from the assessment-derived biomass trend and the catch biomass. The analogy would be with trying to estimate such parameters given 'one-way trip' abundance trend data (Hilborn and Walters 1992). Secondly, the intention is to use the model as a simplified form of the current management approach while preserving the information on the key life-history characteristics in the biomass dynamic model as they are in the fully age-structured model. This type of approach has been applied in a stock assessment context for a range of other species (McAllister *et al.* 2001), particularly when information on life history is available but catch-at-length data and growth information are partially lacking (such as shark and some tuna species), but not for the purposes of ‘translating’ an age-structured model to a biomass dynamic model. It is worth reflecting that the major potential information loss incurred by our translation work is selectivity. Although longline gear is selective, the over-riding driver of selectivity is the depth of fishing (Hillary *et al.* 2006), which is strictly controlled and has not changed for over a decade (Agnew 2004). Assuming no future changes in depth regulations, the lack of ability to model selectivity was considered unlikely to affect our analysis (we justify this assertion later on).

Estimating Carrying Capacity

Catches prior to 1985, when the deep water longline fishery was initiated, were extremely small, limited to exploitation for research purposes and some bottom trawl by-catches of juveniles over the shelf. The main adult population, which lives deeper than 600m, was not impacted by the earlier bottom trawl fisheries on the shelf (Agnew 2004). Thus carrying capacity, *K*, for toothfish is assumed to be equal to the biomass level in 1985. The recent (2007) exploitable biomass is estimated to be 55% of *K* (CV = 0.102) (SC-CAMLR 2007). A paired Monte Carlo approach was used to obtain a distribution of plausible values of *K* for given values of *r*, which gives the current toothfish biomass equal to 55% of *K*. This was done by using a numerical equation solver to estimate *K* — for a given sample value of *r* — that gives $B_{2007} = 0.55*K$, subject to the population dynamics in equation (1). The median and 95% confidence interval for *K* was 109,225 (89,579-126,961) tonnes.

Validation of the Model as a Management Tool

In order to validate whether the simpler model developed here (reduced model) performed well for the South Georgia toothfish fishery, the catch limit or TAC predicted by the reduced model was compared with the catch limit predicted by the age-structured Bayesian assessment model of CCAMLR. TACs are set by CCAMLR according to a constant catch rule:

i) Find the constant catch for which the probability of spawning biomass dropping below 20% of the unfished median spawning biomass during a projection period of one generation time (35 years) is equal to 0.1.
ii) Find the constant catch that generates a median spawning population biomass equal to 50% of the median unfished spawning biomass after a projection period of 35 years.
iii) Choose as a TAC the maximum harvest level that satisfies the two conditions above.

A simple comparison showed that the TAC predicted using the reduced model, given stock size in 2006, was 3,478 tonnes, while the TAC set by CCAMLR for this stock in 2006 was 3,554 tonnes (SC-CAMLR 2007). This equates to a difference of around 2% between predictions of the full stock assessment model and the reduced model. The reduced model should, therefore, provide sufficiently robust results for the analysis of short- and long-run bioeconomic equilibria. Since the model has been shown to be able to replicate recent management decisions, and assuming no future changes in depth regulations, the lack of ability to model selectivity is not considered too restrictive.

Estimating the Production Function Parameters

The harvest level of the legal fleet, *Y*, in period *t* was estimated according to a Cobb-Douglas production function (Cobb and Douglas 1928):

$$Y_t = Y(E_t, B_t) = qE_t^{\alpha} B_t^{\beta}, \quad (3)$$

where q is the catchability coefficient, and E_t is the aggregated fishing effort by fleet in period t; α is the effort output elasticity; and β is the stock output elasticity. For use as an estimation equation it is helpful to re-express the equation in logarithmic form, adding a term for the (assumed normal) estimation error, u:

$$\ln Y_t = \ln q + \alpha \ln E_t + \beta \ln B_t + u_t, \quad (4)$$

Data on catch and effort from the legal fleet are available since the 1984/85 season and were obtained from the most recent published data (SC-CAMLR 2007), but there was a major change in operations in the late 1990s which has previously been identified as producing a discontinuity in the time series and changing the catchability of the fleet (SC-CAMLR 2007). Some of the causes were a shift from a summer fishery to a winter fishery, the introduction of a requirement for nighttime setting of longlines to reduce incidental mortality on seabirds, changes in fleet nationality composition, and the introduction of scientific observers on vessels. All changes were introduced gradually from around the 1995/96 season and completed by 1997 (Agnew 2004). For these reasons, it was decided to use a subset of time series data between 1997/98 and 2007/08 (n=11).

The number of hooks deployed each year was obtained from the SC-CAMLR (2007) assessment and used as an aggregated effort index.[1] Values of stock output elasticity, β, less than one are commonly found for fisheries on schooling stocks, such as Norwegian spring spawning herring (Bjørndal 1987) and juvenile cod (Eide *et al.* 2003). Although toothfish may aggregate around particular features (such as sub-sea canyons) observational evidence is that they are not a schooling species (Yau *et al.* 2001). The South Georgia stock assessment implicitly assumes β to be equal to one (SC-CAMLR 2007), so one must naturally make the same assumption in estimating the production function parameters using such stock assessment data. It is worth noting that alternative work to look for hyperstability in catch-per-unit-effort (CPUE), similar to assuming $\beta < 1$, detected no such effect for this stock (SC-CAMLR 2005), confirming this assumption. Equation (4) was used to estimate the parameters for two models using ordinary least square (OLS) regression with fixed $\beta = 1$. In Model A, α in equation (4) was estimated from the data. In Model B, the standard Schaefer formulation was used, where $\alpha = \beta = 1$.

A number of model selection criteria were used to select the most appropriate form of the production function.[2] Using the likelihood-ratio test the improvement observed from using Model A over Model B was significant, but the estimate of α (1.08, sd 0.08) was not significantly different than one. No difference was found in the adjusted *R*-squared between the two models (both 0.95). Based on the parsimony principle, the simpler Model B was selected as an appropriate form of the production function. No significant autocorrelation was detected in the production function residuals. Once the production functional form was selected, the relevant parameters (in this case only *q*) were estimated for each historical biomass Monte Carlo sample, thereby obtaining a consistent multivariate Monte Carlo sample of *r*, *K*, and *q*, and accounting for uncertainty in the stock and production dynamics simultaneously. Sequentially, the process is summarized as follows:

- *i)* All the relevant life-history parameters are used to derive 1,000 Monte Carlo samples for the intrinsic rate of increase, *r*.
- *ii)* For each of these samples a corresponding estimate of the carrying capacity, *K*, is estimated, given the historical catches and the biomass dynamic model, that give a current-to-unfished biomass ratio of 0.55 as per the stock assessment predictions.
- *iii)* For each sample of *r* and *K* and for the chosen production function, a sample of *q* is estimated given (4) and the historical effort.
- *iv)* The end result is 1,000 (covariant) samples of the key parameter vector (*r, K, q*).

Calculating Optimal Conditions

Optimal policies were based on the usual criterion of maximising the discounted sum of net present value of annual profit from the fishery over an infinite time horizon. Discounted annual profit was calculated according to:

[1] A potential econometric issue arising is that the number of hooks deployed is determined endogenously by the individual fishing agent; hence the effort variable is probably endogenous and consequently OLS estimators may be biased. Using lagged values of the number of hooks as an instrumental variable, a two-stage least squares regression (2SLS) was carried out to test if the model estimates were consistent. The null hypothesis was that the parameters were consistent. The Housman test statistic was 0.01, which follows a chi-square distribution (p-value = 0.943) indicating that the parameter estimates from the full model were consistent.
[2] Even though a distribution of stock biomass values were derived, the median historical biomass was used for the purposes of determining which production function is the most suitable.

$$\Sigma^{npv} = \sum_{t=0}^{\infty} \rho^t \pi(B_t, Y_t), \tag{5}$$

where $\rho = 1/(1+\delta)$ is the discrete discount factor and δ is the annual discount rate. Profit is defined as follows:

$$\pi(B_t, Y_t) = pqE_tB_t - c_vE_t - c_fV. \tag{6}$$

In the above equation, c_f and c_v are the fixed and variable costs and V is the number of vessels in the fleet. Economic data were obtained from a subsample of operators active over a number of years in South Georgia. Given that this was a subsample, there was some uncertainty about the true nature of costs, particularly variable costs, for the fleet as a whole. This uncertainty is accounted for by allowing the variable cost to have a uniform distribution +/- 15% of the actual subsample cost value (using parametric bootstrapping) with no assumed correlation between cost and the other parameters: r, K, and q. Although the price of toothfish has been relatively stable since 2005, price uncertainty was also accounted for by allowing the price to have uniform distribution of +/- 10% with again no assumed correlation between price and the other parameters. As explained in the Introduction, toothfish price over the past 15 years has responded to quite large changes in global supply and not to local (South Georgia) supply, which has remained fairly constant over this time period at an average of about 3,500 tonnes per year. Optimal effort, harvest, and biomass are calculated analytically[3] by maximizing equation (6) subject to the usual constraint: $B_{t+1} - B_t = F(B_t) - Y_t$ and $B_t, Y_t \geq 0$. This was done for each of the 1,000 samples of the full bioeconomic parameter vector (r, K, q, p, c_v, c_f) to obtain a Monte Carlo distribution of optimal effort, harvest, and stock biomass. A detailed display of the key results is given in table 1. It could be argued that there is no specific precautionary element in the objective function— if this was a serious concern, perhaps a more appropriate estimator for the optimal effort would be some lower percentile (*i.e.,* 25th percentile). That way, the higher the uncertainty in the key variables the lower the estimate of effort would be, as per the precautionary principle. However, the primary motivation of including uncertainty in the uniform distribution was to assess the resultant variation in the key derived management quantities and the robustness of the conclusions about optimal levels to this variation. Indeed, it would be interesting to see if a more stochastic-type approach resulted in similar answers.

Evaluation of Current and Effort-based Management Strategies

In the previous section, the calculation of optimal effort implicitly assumed an infinite time horizon. In this section, a management strategy evaluation (MSE) approach is employed to look at ways of reducing effort to the optimal levels over a finite time horizon calculated in the preceding section, while not adversely affecting the profitability of the fishery over the management period. The MSE approach has been applied frequently in a more general fisheries modelling context and provides a framework for both identifying robust management strategies and also sensibly comparing alternative strategies in the presence of

[3] For the simple production function, an analytical solution exists for the optimal stock, effort, and associated harvest (Clark, 1976).

multiple management objectives and system uncertainties (Butterworth and Punt 1999; Campbell and Dowling 2005; Punt and Smith 1999). The Fishery Libraries in R (FLR) framework is a generic, open-source framework for the construction of fisheries management simulations in the R statistical language[4] and was used to construct the bioeconomic operating models used in the following and previous analyses (Kell *et al.* 2007).

The aim is to simulate the whole process of this fishery management from stock assessment and the setting of the relevant TAC/effort level, implementation error, and bias in either the harvest taken or the effort set, to the dynamics of the stock given the management actions. There are already pre-existing management objectives for this stock as defined by CCAMLR, but there are also potential economic objectives to consider. In this article, multiple objective criteria are considered when evaluating the performance of each strategy. A management time horizon of 35 years is selected, since this is the time horizon over which the CCAMLR rules are designed to operate.

Constructing Gradual Effort Reduction Schemes

There are many potential effort reduction paths that can be imagined over a 35-year period, but rather than trying to find the unique optimal path that exists in theory as noted in Clark (1976), for practical reasons we considered the following two candidate functional forms: *i*) a simple piecewise linear reduction in current to optimal steady-state effort over a given time horizon; *ii*) a non-linear 'decay'-type reduction to optimal effort levels. For the piecewise linear effort reduction scheme, future effort can be expressed as follows:

$$E_t = \begin{cases} E^* + (t-1)(E^* - E_{2007})/(t^*-1) & t < t^* \\ E^* & t \geq t^* \end{cases}. \qquad (7)$$

For the non-linear reduction scheme future effort is defined as:

$$E_t = E^* + \left(E_{2007} - E^*\right) \times \left(\frac{1}{1+\upsilon}\right)^{t-1}. \qquad (8)$$

Here, E^* is the optimal effort level, t^* is the year when the effort reaches E^*, E_{2007} is the initial effort level in the 2007 fishing season, and ν is the reduction rate which can be interpreted as the year-to-year proportional reduction in the difference between current and optimal effort.

The relevant parameters of each reduction scheme were estimated by reference to one of two objectives, both of which reduce effort to the long-term optimum over a 35-year period:

i) Estimated as the values which maximise the median sum of the discounted annual profits over the 35-year simulation, subject to the constraint that at the end of the 35 years the effort must be equal to the optimal effort, E^*.

ii) Estimated as the values which yield a median sum of the discounted annual profits *equal* to those obtained under the CCAMLR management scenario, subject to the same constraint as above.

[4] http://www.r-project.org/

The reason for looking at these two objective criteria was to identify the effort reduction strategy expected to be at least as profitable as the current approach and that yielded the largest discounted profits over the traditional management period of 35 years (one generation time of toothfish). Any of the effort reduction paths would be expected to meet the CCAMLR management objectives, which is confirmed in table 2. The decision on which (if any) effort reduction path to take can be settled by the GSGSSI and the relevant stakeholders. No account was taken of potential adjustment costs to the industry, since reducing the effort (number of hooks in this case) is unlikely to cause fleet size reduction.

Simulating Current Management

In the simulations, the stock assessment process is treated as a random misestimation of stock biomass in the given assessment year, with a known CV which is assumed to be 0.1. Based on the results from the stock assessment, the TAC for that year is calculated according to the CCAMLR harvest control rule. Using the historic time-series of TAC and actual catch taken, it was possible to parameterise a simple implementation error model where the historic bias and variation dictate future levels of implementation error. The ability to account for human error in a fishery management process and its impact on the management outcome is one of the major advantages of the MSE approach. This whole process was simulated for 35 years into the future.

Performance Indicators

In evaluating the performance of each strategy, four performance indicators are used: *i*) median sum of discounted annual profits over 35 years at a 2% discount rate; *ii*) probability that the final stock size is greater than 50% of the initial stock size; *iii*) probability of stock size dropping below 20% of *K* at any time over the 35-year projection period; and *iv*) median final year CPUE (tonnes/1,000 hooks).

Results

Steady-state Optimal Conditions

The median optimal steady-state of harvest (Y^*) is estimated at between 3,134 and 3,270 tonnes per year and of biomass (B^*) at between 59,544 tonnes and 66,644 tonnes, where the variability depends largely on the choice of discount rate (table 1). As one would expect, an increasing discount rate resulted in higher estimates of optimal effort and resultant yield, with lower optimal levels of stock biomass.

We recognize that our estimates are sensitive to the choice of discount rate, and choosing an appropriate rate is difficult. Given that: *i*) society views the Antarctic as an ecosystem sanctuary, with high conservation priority, *ii*) both CCAMLR and GSGSSI have strong conservation objectives, and *iii*) applying higher discount rates to a slow-growth species may increase extinction risks[5], we selected a relatively low discount rate (2%) as the base-case assumption for the full simulation evaluation in the following section. It should also be noted that the key qualitative conclusions are robust up to a 4% discount rate. The target biomass level as defined by CCAMLR (around 54,000 tonnes = *K/2*) is actually very

[5] A higher discount rate increases the optimal rate of exploitation of a renewable resource and also increase risk of extinction. See Clark (1973; 1976) for detail. In the USA, estimates of the discount rate have ranged between 2 and 5% (Conrad 1999). This will vary depending on countries/culture and point in time.

close to the lower 95th percentile of the optimal biomass estimated from the bioeconomic analysis and is almost 20% lower than the optimal median biomass of 64,000 tonnes. Harvests for 2007 and 2008 were around 3,600 and 3,900 tonnes, respectively, which are at the edge of (2007) and outside (2008) the upper 95th percentile for the optimal harvest calculated in the bioeconomic analysis. The CCAMLR target biomass appears to be consistent with the results of a high discount rate (table 1). In terms of the median optimal harvest level, both 2007 and 2008 catches are around 20-25% higher. As of 2007, effort was around 15.2 million hooks, which is well outside the upper 95th percentile for optimal effort calculated in the bioeconomic analysis. The indications from the analysis are that if the CCAMLR targets are achieved and the stock is gradually reduced to 50% of *K* (around 54,000 tonnes), this would eventually result in a decrease in efficiency of the fishing operation from an economic perspective. Over the long-term (*i.e.*, an effective infinite time horizon), it would be more profitable to keep the stock biomass at its current level (around 55-60% of *K*) and not reduce it further. The optimal effort levels estimated across all discount rates fall well within the historical levels of effort (figure 1; Agnew 2004). Since such historical changes have been accommodated with no apparent loss of profitability, it is reasonable to assume that the suggested ranges of effort reduction can be implemented in practice without major adjustment costs.

Table 1. Optimal Steady-state Conditions at Different Discount Rates (δ)

Steady-state	δ =0.01			δ =0.02		
	Median	95% CI		Median	95% CI	
B* (tonnes)	66,692	54,792	78,468	64,190	53,163	75,170
E* (1,000 hooks)	11,661	9,861	13,262	12,292	10,577	13,857
Y* (tonnes)	3,143	2,644	3,590	3,197	2,699	3,641
R* (US$ million)	10	5.7	14.9	9.9	5.5	14.8
Steady-state	δ =0.03			δ =0.04		
	Median	95% CI		Median	95% CI	
B* (tonnes)	61,702	51,302	71,458	59,459	50,299	69,007
E* (1,000 hooks)	12,956	11,169	14,465	13,585	11,907	14,957
Y* (tonnes)	3,236	2,732	3,689	3,266	2,747	3,713
R*(US$ million)	9.5	5.5	15.3	9.2	5	14.1

Management Strategy Evaluations

The performance of the CCAMLR management strategy was first compared to an alternative strategy where effort is reduced immediately to the median optimal steady-state level at a 2% discount rate. Over the 35-year management time horizon, the results showed that while both achieved the CCAMLR objectives, the median sum of the discounted annual profits was actually lower ($229 million) in the immediate effort-reduction scheme than under the CCAMLR management strategy ($245 million). This was driven by the size of the initial effort reduction and the low growth rate of the stock; the economic losses associated with the initial rapid reduction in harvest outweighed the future economic gains from stock growth within the 35-year projection period. The effort reduction scheme generated higher discounted annual profits after 15-16 years but longer than 35 years would be required to compensate for the initial economic losses. In the work of Clark (1976) the existence of an optimal path from the current to the optimal effort level was established and in our case clearly the optimal path is not an immediate reduction in effort to the optimal steady-state level. Therefore, gradual effort reduction schedules would be more practical.

Table 2 shows the results and a summary of performance for all strategies considered. The median estimates of future biomass and CPUE for all six scenarios are given in figure 3. For all effort reduction schemes, the biological performance in terms of one of the CCAMLR stock biomass objectives was significantly better than the CCAMLR management (table 2). More specifically, the probability that after the 35 years of future projection, the probability that the final stock size is greater than 50% of the initial stock size was between 0.96 and 0.997 under the reduced-effort management regime, while it was 0.5 under the CCAMLR regime. The probability of stock biomass dropping below 20% of *K* at any time over the 35 years of the future projection was maintained at zero under all scenarios, thus meeting the CCAMLR objectives.

Table 2. Future Performance of Current and Alternative Management Strategies

Management	Effort Reduction Path	NPV in 35 years ($ millions)	$p(B_{2042}>0.5K)$	$p(B_t<0.2K)$	$CPUE_{2042}$
CCAMLR	NA	245.9	50.0%	0%	0.22
Effort Control	Immediate	229.2	99.7%	0%	0.26
	Linear (t^* = 5.66 yrs.)	245.9	99.7%	0%	0.26
	Linear (t^* =35 yrs.)	282.3	96.5%	0%	0.25
	Non-linear (ν =0.538)	245.9	99.7%	0%	0.25
	Non-linear (ν =0.075)	272.4	98.0%	0%	0.24

With respect to the sum of discounted annual profits over 35 years, except for the immediate reduction scenario, both linear and non-linear effort reduction scenarios yielded higher total discounted profits (up to an additional $35 million) than the CCAMLR management strategy. The optimal path at which steady-state effort (E^*) was reached, reducing from the 2007 level, was year 2042 for the linear effort reduction model—the maximum year permitted (figure 2). For the non-linear effort reduction scheme, the decay rate of 0.075 was considered optimal. The year at which an effort reduction regime would generate the sum of discounted annual profits as high as those obtained under the current management was projected to be 2012-2013 for the linear model, and a much stronger reduction rate of 0.538 under the non-linear model[6] (figure 2). This indicates that as long as the effort reduction takes place gradually at the rates defined here, the economic losses from the initial reduced harvest can be avoided.

[6] It is worth reiterating that the non-linear reduction parameter, ν, is not a percentage decrease in total effort; it is the percentage decrease in the difference between the future and optimal effort levels.

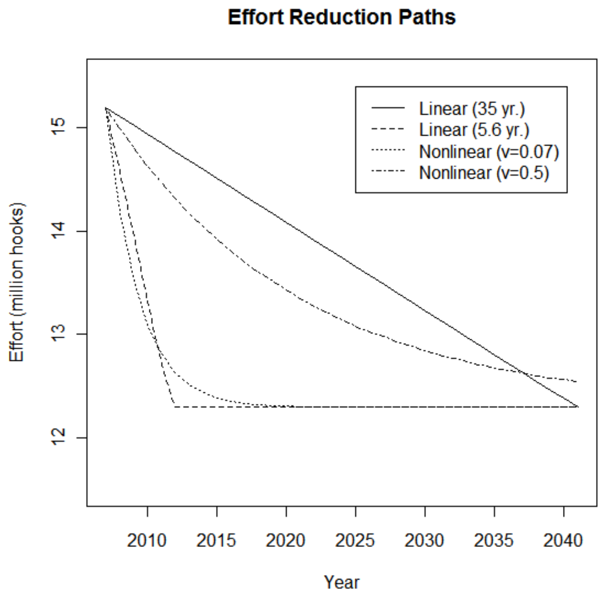


Figure 2: Possible Effort Reduction Paths from 2007 Level to the Steady-state Optimal at 2% Discount Rate (12.3 million hooks)

When comparing the two effort reduction schemes over the 35-year time horizon, the linear scheme performed better in terms of economic performance, but gave a marginally higher risk of depleting the stock below target levels than the non-linear reduction scheme. This is not surprising, as the non-linear scheme by definition affects an initially stronger decrease in effort than the linear scheme. This larger decrease in harvest combined with discounting means that although the stock biomass and catch rates are increasing, it is not fast enough to counteract the reduction in revenue due to lower harvests and discounting. This is also why the immediate effort reduction scheme performs poorer in terms of the sum of discounted annual profits than the current CCAMLR management over the 35-year management period.

In terms of the final year CPUE (tonnes/1,000 hooks) after 35 years, slightly improved CPUE levels (0.24-0.26) were predicted for the effort reduction management regimes compared to the CPUE of 0.22 under CCAMLR management regime (table 2). The CPUE under the CCAMLR regime after 35 years experienced about a 10% reduction from the current (2008) observed CPUE of 0.24-0.25 tonnes/1,000 hooks. This demonstrates that the continuation of the current CCAMLR harvesting strategy would result in the reduction of future CPUE (figure 3), while the effort-reduction regimes described here would at least maintain the current level of CPUE and even higher CPUE is possible at the end of 35 years with more rapid effort reduction.

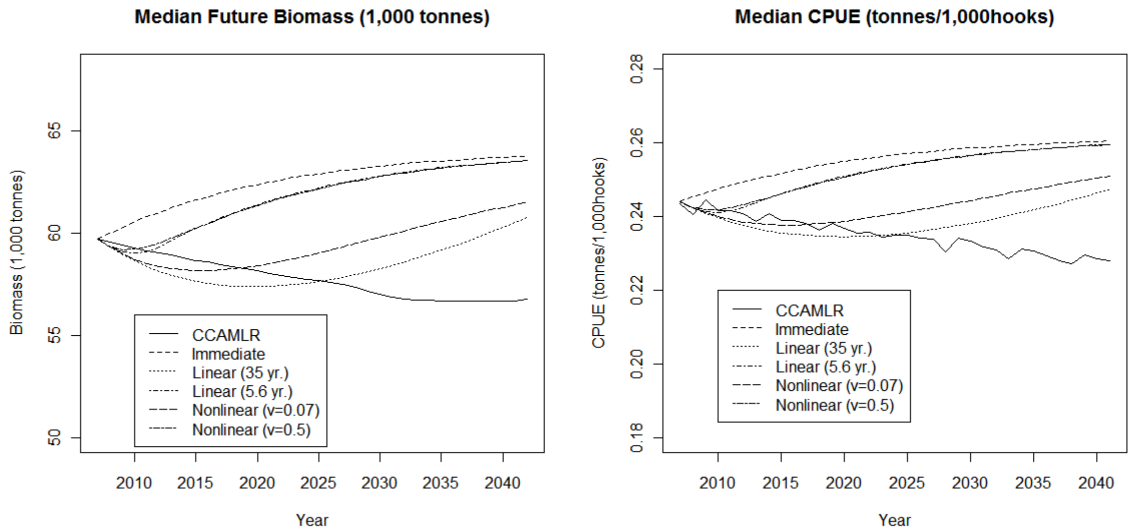


Figure 3. Projection of Median Biomass (left) and CPUE (right) under Different Management Strategies, 2007-2042.

Discussion

In this article, an economically optimal harvesting strategy was identified for the for Patagonian toothfish fishery around the island of South Georgia, and the performance of these candidate management strategies were evaluated in comparison with the current management regime. Using price and cost information from a sub-sample of the operators, a bioeconomic analysis was carried out to estimate the steady-state economically optimal harvesting strategy. The complex age-structured population estimates coming from the stock assessment, along with the key life-history characteristics, were translated into a simpler biomass-dynamic surplus production model while accounting for uncertainty in the population and production function parameters. This simplification enabled us to simulate the performance of the current and alternative management strategies.

Currently, the target stock biomass set by CCAMLR is around 54,000 tonnes, and it is expected that current levels of effort and catch would further decrease the stock biomass. However, the simulation results demonstrate that bringing the stock below the steady-state optimal level would decrease the profitability of the fishery, as higher effort is required to take similar levels of catch. Thus, to maintain the long-term economic sustainability of the fishery would require a gradual reduction in harvest of around 12-20% (400-600 tonnes), and this would imply maintenance of the current biomass level rather than a continued decline in this level to the CCAMLR target of 54,000 tonnes. While most empirical examples of such bioeconomic models in fisheries account for some level of measurement error in the key parameters, few studies have incorporated variance/covariance in the key parameters simultaneously. This analysis consistently accounts for the uncertainty in stock biomass, harvesting, and in the economic parameters themselves. The clear advantage in such an approach is that it permits us not only to assess whether current exploitation levels are significantly higher or lower with respect to the economic optimum, but also allows us to be more confident about the robustness of the conclusions. An MSE of the CCAMLR management regime was previously not possible because of the complexity of the model used for toothfish stock assessment and management by CCAMLR. Translating this complex model into a simple biomass dynamic model allowed for the simulation of the future outcomes of the current and alternative management strategies.

The results presented here provide an economic and conservation-based justification for the gradual reduction of current effort to the steady-state level and also demonstrates the benefits of using economic-based performance criteria. Using the MSE approach allows us to characterize uncertainty across the entire system (biological, economic, assessment, and implementation), more rigorously compare with the current management approach, and explore the practical basis for the implementation of a steady-state paradigm, such as maximum economic yield (MEY) within the constraints of an existing set of management objectives (in this case purely biological) and timelines. This simulation-based approach can be further extended to assess a wider range of impacts from different management scenarios, including the levels of enforcement effort to combat IUU fishing and resultant conservation and social benefits (see Edward et al. 2010).

In order for this approach to be adapted to suit to the Patagonian toothfish fisheries in Australian sub-Antarctic waters, there are several challenges. Australia exploited approximately 2,280 tonnes of Patagonian toothfish resources in Heard Island and McDonald Islands (HIMI) within the Convention area (Division 58.5.2) in the 2007/08 season, and to a lesser extent (less than 300 tonnes) around Macquarie Island (MI) outside of the Convention area. In both areas the primary gear is demersal trawl, although demersal longline has been formally permitted since 2005 in HIMI. Trawl operators target younger fish (less than 60cm), while older fish that inhabit deeper waters are targeted by longline gear. Due to the differences in gear selectivity, it is more appropriate to employ an age-structured bioeconomic operating model to accommodate different fishing mortalities at different age classes. It is also required to obtain separate production function parameters and economic variables for trawlers. Moreover, genetic studies have demonstrated that there appears to be no distinction between the *D. eleginoides* population at HIMI,the Kerguelen (inside the French EEZ, Division 58.5.1) and Crozet Islands (French EEZ, Subarea 58.6), or Marion/Prince Edward Islands (inside South African EEZ, Subarea 58.6 and 58.7) (Appleyard et al., 2004). This makes the modelling approach much more complex than the case in South Georgia, as it needs to take into account meta-population issues with a multi-national, multi-fleet structure. Previous studies have shown that uncertainty in stock structure can result in different estimates of biological target reference points, but little studies have investigated their impacts on bioeconomic modelling. Lastly, obtaining economic data is a major constraint for a straddling stock. Despite these challenges, this MSE framework has potential to incorporate the complex structure of the fish stocks and the fisheries.

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