Empirical estimation of safe aboriginal whaling limits for bowhead whales

GEOF H. GIVENS

Associate Professor of Statistics at the Department of Statistics, Colorado State University, Fort Collins, CO 80523 USA
Contact e-mail: geof@lamar.colostate.edu

ABSTRACT

This paper provides a complete description of a *Strike Limit Algorithm* (*SLA*) considered by the International Whaling Commission (IWC) for the management of hunting of the Bering-Chukchi-Beaufort Seas stock of bowhead whales by native Alaskans to meet their cultural and subsistence needs. The algorithm applies a statistical estimation and optimisation strategy to extract the best features of selected *SLA*s to form a Bayes rule estimator. It focuses on safely satisfying moderate subsistence need, while favouring stock protection by setting strike limits below what would be required to fully satisfy need in the final portion of this century if need were more than doubled.

KEYWORDS: WHALING-ABORIGINAL; MANAGEMENT PROCEDURE; STATISTICS; MODELLING; ARCTIC

INTRODUCTION

After resolving (IWC, 1995) to develop an Aboriginal Subsistence Whaling Management Procedure (AWMP), the IWC has seen the Scientific Committee and its relevant Standing Working Group (SWG) spend seven years developing a complex and expansive simulation framework for testing and evaluating performance of candidate AWMP *Strike Limit Algorithms* (*SLA*s). AWMP *SLA*s calculate hunting limits (as strike limits) based on available survey abundance data and other information. The framework for testing them is described in IWC (2003b).

This paper describes an *SLA* for management of the Bering-Chukchi-Beaufort Seas stock of bowhead whales, which is increasing about 3.2% (1.4%, 5.1%) annually while being subject to an annual aboriginal harvest of around 50 whales from a stock numbering about 8,200 (7,200, 9,400; Raftery and Zeh, 1998). The IWC recognises 'aboriginal subsistence and cultural need' as the justification for this limited hunt (Donovan, 1982). Strike limits are intended to meet pre-determined 'need' to the extent possible without endangering the stock.

This *SLA* was developed using a statistical merging and optimising strategy to extract the best features of selected *SLA*s to form a Bayes rule estimator (Givens, 1997; 1999; 2000). It focuses on safely satisfying moderate need, while favouring stock protection by setting strike limits below what would be required to fully satisfy need in the final portion of this century in extreme scenarios where need might triple from current levels. This trade-off is consistent with the priorities of bowhead hunters, as expressed by the Alaskan Eskimo Whaling Commission (M. Ahmaogak, pers. comm.).

At its 2002 meeting, the IWC adopted and endorsed a 'Bowhead *SLA*' that includes the *SLA* presented here when calculating strike limits (IWC, 2003a). Complete adoption of a bowhead management procedure awaits IWC finalisation of: guidelines for data and surveys, operational matters such as the carryover of unused strikes and the phase-out of strike limits after a prolonged absence of new survey data, and other procedural and political matters.

THE CORE ESTIMATOR

The statistical merging and optimising strategy employed here can be applied to several individual procedures, and/or to several estimators from a single procedure. The *SLA* described in this paper relies only on the latter approach: combining several estimates from a single core assessment procedure.

The core procedure was developed by other *SLA* experts (Punt and Butterworth, 1997; Johnston and Butterworth, 2000). Of the estimators in various bowhead *SLA*s proposed since 1994, this one was chosen because it is simplest and fastest. It is, in turn, based on the estimator underlying the catch limit algorithm of the IWC's Revised Management Procedure for commercial whaling of baleen whales (IWC, 1994). A bias parameter has been added for greater flexibility.

The population model underlying this procedure is:

$$P_{t+1} = P_t + r\, P_t(1-(P_t/K)^{2.39}) - C_t \qquad (1)$$

where P_t is the abundance and C_t is the catch in year t, and r and K are parameters. For a given time series of survey abundance estimates, $\hat{S}_t$, with corresponding coefficients of variation, Ψ_t, and biases, b_t, the model is fit by maximising the penalised log likelihood function

$$L(r,K) = \sum_{t\in T} (\log\, \hat{S}_t - \log\, b_t P_t)^2 / 2\, \Psi_t^{\,2} + (r - r^*)/2\sigma_r^2 \qquad (2)$$

where T is the set of years in which surveys have been taken and r^* and σ_r are fixed parameters whose values may be set to change the performance of the estimator.

The authors' work diverges at this point from our needs. However, this model is used to produce the following estimates listed below.

- $\hat{K}_t$: The 'carrying capacity' parameter estimated in year t when $\sigma_r = 0.005$, $r^* = 0.01$, and a survey bias factor of b_t is assumed for $t \geq 0$.
- $\hat{Y}_t$: The estimated net yield in year t (namely $\hat{P}_t - \hat{P}_{t-1}$), when $\sigma_r = 0.005$, $r^* = 0.01$, and a survey bias factor of b_t is assumed for $t \geq 0$. For this calculation, the actual catch history applies except for the most recent year, for which a catch of $C_{t-1} = 120$ whales is used. Therefore, $\hat{Y} + 120$ is analogous to the concept of 'replacement yield'.
- $\hat{P}_t$: The current stock size estimate when $\sigma_r = 0.01$, $r^* = 0.02$, and a survey bias factor of b_t is assumed for $t \geq 0$. Note that this is the model estimate based on all available data, not the survey estimate.

The value b_t is a tuning parameter whose value can be set to adjust the performance of the *SLA* described below.

THE *SLA*

Let N_t denote the total block need for a block of years starting in year t, and let $L \geq 5$ be the length of the block. Denote the true stock abundance as A_t, and recall that the survey abundance estimate of A_t is denoted $\hat{S}_t$.

The raw strike limit is then calculated by defining

$$q_t = a_0 + a_1 \hat{K}_t + (a_2 + a_3\varepsilon_t)\hat{Y}_t + a_4 \hat{P}_t + a_5 \hat{Y}_t / \hat{K}_t \qquad (3)$$

and then setting $Q_t^{raw} = Lq_t$, subject to the constraints that this value must be between 0 and N_t. For the baseline tuning of this *SLA*, the constants in (3) are roughly $a_0 = 275$, $a_1 = -0.0125$, $a_2 = -3.05$, $a_3 = 1.4$, $a_4 = 0.0114$, and $a_5 = 35{,}200$; as t changes from 0 to 50, ε_t changes linearly from 0 to 1, and is 1 thereafter. Exact values for the coefficients are given in the code, which is available from the IWC Secretariat. The bias parameter is set to $b_t = 1.4$.

Both the choice of predictor variables and their coefficients in (3) were optimised to provide a Bayes rule solution to a carefully crafted multi-criterion decision problem. The framework described in earlier papers (Givens, 1997; 1999; 2000) was applied with the following specifications. Four simulation trials were used to span best-case through worst-case possibilities (in IWC parlance, these trials were 'BE1', 'BE9', 'BE10' and 'BE12', with final need set to 201 in each case). The ideal quotas were taken as given in (IWC, 2002b, p.437). All deviations from ideal were expressed relative to the ideal quotas. Sums of squares of relative deviations were penalised with the following weights: for over-allotments, weight of 1.5 for 'BE1', 'BE9' and 'BE10' and weight of 3.0 for 'BE12'; for under-allotments, weight of 1.0 for each trial.

A subsequent subsection provides interpretation of the function in (3). One should not look merely at the signs of the coefficients because the predictors co-vary and the model includes an interaction. Generally, strike limits increase as estimated stock size or yield increases, and decrease as estimated carrying capacity increases, for a fixed current abundance.

To this raw limit, the following adjustments are made if necessary in the order listed.

(1) Variability dampening

The strike limit is not allowed to be less than 90% of the previous strike limit, nor to exceed the previous strike limit by 15 whales per year or 15%, whichever is greater. If Q_t^{raw} violates one of these bounds, it is set equal to the bounding value.

(2) Snap-to-need feature

If Q_t^{raw} would satisfy at least 95% of need, then the strike limit is raised to 100% of need.

(3) Protection levels

These supersede all other calculations. There is a 30% quota reduction phased in if the stock is believed to be below A_{mild}. This quota reduction is continuous with respect to time and surveyed abundance, as described in the next subsection. There is also an absolute protection level: if $\hat{P}_t < 2{,}000$ at any time then the quota is set to zero.

The resulting block strike limit is Q_t. This *SLA* is considerably simpler and smoother than previous versions (e.g. Givens, 2001).

Protection level

The abundance triggering a protective quota reduction is phased in gradually. A_{mild} changes from 4,400 to 6,700, as t changes from 0 to 35, and is 6,700 thereafter. The SWG has instructed that the absolute protection level should be set at 2,000.

The 30% protection level is phased in if a resistant estimate of stock size is too small. The estimator is $\bar{\bar{P}}_t$, a double-rolling (trailing) mean estimated stock size that is intentionally insensitive to variation in survey abundance estimates, i.e. resistant. Although the idea is straightforward, the equations defining $\bar{\bar{P}}_t$ require careful indexing because the timing of surveys and calls to the *SLA* can vary. Thus the mathematical specification is given in Table 1.

The SWG (IWC, 2002a) suggested that

> Givens should examine the quantity that triggers the... protection level effect to determine how much variation in it is induced by a 2 standard error variation in the current abundance estimate. Then, he should interpolate the desired protection level (e.g. reduction from 100% to 70% of the nominal strike limit) over this range of the estimator.

Table 1

These equations define $\bar{\bar{P}}_t$ explicitly for times corresponding to the first several calls to the *SLA*, and by induction thereafter.

Time	$\bar{P}$	$\bar{\bar{P}}$
$t_0 = 1^{st}\ t \geq 0$	$\bar{P}_{t_0} = \hat{P}_{t_0}$	$\bar{\bar{P}}_{t_0} = \hat{P}_{t_0}$
$t_1 = 1^{st}\ t \geq 5$	$\bar{P}_{t_1} = (\hat{P}_{t_0} + \hat{P}_{t_1})/2$	$\bar{\bar{P}}_{t_1} = \hat{P}_{t_1}$
$t_2 = 1^{st}\ t \geq 10$	$\bar{P}_{t_2} = (\hat{P}_{t_0} + \hat{P}_{t_1} + \hat{P}_{t_2})/3$	$\bar{\bar{P}}_{t_2} = \hat{P}_{t_2}$
$t_3 = 1^{st}\ t \geq 15$	$\bar{P}_{t_3} = (\hat{P}_{t_0} + \hat{P}_{t_1} + \hat{P}_{t_2} + \hat{P}_{t_3})/4$	$\bar{\bar{P}}_{t_3} = \hat{P}_{t_3}$
$t_4 = 1^{st}\ t \geq 20$	$\bar{P}_{t_4} = (\hat{P}_{t_0} + \hat{P}_{t_1} + \hat{P}_{t_2} + \hat{P}_{t_3} + \hat{P}_{t_4})/5$	$\bar{\bar{P}}_{t_4} = (\hat{P}_{t_0} + \hat{P}_{t_1} + \hat{P}_{t_2} + \hat{P}_{t_3} + \bar{P}_{t_4})/5$
$t_5 = 2^{nd}\ t \geq 20$	$\bar{P}_{t_5} = (\hat{P}_{t_1} + \hat{P}_{t_2} + \hat{P}_{t_3} + \bar{P}_{t_4} + \hat{P}_{t_5})/5$	$\bar{\bar{P}}_{t_5} = (\hat{P}_{t_1} + \hat{P}_{t_2} + \hat{P}_{t_3} + \bar{P}_{t_4} + \bar{P}_{t_5})/5$
$t_6 = 3^{rd}\ t \geq 20$	$\bar{P}_{t_6} = (\hat{P}_{t_2} + \hat{P}_{t_3} + \bar{P}_{t_4} + \bar{P}_{t_5} + \hat{P}_{t_6})/5$	$\bar{\bar{P}}_{t_6} = (\hat{P}_{t_2} + \hat{P}_{t_3} + \bar{P}_{t_4} + \bar{P}_{t_5} + \bar{P}_{t_6})/5$
$t_7 = 4^{th}\ t \geq 20$	$\bar{P}_{t_7} = (\hat{P}_{t_3} + \bar{P}_{t_4} + \bar{P}_{t_5} + \bar{P}_{t_6} + \hat{P}_{t_7})/5$	$\bar{\bar{P}}_{t_7} = (\hat{P}_{t_3} + \bar{P}_{t_4} + \bar{P}_{t_5} + \bar{P}_{t_6} + \bar{P}_{t_7})/5$
$t_8 = 5^{th}\ t \geq 20$	$\bar{P}_{t_8} = (\bar{P}_{t_4} + \bar{P}_{t_5} + \bar{P}_{t_6} + \bar{P}_{t_7} + \hat{P}_{t_8})/5$	$\bar{\bar{P}}_{t_8} = (\bar{P}_{t_4} + \bar{P}_{t_5} + \bar{P}_{t_6} + \bar{P}_{t_7} + \bar{P}_{t_8})/5$
$t_9 = 6^{th}\ t \geq 20$	$\bar{P}_{t_9} = (\bar{P}_{t_5} + \bar{P}_{t_6} + \bar{P}_{t_7} + \bar{P}_{t_8} + \hat{P}_{t_9})/5$	$\bar{\bar{P}}_{t_9} = (\bar{P}_{t_5} + \bar{P}_{t_6} + \bar{P}_{t_7} + \bar{P}_{t_8} + \bar{P}_{t_9})/5$
⋮	⋮	⋮

Previous work has shown that the range referred to above is roughly 100 whales (Givens, 2002). The range is so small because $\overline{\overline{P}}_t$ is intentionally insensitive to any single observed data point.

To phase in the protection over this range, let f_{mild} denote the proportion of a nominal 30% reduction to be applied. Letting $f_{mild}(\overline{\overline{P}}_t) = \min(1, \max(0, (A_{mild}+50 - \overline{\overline{P}}_t)/100))$ ensures that f_{mild} ranges between 0 and 1 as $\overline{\overline{P}}_t$ decreases from 50 whales above to 50 whales below A_{mild}. Then the protection level reduction is smoothly phased in as $Q_t = (1 - 0.3\, f_{mild}(\overline{\overline{P}}_t))Q_t^{raw}$.

Interpretation

Figs 1[1], 2 and 3 show the relationship between the annual quotas provided by this *SLA* and the predictor variables used in (3). These figures were generated by applying (3) to the sets of $(\hat{K}_t, \hat{Y}_t, \hat{P}_t$ generated over all times and replications of a simulation trial that samples many likely possibilities from a wide range of plausible scenarios ('BE21' in IWC parlance). The three predictors are strongly dependent: only a certain region of predictor combinations can occur. Inside this region, the grey level corresponds to the value of q_t given by (3). Generally, strike limits increase as estimated stock size or yield increases, and decrease as estimated carrying capacity increases, for a fixed current abundance. These figures show that equation (3) corresponds to a smooth, biologically sensible catch control law.

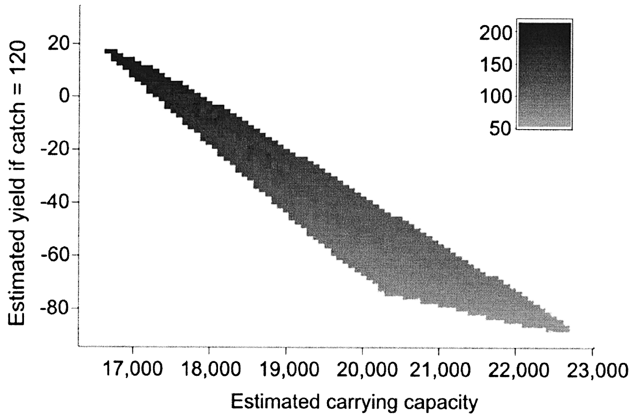

Fig. 1. The shading indicates the value of q_t for given levels of two predictors over a trial encompassing many plausible scenarios. Colour versions of Figs 1-5 are available at *http://www.iwcoffice.org/Publications/additions.htm.*

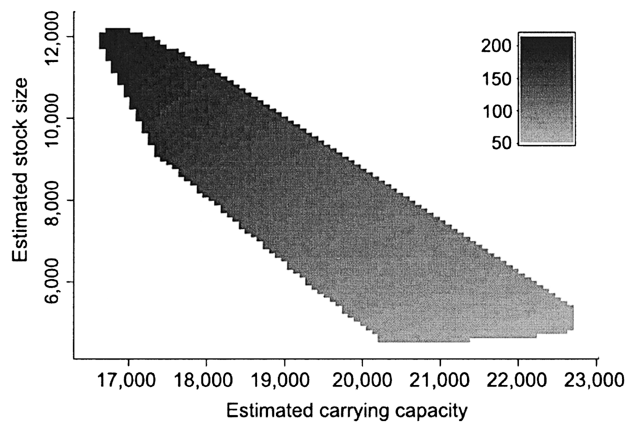

Fig. 2. The shading indicates the value of q_t for given levels of two predictors over a trial encompassing many plausible scenarios.

[1] Colour versions of Figs 1-5 are available at *http://www.iwcoffice.org/Publications/additions.htm.*

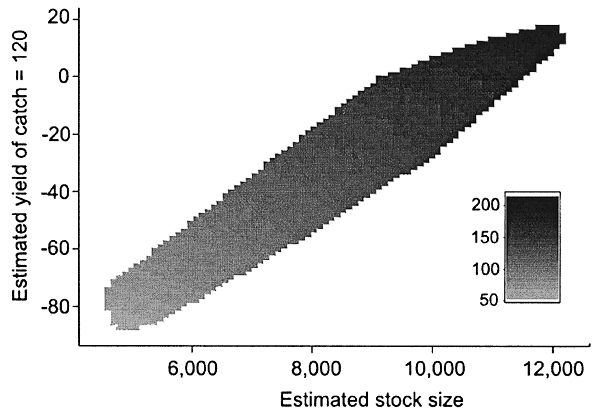

Fig. 3. The shading indicates the value of q_t for given levels of two predictors over a trial encompassing many plausible scenarios.

The form of (3) may seem unfamiliar to some readers. However, for appropriate constants b_i, the equation can be roughly translated as $q \approx b_0 + b_1 K + b_2\, RY + b_3 P + b_4\, RY/MSY$, where K is carrying capacity, RY is replacement yield, P is current stock size and MSY is maximum sustainable yield. When the stock is near $MSYL$ and for a different set of b_i, the translation is roughly $q \approx b_0 + b_1 K + b_2\, RY + b_3 P + b_4\, MSYR$. If information about appropriate catch is contained somewhere beyond information about K, RY, P and $MSYR$, it is well hidden indeed.

TUNING

There are several trade-offs that prevent perfect fulfillment of all IWC management objectives. An *SLA* interprets available data to assess the risk to the stock resulting from potential levels of aboriginal hunting. The job of an *SLA* is to limit quotas to safe levels accordingly. However, the true risk to the stock may differ from the *SLA* assessment. Some unintended management consequences are therefore inevitable. Tuning the *SLA* allows one to prioritise various aspects of *SLA* performance to reduce the frequency and impact of such mistakes.

Subsequent to fitting the model in (3), a balanced factorial tuning experiment was run, adjusting each parameter up and down by an amount that changed strike limits by about 10 whales. Small adjustments to the fitted parameters were then empirically estimated to achieve desired performance tunings.

A fundamental choice faced by any *SLA* is how to treat misleading data. In the set of trials (and their variants) used by the IWC Scientific Committee for evaluation of *SLA*s, the *SLA* presented here has a tendency to limit the quota if the data suggest that the stock is in danger, regardless of whether this appearance is correct. The sacrifice is that need may not be fully met if misleading data indicate stock risk when in fact the stock is safe. This chosen trade-off reflects IWC objectives and priorities. The IWC has explicitly assigned stock protection the highest priority and need satisfaction the lowest priority. Therefore, when the data indicate danger to the stock, the *SLA* should trim the quota.

Another basic trade-off faced by any *SLA* is the value assigned to incremental need satisfaction. At one extreme, constant value could be assigned. On a percentage scale, this choice would assert that improving from 95% to 100% need satisfaction is as beneficial as improving from 50% to 55%. If this was true, then the same cost (in terms of risk to the stock) should be tolerated to achieve either increase. On a unit scale, one would tolerate the same amount of increased risk to gain, say, a 10 whale increase in the quota whether the quota would otherwise be 20 or 200.

The *SLA* presented here does not follow this philosophy. Instead, as need approaches full satisfaction, the *SLA* focuses increasingly on risk avoidance. The reason for this choice is that the last few needed whales typically come at a disproportionately high risk cost in most likely scenarios.

Presented here are a 'baseline' tuning of this *SLA* and an alternative 'tempered' tuning that more severely underweights incremental need satisfaction at high levels. By resisting the temptation to enable the very highest levels of need satisfaction, the tempered tuning enables very good median levels of need satisfaction while achieving far greater risk avoidance than would be possible in an untempered tuning that met these median need satisfaction levels and/or sought to satisfy the final few percentage points of need in most cases.

For both the baseline and tempered tunings, there are three sub-tunings presented: risk-averse[2], neutral, and need-prioritised. Of these six tunings, the neutral baseline and the risk-averse tempered tunings perform best. The six tunings are given in Table 2.

Table 2

Parameters for the six tunings of the *SLA*, expressed relative to the parameters for the neutral baseline. Values shown are multiplicative factors except for a_0, which are additive changes.

	Baseline			Tempered		
	Risk-averse	Neutral	Need-prioritised	Risk-averse	Neutral	Need-prioritised
b_t	1	1	1	0.9571	0.9821	1
a_0	$14E_t$ -10	0	20	-30	-10	5
a_1	1.0695	1	1.230	1.1497	1.2299	1.2299
a_2	0.93	1	1.07	1.065	1.14	1.07
a_3	1	1	0.7143	0.65	0.7143	0.55
a_4	0.8889	1	1	1.111	1.1111	1
a_5	1	1	1	0.8873	0.7542	0.8873

PERFORMANCE AND DISCUSSION

Fig. 4 illustrates the performance of the three variants of the baseline tuning. The horizontal axis in this figure is the ratio of stock size after 100 years of simulated management to stock size before the simulation, under a scenario that pessimistically assumes low whale productivity and biased survey data ('BE12A D10' in IWC parlance). Clearly values exceeding 1.0 are strongly preferred. The vertical axis is the average rate of need satisfaction in a baseline simulation scenario ('BE01 N9'); larger rates are preferred. For each tuning, boxes are drawn connecting the 5th and 95th percentile performance of each *SLA* tuning; interior shaded boxes connect the 25th and 75th percentile performance; and a large dot indicates median performance. The three tunings are coded by line type. Fig. 5 shows the same graph for the three variants of the tempered tuning.

Figs 4 and 5 clearly illustrate the basic catch-risk trade-off inherent in management of any exploited population. Note, however, that adjustments to this trade-off are not as simple

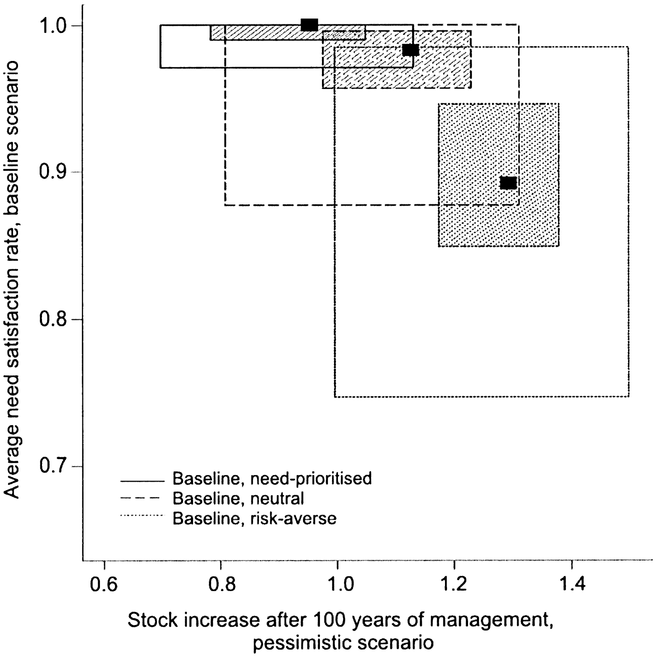

Fig. 4. Performance summary for the three variants of the baseline tuning; see text for interpretation.

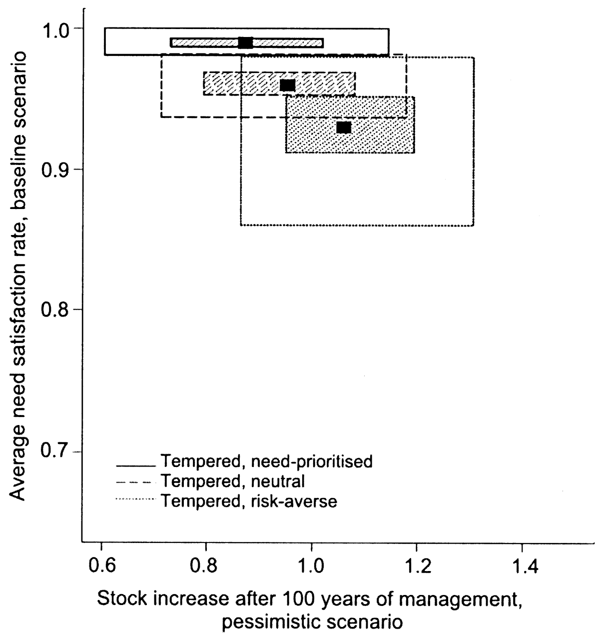

Fig. 5. Performance summary for the three variants of the tempered tuning; see text for interpretation.

as 'sliding' the performance box northwest or southeast: as the box slides, its shape changes. This is particularly true for the baseline tuning; the boxes are more similar for the tempered tuning. The reason for this is that the baseline tuning seeks to retain the possibility of high need satisfaction even when tuned overall to avoid risk. This yields more variable risk performance than for the tempered tuning, which does not aspire to perfect need satisfaction when tuned overall to avoid risk.

The two non-neutral tunings of the baseline *SLA* are not likely to be preferred for management; they represent more extreme trade-offs. However, the *SLA* is easily tuned modestly in either direction by interpolation. Fig. 6 shows that interpolative tuning is effective. This graph shows median and fifth percentile performance for all three variants

[2] The risk-averse tuning of the baseline *SLA* has one additional modification: quotas are bounded below by a quantity that changes linearly from 0 to 0.8% as increases from 2,000 to 5,000. This prevents rare, excessively low quotas while retaining the feature that quotas are reduced to zero as the estimated stock status becomes increasingly grim.

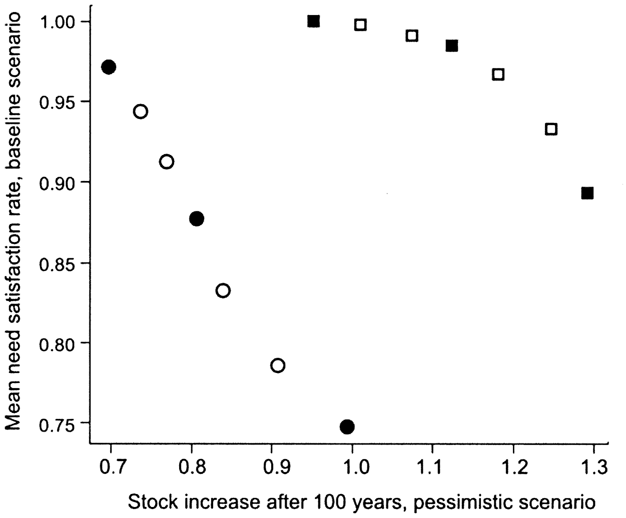

Fig. 6. Median (squares) and fifth percentile (circles) performance for the baseline tuning. Solid symbols correspond to the three baseline variants presented in the text. Hollow symbols correspond to performance of tunings where parameters have been interpolated between these variants, in fractions of one third.

of the baseline tuning (solid symbols). Hollow symbols correspond to performance of tunings where parameters have been interpolated between these variants, in fractions of one third. There is modest nonlinearity shown, but interpolation between these points will clearly allow accurate adjustment of the *SLA* to any desired intermediate performance. For example, to produce a slightly more conservative tuning than neutral baseline, choose tuning parameters that are a desired proportion of the way between the values used for the neutral and risk-averse tunings given in Table 2. One of the strengths of the *SLA* presented here is the flexibility with which it can be tuned.

The approach described here tailors the optimisation problem to the specific application. Therefore, the *SLA* given here is unlikely to be appropriate for management of other stocks or species without refitting and retuning. However, the optimisation approach itself is adaptable to a wide range of applications.

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