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**An evaluation of the management utility of fishery performance  
indicators commonly used in New Zealand stock assessments**

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## EXECUTIVE SUMMARY

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This report describes a review of fishery performance indicators (FPIs) used in New Zealand stock assessments and a simulation study to test the effectiveness of three management strategies. Two of the strategies were based on estimation of virgin or "unfished biomass" ( $B_0$ ), while the third was based on an average biomass ( $B_{AV}$ ) over a specified reference period (where the average biomass was greater than the current biomass).

The review of FPIs (which actually normally relate to "stock status" rather than "fishery performance") found consistent approaches within blocks of species/stocks, but a lack of consistency across all species. No single FPI was estimated for all species/stocks.

The effect of "regime shifts" (when virgin biomass is not equal to unfished biomass) on FPIs was considered from a theoretical point of view. It was found that  $B_0$  based FPIs have some good compensatory properties under regime shifts which are not shared by  $B_{AV}$  based FPIs.

In the case study, hake and ling stocks on the Chatham Rise were simulated and managed under three alternative strategies from 2002 to 2010. The two  $B_0$  based strategies performed adequately at all biomass levels investigated (from "low" to "high" true  $B_0$ ), but the  $B_{AV}$  based strategy performed very badly at high biomass levels. This was an obvious consequence of using the  $B_{AV}$  strategy to rebuild biomass levels irrespective of the starting point. At high biomass levels, the strategy was essentially "rebuilding" from a high level to an even higher level. In practice, when used sensibly, a  $B_{AV}$  based strategy can no doubt be as effective as  $B_0$  based strategies.

The average accuracy of the maximum likelihood estimators of  $B_0$ ,  $B_{2002}$ ,  $B_{cur}/B_0$ , and  $B_{cur}/B_{AV}$  were examined for the case study. Estimation of  $B_0$  and related ratios appears to be somewhat problematic. The accuracy levels were far better for  $B_{cur}/B_{AV}$  than  $B_{cur}/B_0$ . Also, there was little or no improvement in accuracy levels for  $B_0$  with the addition of more data, but there was noticeable improvement when estimating  $B_{2002}$ . However, the level of accuracy was adequate in terms of the management strategies investigated as  $B_0$  based strategies performed well.

To provide a common reference point across all species and stocks and because of its fundamental importance in terms of "biological loss" it is recommended that  $B_{cur}/B_0$  be estimated for all stock assessments. An interval estimate should be provided in addition to a point estimate (to properly convey the level of precision associated with the point estimate).

## 1. INTRODUCTION

In New Zealand stock assessments, many different fishery performance indicators (FPIs) are estimated. There has been little work in New Zealand looking at the robustness of the FPIs to common model assumptions, or in considering their relevance to management strategies. In this report a review of FPIs used in New Zealand assessments is presented with a detailed case study which examines the effectiveness of different subsets of FPIs with regard to a particular management strategy. There is also some consideration of how different FPIs are affected by a regime shift.

The chosen management strategy is the author's approximation of the decision process underlying the setting of TACs for those stocks where there are adequate data to conduct a full stock assessment, including the estimation of FPIs (but for which no specified decision rule exists). The subsets of FPIs examined were chosen to contrast the performance of virgin biomass ( $B_0$ ) based reference points and reference points based on an average biomass during a specified biomass period ( $B_{AV}$ ). The latter approach has become the standard for paua and rock lobster stocks in recent years and its supporters suggest that it is superior to  $B_0$  based approaches.

## 2. METHODS

Most of the methods description is concerned with the management strategy evaluation in the case study (given that it involves so many components). However, there are also a few matters to do with the review of "fishery performance indicators" used in New Zealand assessments, and the definition of an FPI.

### 2.1 Definition of "Fishery Performance Indicator"

The definition of FPIs used by Bull & Cordue (2000) was adopted:

"A fishery performance indicator (FPI) is a quantity estimated during a stock assessment which is directly informative about the current and/or future status of the stock".

Note, *estimates* of FPIs may or may not be informative about the stock; an FPI is a "true" but unknown quantity. During a stock assessment, estimates of FPIs are produced and they are used as part of a management strategy (through a decision rule – which is usually not explicit) to set a TAC and TACC (or impose some other limits on the fishery). This definition is consistent with the normal usage of the term in a New Zealand fisheries setting, but it differs from what a lay-person would take as its meaning. It does not refer to the "performance of the fishery" as such, but to the "status of the stock", so while (good or bad) "fishery performance" may be related to an FPI, an FPI does not measure the "performance of the fishery".

The usage adopted is similar to that in an Australian fisheries setting in terms of "performance indicators" as specified as part of a fisheries plan, but the usage here is much more restrictive. Worthington et al. (2001) gave examples of performance indicators in relation to objectives of a management plan. In their setting, a performance indicator is any event which can be determined to have taken place or not, and its occurrence is directly relevant to a specified objective. Hence, their performance indicators need not relate to stock status and need not be quantifiable (the only associated measure relates to occurrence or not).

## 2.2 Review of FPIs and management strategies for N.Z. stock assessments

The 2002 Fishery Assessment Plenary and Mid-Year Plenary reports (Annala et al. 2002, Sullivan & O'Brien 2002) were used to group Fishstocks on the basis of like management strategies. In many cases the management strategy was not explicitly stated, but was inferred. Fishstocks were partitioned into five groups corresponding to the management strategies described below.

|                          |   |
|--------------------------|---|
| Status quo policy:       | Given the absence of any useful information on stock status, the catch limits or TACC and TAC are constant.   |
| AMP:                     | The TACC is at a higher level than it would be under a status quo policy because the stock is managed as part of the Adaptive Management Programme (AMP).   |
| Reactive policy:         | The TAC and TACC are changed only in response to assessments which strongly indicate that a change is needed (e.g., an estimated high risk of stock collapse, or the stock is estimated to be at a high level and an increased TACC would be beneficial to the Industry). |
| Active management:       | A rule is in place for changing TACCs on the basis of stock assessment results.   |
| International agreement: | Stocks are managed by joint agreement of New Zealand and other countries.   |

The reactive policy is not an explicitly stated Mfish policy, but it encapsulates the author's experience of how stock assessment results are used in setting quotas. Simply put, if an assessment strongly indicates that a stock may be reduced to a level well below  $B_{MSY}$ , then a TAC reduction is likely. However, if the stock appears to be at or above  $B_{MSY}$ , there will be an increase in TAC only if the fishing industry indicates a real desire for such an increase to occur (e.g., for several years in the 1990s hoki stock assessments indicated that a much larger TAC could be sustained, but increases did not occur because industry had concerns about the economic impact of extra hoki in the market place).

## 2.3 Choice of Fishstock

After the review of FPIs used in New Zealand stock assessments, two Chatham Rise Fishstocks were chosen for the simulation study. Discussions with the Ministry did not reveal any great preference for the stocks to be used. Requirements of the study were that the stocks had adequate data to allow the estimation of the typically used FPIs. The choice was made on the basis of the author's familiarity with middle depths stocks.

## 2.4 Case study

The objective of the case study was to evaluate the performance of different FPIs when used to manage simulated Fishstocks under the reactive policy (the most commonly used policy). The background to this project involves some debate as to the effectiveness of  $B_0$  based FPIs as opposed to a  $B_{AP}$  approach. The focus is therefore on the contrast between subsets of FPIs which do and do not include  $B_0$  based FPIs.

The case study is in essence a Management Strategy Evaluation (MSE), but it does not involve an agreement with stakeholders as to the management objectives for the Fishstocks concerned. There is necessarily a formal specification of an objective function, but in the absence of an agreement on the appropriate weighting of the different components of the function, a range of weights is investigated.

Three species are used in the simulation: hoki, hake, and ling. However, assessments are simulated only for hake and ling. Hoki was included in the simulations as there were plans to use hoki TACs to “drive” the catches for hake and ling in the bycatch trawl fishery. Such scenarios are not presented, but the description of the hoki components of the operating model are included for completeness.

An MSE is relatively straightforward in concept, but is very complicated in practice because it involves so many different components, each of which needs detailed specification. The technical details of the operating and estimation models are contained in appendices. The following text aims to provide an easily accessible summary of the overall approach and of each of the components.

### 2.4.1 Operating model

The operating model (structure) is used to represent “reality”. In this case, it models three species (hoki, hake, and ling) in four areas (Chatham Rise (CR), Sub-Antarctic (SA), west coast South Island (WCSI), and Cook Strait (CKST)). Fish are further characterised by sex and age and for hoki there are the usual eastern and western stocks (Annala et al. 2002). The main fisheries are included: a mixed trawl fishery, a target line fishery for ling, and a target trawl fishery for hake, all on the CR; and target hoki fisheries in the SA and in the two spawning grounds (WCSI and CKST).

The annual cycle of the model includes five fishing periods which allows time steps for migrations undertaken by hoki: western hoki migrate from CR to SA, eastern hoki migrate from CR to CKST to spawn, western hoki migrate from SA to WCSI to spawn, adult hoki migrate from their spawning ground to their home ground, newly spawned hoki migrate from the spawning ground to CR (the shared nursery ground). The hake and ling stocks reside and spawn on the CR.

Fishing selection patterns and maturity parameters depend on age and sex and are based on assessment results by Annala et al. (2002) and Francis et al. (2003), as are the various biological parameters (e.g., natural mortality and growth). Fishing mortality is modelled using the Baranov catch equation and the catch histories used in recent assessments (Annala et al. 2003). Further details of the operating model are contained in Appendix A.

### 2.4.2 Model runs

Model runs covered the period 1940 to 2010. An equilibrium age structure, resulting from average recruitment and no fishing mortality, was assumed in 1940 (i.e.,  $B_0 = B_{1940}$ ) and stochastic recruitment was used from 1941 onwards. Since the catch histories do not start until 1971 and the maximum age of fish in the model is 30 years, this allows the initial biomass ( $B_{init} = B_{1970}$ ) to differ substantially from the virgin biomass ( $B_0$ ).

The catch histories used for hake and ling were for biological stocks on the CR for 1971 to 2002. In order to simulate management strategies it was necessary to specify a “TAC” for the simulated hake and ling stocks. This was done by comparing the biological catch histories (CR) with the recorded catches in the associated Fishstocks (hake: HAK 4, HAK 1; ling: LIN 3, LIN 4). For hake, the CR catch includes all of the HAK 4 catch and a proportion of the HAK 1 catch (Dunn 2003). The average proportion since 1992 was used (TAC was much lower before then) which gave: CR catch = HAK 4 catch + 0.18 HAK 1 catch. For ling, the CR catch includes all of the LIN 4 catch and a proportion of the LIN 3 catch. The average proportion since 1990 was 0.97 which was near enough to 1, so that CR catch = LIN 3 catch + LIN 4 catch, was adopted. Applying these equations to TACs (rather than catches) gave the 2003 TACs for the CR “Fishstocks” of 4154 t (HAK) and 6260 t (LIN). The TACs were potentially changed according to the

results of assessments which were conducted in 2002, 2004, 2006, 2008 (for hake) and 2003, 2005, 2007, 2009 (for ling).

Runs were done with five different levels of average recruitment for hake and ling (and a single level for hoki). The corresponding values of  $B_0$  ('000 t) for hake and ling were:

|     | LOW | MED1 | MED2 | MED3 | HIGH |
|-----|-----|------|------|------|------|
| HAK | 30  | 40   | 55   | 80   | 120  |
| LIN | 85  | 95   | 115  | 140  | 200  |

For each of the biomass levels above (LOW, MED1, MED2, MED3, HIGH) four different subsets of FPIs were used in simulated management strategies using the "reactive policy" (including an empty subset, corresponding to no assessments and leaving the TACs unchanged). The three (non-empty) management strategies are described below after definition of the FPI loss functions which were used in the management strategies.

For each of the five biomass levels and four management strategies, 120 runs were done with stochastic recruitment (from 1940 to 2010). Each run (with a non-empty subset of FPIs) had 8 assessments (4 each for hake and ling) during which 3 future TAC levels were evaluated using 5 year projections (with 100 runs in each projection).

### 2.4.3 FPI loss functions

Each FPI was assigned a loss function (of type ASYM or SQ – see Table 3 and Appendix C). A weight of  $a = 1$  was assigned to each loss function. For the ASYM functions,  $c = b/3$  was used throughout (this gives equal losses at  $x = b/2$  and  $x = 3b$ ).

### 2.4.4 Reactive policy

The reactive policy was implemented by evaluating each of three possible future TAC levels at each assessment. The candidates were the current TAC, a 25% increase, or a 25% decrease. For a given subset of FPIs, the total loss associated with a candidate TAC was calculated as the sum of the losses for each FPI. Each FPI was given equal weight. The TAC was changed if either the increased or decreased TAC was associated with a lower loss and the total loss at the current TAC was greater than a threshold value (set equal to 0.05 in each case).

The names of the three management strategies and the associated subsets of FPIs are:

ASSESS:  $B_{cur} / B_0, P(B_{cur+5} > 0.2B_0)$   
 MAY target:  $B_{cur} / B_{MAY}, E(B_{cur+5}) / B_{MAY}, P(B_{cur+5} > 0.2B_{MAY})$   
 BAV target:  $B_{cur} / B_{AV}, E(B_{cur+5}) / B_{AV}, P(B_{cur+5} > B_{AV})$

where "E" denotes expected value, and "P" denotes probability. For the BAV target strategy the reference biomass period was 1995–1997 (i.e.,  $B_{AV}$  is the average spawning biomass over those three years).

## 2.4.5 Estimation models

Each assessment was done using a single-stock, two-sex, age-structured model with maximum likelihood estimation (together with some penalty functions). The estimation models were basically single-stock, single-area versions of the operating model. Parameters not estimated in the estimation models were fixed at the true values in the operating model. For both species estimated parameters included: average recruitment, year class strengths, trawl survey and trawl fishery selection parameters, and the proportionality constant for the trawl survey. For the ling model, there was an additional proportionality constant for a longline CPUE index. Further details of the hake and ling model structures are in Appendix B.

## 2.4.6 Determination of $B_{MAY}$

For the ASSESS and MAY target strategies  $B_{MAY}$  was determined for the hake and ling stocks following the definition of Francis (1992). In this definition,  $B_{MAY}$  is the mean biomass resulting from fishing at  $F_{MAY}$  which is the fishing mortality which maximises average yield subject to the constraint that spawning biomass is below  $20\%B_0$  no more than 10% of the time.

In the simulations to determine  $F_{MAY}$  and  $B_{MAY}$ , the initial population had an equilibrium age structure with no fishing mortality. At various trial fishing mortalities, recruitment was applied in the following ways and timeframes: average recruitment for 60 years ( $2 \times$  maximum age); stochastic recruitment for 30 years; and stochastic recruitment for 60 years. The average yield and proportion of time below  $20\%B_0$  were evaluated for the last 60 years on each run (500 runs were used at each trial fishing mortality).

Results were very similar to those previously (Annala et al. 2002, given in parentheses): hake,  $B_{MAY} = 27.1\% B_0$  (27.3%); ling,  $B_{MAY} = 26.0\% B_0$  (26.4%).

## 2.4.7 Observations

Data available to the models was specified to mimic what is actually available for the hake and ling assessments (ignoring length data for ling, given there are plans to convert such data to age frequencies):

- CR trawl survey 1992–2010 as numbers at age and sex (HAK and LIN)
- Commercial trawl catch, proportions at age and sex, 1998–2010 (HAK), 1991–2010 (LIN)
- CPUE longline 1990–2010 (LIN)

The annual timing for the time series differs slightly between the operating model and the estimation models because of the different fishing periods. Note, in the operating model the values of the observations are determined for each run by applying observation error to the “true” values in the operating model (e.g., the observed CPUE longline index in a given year is the selected biomass in that year multiplied by a lognormal random variable with mean 1 and a specified c.v.). The timing of each time series, in the operating and estimation models was as follows:

|                  | Operating                | Estimation               |
|------------------|--------------------------|--------------------------|
| CR trawl survey  | 50% point of 1 Oct–1 Apr | 40% point of 1 Oct–1 Jun |
| Commercial trawl | catch from 1 Oct–1 Jun   | catch from 1 Oct–1 Jun   |
| Longline CPUE    | 1 Apr                    | 1 Jun                    |

Specified c.v.s for the multiplicative lognormal errors in the operating model were dependent only on age and species:

|            | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   | 17   | 18   | 19   | Age<br>20 |
|------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|-----------|
| <b>HAK</b> |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |           |
| com.       | 0.50 | 0.37 | 0.30 | 0.25 | 0.20 | 0.20 | 0.23 | 0.28 | 0.33 | 0.38 | 0.43 | 0.49 | 0.55 | 0.62 | 0.70 | 0.80 | 0.90 | 1.00      |
| survey     | 0.60 | 0.47 | 0.40 | 0.35 | 0.30 | 0.30 | 0.33 | 0.38 | 0.43 | 0.48 | 0.53 | 0.59 | 0.65 | 0.72 | 0.80 | 0.90 | 1.00 | 1.10      |
| <b>LIN</b> |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |           |
| com.       | 0.45 | 0.35 | 0.30 | 0.25 | 0.25 | 0.28 | 0.33 | 0.38 | 0.43 | 0.47 | 0.51 | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 | 0.80 | 0.90      |
| survey     | 0.35 | 0.25 | 0.20 | 0.15 | 0.15 | 0.18 | 0.23 | 0.28 | 0.33 | 0.37 | 0.41 | 0.45 | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 | 0.80      |

The absolute values and the pattern of high c.v. at low and high ages are typical of the sort of estimates obtained from the actual data (e.g., see Appendix A in Horn & Dunn (2003)). For hake, the survey c.v.s were taken to be 0.1 higher than the commercial sampling c.v.s at age (reflecting the low number of hake caught during the survey). For ling, the commercial sampling was assumed to have lower precision than the trawl survey (0.1 difference at age).

A constant c.v. of 35% was used for the longline CPUE in the operating model.

The assumed c.v.s in the estimation models were equal to those used in the operating model.

#### 2.4.8 Objective function

In order to compare the performance of the different management strategies there must be a measure of the success of the strategy. This was done using a loss function composed of three components (in a particular year, for a given species):

$$\text{Loss} = \text{biological loss} + \text{fishing cost} - \text{fishing return}$$

The fishing return is the "value" of the catches:

$$\text{fishing return} = w_1 C + w_2 A$$

where  $C$  is the catch within quota,  $A$  is the catch above quota ( $A = 0$  for the runs in this study), and  $w_1$  and  $w_2$  are specified weights.

The cost of fishing was taken to depend on the level of biomass as well as the amount of catch taken:

$$\text{fishing cost} = w_3 [ F + (C + A)^2 / B ]$$

where  $F$  is a fixed cost (expressed in catch units),  $B$  is the spawning biomass (giving a measure of how easily available the fish are), and  $w_3$  is a specified weight.

The biological loss was taken to depend on the "carrying capacity" of the stock ( $B_0$ ) and the current size of the stock relative to a threshold proportion:

$$\text{biological loss} = w_4 [ pB_0 / B - 1 ] pB_0$$

where  $p$  is the threshold proportion (the loss is positive when  $B$  is less than  $pB_0$ ) and  $w_4$  is a specified weight. Note, the biological loss becomes infinite if the stock becomes extinct.

The functional forms have been chosen so that each component of the overall loss has the same units (the units in which the catch is expressed).

The first two weights were assigned values:  $w_1 = 1.0$  and  $w_2 = 0.1$ , which were used in all runs. The threshold proportion was set equal to a commonly used value:  $p = 0.2$ . The fixed cost was set equal to low value relative to  $pB_0$ :  $F = 1000$ . Two constraints were imposed on the loss function in order to determine "reasonable values" for  $w_3$  and  $w_4$ :

- the cost of fishing equals the fishing return when the biomass is at half the threshold level (in which case, loss =  $w_4 pB_0$ )
- when the biomass is at twice the threshold level, loss =  $-pB_0$

Given the values used for the threshold proportion, the fixed cost, and the first two weights, it follows (when some approximations are made) that:

- $w_3 \cong 1$
- $1.5 < w_4 < 1.75$

The main results are presented with  $w_3 = 1$  and  $w_4 = 1.5$ , but the sensitivity of the conclusions is tested by looking at  $w_4$  in the range [1, 2].

### 3. RESULTS

#### 3.1 Grouping of Fishstocks by management strategy

Of approximately 65 species covered in the 2002 Plenary Reports (Annala et al. 2002, Sullivan & O'Brien 2002), only 29 of the species include Fishstocks which are managed other than by a "status quo policy" (Table 1). The stocks managed under an AMP or by international agreement were determined as a matter of fact. The allocation of other stocks to an "active", "reactive", or "status quo policy", was usually straightforward. The stocks with active management were required to have a rule in place for determining TACCs or catch limits. Only some scallop and rock lobster stocks fell into this category (Table 1). Stocks which are actively managed but do not have a rule in place for setting TACCs or catch limits were assigned to the reactive class. For example, southern blue whiting stocks are regularly surveyed and CAY estimates have in the past been used to set catch limits. However, there is no agreement for limits to be set on this basis.

The stocks in the reactive class correspond almost exclusively to those stocks which have been assessed using observation-error population dynamics models (e.g., by NIWA using their CASAL software). The exceptions to this rule were some cockle and oyster stocks which use recent absolute biomass estimates in conjunction with yield-per-recruit models to obtain an estimate of CAY (using either  $F_{0.1}$  or  $F_{max}$  in a Baranov type equation).

### 3.2 Fishery Performance Indicators

When the observation-error population dynamics models were used, estimates of current biomass were usually presented both as a tonnage and as a percentage of virgin biomass (Table 1). The main exceptions to this were from the use of MIAEL estimation (Cordue 1998) as the standard formulation estimated current biomass only as a percentage of virgin (e.g., see Dunn et al. 2000). This was given priority over absolute biomass to allow comparison with targets such as  $B_{MAY}$  which are expressed as a percentage of virgin biomass in terms of the definition of Francis (1992). Also, for snapper, paua, and rock lobster stocks current biomass was estimated only as a tonnage (Table 1). For these stocks, estimation of MCY and CAY was usually omitted (except for SNA 1 and 8).

For those stocks with reactive management, the most commonly estimated FPIs were a measure of "stock status" being either  $B_{cur}/B_0$  or  $B_{cur}/B_{MSY}$  (Table 2). For those stocks where projections were done, an estimate of the probability of being above or below a target biomass was usually presented (Table 2). The target biomass was typically given as  $B_{MSY}$ ; for orange roughy, this was a synonym for  $B_{MAY}$ , but for snapper it was a deterministic  $B_{MSY}$ . For oreos, estimated probabilities relative to both  $B_{MCY}$  and  $B_{MAY}$  were presented. For southern blue whiting (Campbell), estimates of probabilities relative to the 1991 biomass level were presented (this was a biomass at which a strong year class strength was spawned). For rock lobster and paua stocks the target biomass was an average biomass over a specified reference period (chosen to represent a period when biomass was "relatively stable").

The most common other type of FPI estimated was a measure of the probability of a future biomass being greater or less than the current biomass (Table 2). For orange roughy stocks, CSP was often estimated and for rock lobster and paua stocks, current and future exploitation rates also featured (Table 2).

### 3.3 Effect of regime shifts on FPIs

In order to define a "regime shift" we will first clarify some commonly used terms in relation to fish population dynamics:

|                   |  |
|-------------------|--|
| Biomass:          | This is the weight of fish in a population. Different types of biomass are defined, e.g., mature, spawning, female, etc.   |
| Virgin biomass:   | This is the mean level of biomass (of some specified type, e.g., female spawning) as measured at a specified time of the year (e.g., mid spawning season) before the start of fishing.   |
| Initial biomass:  | The biomass (of the same type and measured at the same time of year as virgin biomass) in the year before the first catch is taken.  |
| Current biomass:  | The biomass (of the same type and measured at the same time of year as virgin biomass) in the current year.  |
| Unfished biomass: | The mean level of biomass (of the same type and measured at the same time of year as virgin biomass) which would be present if no catches had been taken (and which will occur in the future if no further catches are taken). |

If the population dynamics of a given stock are stationary (i.e., nothing changes) then virgin biomass and unfished biomass will be equal. If virgin biomass and unfished biomass are not equal, then a "regime shift" has occurred. The most commonly considered effect of a regime shift is a change in the mean level of recruitment. We shall examine the general effect of such a shift on the most commonly estimated FPIs (Table 3). In order to do this several assumptions have been made with regard to the estimation model being used.

- A biomass trajectory and associated recruitments are *accurately* estimated from some time in the history of the fishery up to the current time.
- Projections are done at various catch levels assuming mean recruitment based on a period of the modeled history.
- An unaccounted for regime shift occurs at some time during the recruitment period used to determine mean recruitment.

Note that because the estimation model can be used for projections then it can also be used to determine an unfished biomass. Also, because the regime shift is not accounted for in the estimation model, then virgin biomass (in the estimation model) is equal to the unfished biomass. Note, when a regime shift of this nature does occur, virgin biomass becomes *irrelevant*, but unfished biomass is still vitally important as it represents the carrying capacity of the stock. Two cases are considered:

#### Regime shift giving lower mean recruitment

Estimates of the cohorts in the model will include some from the current regime and some from the earlier regime which had higher mean recruitment. The model estimates of recruitment will on average be too high for the current regime. This will lead to all projected biomasses, including unfished biomass (and hence virgin biomass), being too high (or over-estimated).

#### Regime shift giving higher mean recruitment

An analogous argument leads to all projected biomasses, including unfished biomass (and hence virgin biomass), being too low (or under-estimated).

The consequences for the commonly estimated FPIs are given in Table 4 for each scenario (assuming accurate historic and current estimates in the model). For example, when there is a shift to lower mean recruitment, then  $B_{cur}/B_0$  will be *under-estimated* because  $B_0$  will be over-estimated (relative to its true value which we are taking to be equivalent to the true unfished biomass). This looks like a good compensating effect as a shift to lower mean recruitment has caused the stock status to be reported more pessimistically than it should be, which in turn may lead to a reduction in catch, which is sensible given that the carrying capacity of the stock has been reduced. There is a similar useful compensating effect for  $B_{cur}/B_0$  if the shift has been to higher recruitment, in that the stock status is over-estimated (hence more likely to lead to increased catch). Other FPIs referenced to  $B_0$  have a similar compensatory effect or the effect of the shifts is indeterminate. For example, both  $E(B_{cur+n})$  and  $B_0$  will be higher than they should be under a shift to lower recruitment, so it is not known whether the ratio will be higher or lower.

The FPIs which do not have a compensatory effect to the shifts are all of a type referenced to current biomass or an historic average biomass. For example,  $E(B_{cur+n})/B_{AV}$  will be over-estimated when there is a shift to lower recruitment and under-estimated when there is a shift to higher recruitment (Table 4). This suggests that they will not be very useful in terms of driving a responsive management strategy, as they will tend to move the catches in the wrong direction under a regime shift.

The question of how the FPIs would be affected if the current and historic estimates were not accurate depends very much on the properties of the errors. As a general rule, if there has been a regime shift (or two) then virgin biomass could be impossible to estimate accurately. However, the fundamental parameter for which we would like an accurate estimate is unfished biomass as this represents the current carrying capacity of the stock (which in most models is very nearly equal to the parameter denoted by  $B_0$ ). The question of whether a reference average biomass can be more accurately estimated than the unfished biomass is moot (but see the results of the simulation study and subsequent discussion).

### 3.4 Case study

The simulation runs produced a multitude of results which can be examined in numerous ways. The following text and figures attempt to present the key results from the case study. The focus is on the contrast across management strategies, and across biomass levels within management strategy. Descriptive plots of two key drivers of the results are considered first, and then the focus is on mean trends of total loss and individual loss components. In the final section, the accuracy of estimates is considered.

#### 3.4.1 Spawning biomass and TAC trajectories

Stochastic recruitment starts in the operating model in 1941 which allows the initial biomass (before the start of catches) to be quite different from the virgin biomass (see example box and whisker plots of spawning biomass trajectories ( $B/B_0$ ) in Figures 1–4). At the LOW hake biomass an absence of assessment (and TAC changes) results in sharply lower biomass in 2010 (Figure 1). In contrast, all the other management strategies show an initial decline in biomass (from 2002) but appear to provide an increasing trend in biomass by 2010 (Figure 1). For HIGH hake biomass, the BAV target strategy appears to maintain the biomass level through to 2010, but the other strategies have downward trends from 2002 to 2010 (Figure 2).

For the LOW ling biomass, there is a substantial drop in biomass during the mid 1970s (Figure 3) when there were substantial longline catches (see Table A5). The NO ASSESS management strategy shows a declining trend in biomass from 2002, but the other strategies show either a stable biomass or some increase (Figure 3). At the HIGH ling biomass, the dip in the 1970s is still apparent (Figure 4). The BAV target strategy appears to maintain or increase the biomass from 2002 to 2010, but the other strategies have downward trends from 2002 to 2010.

Under the ASSESS strategy there is an increasing likelihood of the TAC being increased as the biomass level changes from LOW to HIGH, for both hake (Figure 5) and ling (Figure 6). At the LOW biomass for hake, the TAC is always reduced from 2002 to 2010, and at the HIGH level it is never reduced and almost always increased (Figure 5). For ling, the same is almost true, but there are two exceptions at the LOW biomass, when the TAC is increased, and one exception at the HIGH biomass, when the TAC is decreased (Figure 6).

Under the MAY target strategy the same increasing likelihood of the TAC being increased as the biomass level changes from LOW to HIGH is again seen for hake (Figure 7) and ling (Figure 8). However, there is a greater chance, at each biomass level, of an increase in TAC under the MAY target strategy compared to the ASSESS strategy (compare Figures 5 & 7, Figures 6 & 8). At the HIGH biomass, the TAC is almost exclusively increased through to 2008–2009 for both hake (Figure 7) and ling (Figure 8).

Under the BAV target policy a different pattern is seen. Although there is still the increasing likelihood of an increase in TAC with an increase in the biomass level, there is a preponderance of decreasing TAC trajectories, even at the highest biomass level for both hake (Figure 9) and ling (Figure 10).

#### 3.4.2 Loss function and its components

A “good” management strategy must be able to cope with poor recruitment and take advantage of strong recruitment. In evaluating a management strategy, it is therefore important to take account of the tails in

the distributions of the total loss function and its components. For this reason, it is preferable to use the mean rather than the median as the measure of overall performance. The following text and figures primarily look at mean trends.

At LOW hake biomass, the absence of assessments leads to a sharp decline in spawning biomass from 2002 to 2010 (Figure 11). The TAC is stable, but the average catches are not maintained at that level (as the TAC sometimes exceeds maximum exploitation rates). The NO ASSESS policy leads to a high biological loss and a correspondingly high overall loss (Figure 11). The other three strategies all lead to declining average TACs with an eventual recovery in average biomass and a decreasing total loss because of the associated decrease in biological loss (Figure 11). The MAY target strategy reduces TACs least (on average), while the BAV target strategy reduces TACs most; the ASSESS strategy is between these two (Figure 11).

The statements in the above paragraph apply almost equally to ling at the LOW biomass (Figure 12). There are two main differences: the average ling catches under the NO ASSESS strategy are not much less than the TAC (whereas they are substantially lower than the TAC for hake); and the average biological loss (and subsequent total loss) are very large by 2010 under the NO ASSESS strategy (Figure 12). In terms of median trends for ling at the LOW biomass, the picture looks similar for spawning biomass, TAC, and catch, but very different for biological loss and total loss (Figure 13). Under the NO ASSESS strategy, the biological loss and total loss are still negative in 2010 (Figure 13) rather than very large and positive for the mean (Figure 12). The reason for the difference is that the median spawning biomass under the NO ASSESS strategy stays above the threshold proportion (0.2), while an increasingly large proportion of the distribution is below the threshold (Figure 14). The effect of this on total loss is that the median for the NO ASSESS strategy remains negative through to 2010, but there is an increasingly long tailed distribution of positive losses (Figure 15). In contrast, the maximum total loss for the other three management strategies peaks in 2005 and is consistently reduced through to 2010 (Figure 15).

As the biomass level increases, the three assessment strategies maintain their relative order with regard to mean spawning biomass, TAC, catch, and biological loss, but their position changes relative to the NO ASSESS strategy (Figures 16–19). At the MED2 biomass, the ASSESS strategy behaves very similarly to the NO ASSESS strategy in terms of mean values (Figures 16 & 17). The MAY target strategy, on average, increases TACs through to 2006–2007, before decreasing them somewhat. In contrast, the BAV target strategy consistently reduces TACs (Figures 16 & 17). In terms of total loss in 2010, the MAY target strategy performs least well for both hake (Figure 16) and ling (Figure 17). At the high biomass level, the MAY target strategy is slightly better than the other strategies in terms of total loss, but they are all very good because biomass is maintained at a high level (Figures 18 & 19). The BAV target strategy performs very badly at this biomass level in terms of fishing return, giving on average about 4 times less than the MAY target strategy in 2010 (Figures 18 & 19).

The effect on total loss of altering the weight on biological loss was investigated. Over the range of weights explored (which was larger than that implied by the suggested constraints) there was a large change in the scale of the total loss, but almost no effect on the relative differences between the management strategies for a given biomass level (illustrative examples in Figures 20 & 21).

### 3.4.3 Accuracy of estimates

Although it is ancillary to the main work of the case study, it is useful to assess the accuracy of the stock assessment estimators and to examine how the level of accuracy depends on the quantity of data and the level of virgin biomass. The results presented here are restricted to estimation of  $B_0$ ,  $B_{2002}$ ,  $B_{cur}/B_0$ , and  $B_{cur}/B_{AV}$  for the ASSESS management strategy for ling. The results for other management strategies would

be almost identical (as the only difference is the amount of catch removed from 2004 onwards) and the results for hake are qualitatively very similar.

The measures of accuracy are based on relative error: estimate – true value, as a fraction of the true value. Two average measures are presented: mean relative error (which gives an indication of bias); and root mean squared relative error (RMS, which is an overall measure of accuracy – i.e., how close on average the estimates are to the true value).

Estimation of  $B_0$  for ling at the LOW biomass showed relative errors ranging from about –0.3 to 0.4 (Figure 22). There is an indication of truncation at the lower end of the relative error distribution (Figure 22) showing that the lower bound placed on the estimate did have an effect. There is little indication of any improvement in the accuracy of the estimates from 2003 to 2009 (Figure 22). For the MED2 biomass, the relative errors have a somewhat larger range of about –0.4 to 0.6, but there is no indication of truncation of the distribution (Figure 23). For the HIGH biomass, truncation is evident at the top end of the distribution, and again there is little indication of improvement in the accuracy of the estimates from 2003 to 2009 (Figure 24).

Estimation of  $B_{2002}$  shows a different pattern, with no indication of truncation at any of the biomass levels, a smaller range of relative errors than  $B_0$  (except for MED2 in 2007), and with improvement in accuracy evident from 2003 to 2009 at each level (Figures 25–27).

The lack of improvement in accuracy from the 2003 to 2009 assessments for  $B_0$  is confirmed when the mean relative error and RMS are plotted. There is a pattern of improved accuracy and less bias at lower biomass levels, but no indication of an improvement in performance with more data (Figure 28). For estimation of  $B_{2002}$  the different patterns are also confirmed when the mean relative error and RMS are plotted. There is generally substantial improvement in accuracy as more data are added and there is a strong pattern of improving accuracy with decreasing biomass level (Figure 29). Compared to estimation of  $B_0$ , there is less bias and similar or greater accuracy at every level. The accuracy is much better for  $B_{2002}$  at the lower biomass levels (compare Figures 28 & 29).

The estimator of  $B_{cur}/B_0$  has a similar level of RMS when compared to the estimator of  $B_0$ , but shows a positive rather than negative bias (Figure 30). The estimation of  $B_{AV}/B_0$  shows a high level of accuracy and very little bias (Figure 31). There is the usual pattern of increasing accuracy with decreasing biomass level, but in the 2009 assessment the RMS is almost identical for all biomass levels (Figure 31).

#### 4. DISCUSSION

The sensitivity of FPIs to operating model parameters has been studied in a New Zealand setting for a single stock model (Bull & Cordue 2000). The purpose of that work was to assess the reliability with which typical FPIs could be estimated, arguing that if an FPI was sensitive to a parameter which could not be well estimated, then the FPI could not be well estimated. Cordue & Francis (1994) demonstrated that some performance indicators were inherently easier (or harder) to estimate than others.

Bull & Cordue (2000) did not consider the use of (estimated) FPIs in management strategies. It could be argued that poorly estimated FPIs are less likely to be of use in management strategies than well estimated FPIs. However, this is only an hypothesis. In some situations it may be that some management decision rules perform adequately with poorly estimated FPIs. Indeed, in this study it was found that  $B_0$  based management strategies performed better than the  $B_{AV}$  based strategy despite  $B_{cur}/B_0$  being much more poorly estimated than  $B_{cur}/B_{AV}$ . Estimation of  $B_0$  also appeared problematic in that there was little or no improvement in estimation accuracy as more data were added.

The evaluation of management strategies has an extensive literature. There are many examples of specific applications of some form of management strategy evaluation (e.g., Quinn et al. 1990, DiNardo & Wetherall 1999, Geromont et al. 1999, Polacheck et al. 1999, Punt & Smith 1999). There are also general descriptions of a management strategy evaluation framework (e.g., McAllister & Kirkwood 1998, Chesson et al. 1999, Cooke 1999, Kell et al. 1999, Smith et al. 1999, Sainsbury et al. 2000). Punt & Smith (1999) showed how the value of collecting different types of data, with different frequencies, can be included in the management strategies and thus tested as part of the evaluation. Sainsbury et al. (2000) showed that a broad mix of competing components can be included in the overall objective function, including ecosystem considerations.

The use of single species models is prevalent in the literature and constitutes one of the main model assumptions which is violated to a lesser or greater extent in every fishery. For example, the occurrence of a significant "predator" species will normally introduce process errors in the recruitment of the prey species which cannot be accounted for in a single species model. Multi-species assessment models, or those including explicit predation on the primary species of interest, certainly have been used (e.g., Punt & Hilborn 1994, Walters & Bonfil 1999, Garrison et al. 2000, Carscadden et al. 2001, Fu et al. 2001, Köster et al. 2001), but their advantage over single species models is moot (Hollowed et al. 2000). There is the problem of all the extra data that are needed to fit such models and also there may be no advantage gained when they are incorporated in the management strategy (Punt & Hilborn 1994). However, it is certain that reference points (and hence desirable management strategies) can be greatly changed when multi-species considerations are included. Gislason (1999) gives the example of a cod, herring, and sprat ecosystem; it appears that the "best" management strategy may be to reduce the cod population to allow greater yields from (their prey) the herring and sprat.

One of the crucial model assumptions for stocks at low levels is the nature of the spawning stock-recruitment relationship (if any). Many FPIs can be greatly affected by the assumptions made in this regard. There is great difficulty in estimating the parameters of an assumed relationship (Hinrichsen 2001) because of the typically high level of recruitment variability in fish stocks. However, there are reports from authors who find evidence of stock-recruit relationships (e.g., Brodziak et al. 2001), while there are those who provide alternative explanations (Gilbert 1997). Regime shifts may be a real possibility within many ecosystems (e.g., Cardinale & Arrhenius 2000, Carscadden et al. 2001) and such shifts, combined with the fact that low recruitment gives rise to low spawning stock biomass, can lead to the appearance of spurious stock-recruit relationships. Robustness testing of FPIs to regime shifts and stock-recruit relationships would seem to be prudent. Other model assumptions which may need to be considered are density dependent growth and maturity (Helsler & Brodziak 1998) and age and size specific fecundity (Scott et al. 1999).

In this study, there were very limited structural differences between the estimation and operating models. The main difference was that the initial biomass was allowed to differ from the virgin biomass in the operating model (and not in the estimation models). The introduction of structural differences would degrade estimation performance and would eventually degrade management performance. However, this would likely be the case for all the management strategies investigated. The main conclusion with regard to their relative performance would not be altered: the BAV target strategy will always attempt to rebuild the stock, even when the stock is at an already "high level". This is because the reference period in the models corresponds to a time when biomass was at a higher level than in the present, and  $B_{AV}$  is taken as a target reference point in the management strategy.

In practice,  $B_{AV}$  may or may not be a target. It appears to be the case in the paua stocks (where the reference period, 1985 to 1987, has biomass which is higher than the current biomass), although this is denied in the text (Annala et al. 2002). In rock lobster (CRA 1 and CRA 2), the reference period (1979 to

1988) was chosen because model fits suggested that “the biomass was relatively stable during this period” (Sullivan & O’Brien 2002). In the “Status of the stocks” section it appears that the reference biomass is a threshold and certainly not a target.

The use of a reference biomass period for paua and rock lobster stocks can be traced to the 2001 assessment of PAU 7 (Annala et al. 2001). (Note, the same modeller is involved with both paua and rock lobster.) Quoting from the PAU 7 assessment in Annala et al. (2001): “Retrospective analyses, ... , suggested the assessment was stable but that  $B_0$  and  $B_{MSY}$  were poorly estimated. For this reason,  $B_0$ ,  $B_{MSY}$  and derived ratios are not used as performance indicators.” The use of mean biomass over a period as a “reference biomass” may or may not be a good idea, but to dispense with  $B_0$  and  $B_{MSY}$  for the reasons given is erroneous.

A retrospective analysis cannot correctly be used to conclude anything about the properties of an estimator (and hence whether a quantity is being “poorly” or “well” estimated). In such an analysis, one is examining a series of estimates from closely related data sets. One of the key points is that these are *estimates*, being a *single* realisation of a sequence of random variables (the *estimators*). Properties of estimators can be reliably determined only mathematically or through extensive simulations. In Appendix D, this erroneous use of retrospective analysis is dealt with by way of a formal definition and examples which demonstrate two conclusions: a “bad” retrospective pattern (by way of a trend in estimates and large differences between estimates) does not imply that a “bad” estimator has been used, or that the quantity is poorly estimated; and a “good” retrospective pattern does not imply a “good” estimator or that the quantity is “well estimated”.

Despite the erroneous method of reaching the conclusion, it is quite possible that  $B_0$  and related ratios are poorly estimated in the rock lobster and paua models. Certainly, given the simulation results of this study, it may be that a suitably chosen  $B_{AV}$  is generally more accurately estimated than  $B_0$ . However, as this study also shows, that does not mean that a management strategy based on a  $B_{AV}$  will out perform one based on  $B_0$ . There are obvious dangers in not estimating stock status relative to  $B_0$ , and the unfished biomass is a parameter of such fundamental importance (in terms of “biological loss” however this is defined) that it should always be estimated in a stock assessment.

## 5. ACKNOWLEDGMENTS

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## 6. REFERENCES

- Annala, J.H.; Sullivan, K.J.; O'Brien, C.J.; Smith, N.W.McL (comps.) (2001). Report from the Fishery Assessment Plenary, May 2001: stock assessments and yield estimates. 515 p. (Unpublished report held in NIWA library Wellington.)
- Annala, J.H.; Sullivan, K.J.; O'Brien, C.J.; Smith, N.W.McL.; Varian, S.J.A. (comps.) (2002). Report from the Fishery Assessment Plenary, May 2002: stock assessments and yield estimates. 640 p. (Unpublished report held in NIWA library Wellington.)
- Annala, J.H.; Sullivan, K.J.; O'Brien, C.J.; Smith, N.W.McL.; Grayling, S.M. (comps.) (2003). Report from the Fishery Assessment Plenary, May 2003: stock assessments and yield estimates. 637 p. (Unpublished report held in NIWA library Wellington.)
- Brodziak, J.K.T.; Overholtz, W.J.; Rago, P.J. (2001). Does spawning stock affect recruitment of New England groundfish? *Can. J. Fish. Aquat. Sci* 58: 306–318.
- Bull, B.; Cordue, P.L. (2000). Sensitivities of fishery performance indicators to the assumptions of a single stock model. *New Zealand Fisheries Assessment Report 2000/39*. 33 p.
- Cardinale, M.; Arrhenius, F. (2000). The influence of stock structure and environmental conditions on the recruitment process of Baltic cod estimated using a generalized additive model. *Can. J. Fish. Aquat. Sci.* 57: 2402–2409.
- Carscadden, J.E.; Frank, K.T.; Leggett, W.C. (2001). Ecosystem changes and the effects on capelin (*Mallotus villosus*), a major forage species. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 73–85.
- Chesson, J.; Clayton, H.; Whitworth, B. (1999). Evaluation of fisheries-management systems with respect to sustainable development. *ICES Journal of Marine Science* 56: 980–984.
- Cooke, J.G. (1999). Improvement of fishery-management advice through simulation testing of harvest algorithms. *ICES Journal of Marine Science* 56: 797–810.
- Cordue, P.L. (1998). Designing optimal estimators for fish stock assessment. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 376–386.
- Cordue, P.L.; Francis, R.I.C.C. (1994). Accuracy and choice in risk estimation for fisheries assessment. *Canadian Journal of Fisheries and Aquatic Sciences* 51: 817–829.
- DiNardo, G.T.; Wetherall, J.A. (1999). Accounting for uncertainty in the development of harvest strategies for the Northwestern Hawaiian Islands lobster trap fishery. *ICES Journal of Marine Science* Vol. 56: 943–951.
- Dunn, A. (2003). Stock assessment of hake (*Merluccius australis*) for the 2002–03 fishing year. *New Zealand Fisheries Assessment Report 2003/38*. 57 p.
- Dunn, A.; Horn, P.L.; Cordue, P.L.; Kendrick, T.H. (2000). Stock assessment of hake (*Merluccius australis*) for the 1999–2000 fishing year. *New Zealand Fisheries Assessment Report 2000/50*. 50 p.
- Francis, R.I.C.C. (1992). Recommendations concerning the calculation of maximum constant yield (MCY) and current annual yield (CAY). New Zealand Fisheries Assessment Research Document 92/8. 27 p. (Unpublished report held in NIWA library Wellington.)
- Francis, R.I.C.C.; Haist, V.; Bull, B. (2003). Assessment of hoki (*Macruronus novaezelandiae*) in 2002 using a new model. *New Zealand Fisheries Assessment Report 2003/6*. 69 p.
- Fu, C.; Mohn, R.; Fanning, L.P. (2001). Why the Atlantic cod (*Gadus morhua*) stock off eastern Nova Scotia has not recovered. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 1613–1623.
- Garrison, L.P.; Michaels, W.; Link, J.S.; Fogarty, M.J. (2000). Predation risk on larval gadids by pelagic fish in the Georges Bank ecosystem. I. Spatial overlap associated with hydrographic features. *Canadian Journal of Fisheries and Aquatic Sciences* 57: 2455–2469.
- Geromont, H.F., De Oliveira, J.A.A.; Johnston, S.J.; Cunningham C.L. (1999). Development and application of management procedures for fisheries in southern Africa. *ICES Journal of Marine Science* 56: 952–966.

- Gilbert, D.J. (1997). Towards a new recruitment paradigm for fish stocks. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 969–977.
- Gislason, H. (1999). Single and multispecies reference points for Baltic fish stocks. *ICES Journal of Marine Science* 56: 571–583.
- Helser, T.E.; Brodziak, J.K.T. (1998). Impacts of density-dependent growth and maturation on assessment advice to rebuild depleted U.S. silver hake (*Merluccius bilinearis*) stocks. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 882–892.
- Hinrichsen, R.A. (2001). High variability in spawner-recruit data hampers learning. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 769–776.
- Hollowed, A.B.; Bax, N.; Beamish, R.; Collie, J.; Fogarty, M.; Livingston, P.; Pope, J.; Rice, J.C. (2000). Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems? *ICES Journal of Marine Science* 57: 707–719.
- Horn, P.L. (2002). Stock assessment of ling (*Genypterus blacodes*) around the South Island (Fishstocks LIN 3, 4, 5, 6, and 7) for the 2001–02 fishing year. *New Zealand Fisheries Assessment Report 2002/20*. 53 p.
- Horn, P.L.; Dunn, A. (2003). Stock assessment of ling (*Genypterus blacodes*) around the South Island (Fishstocks LIN 3, 4, 5, 6, and 7) for the 2002–03 fishing year. *New Zealand Fisheries Assessment Report 2003/47*. 59 p.
- Kell, L.T.; O'Brien, C.M.; Smith, M.T.; Stokes, T.K.; Rackham, B.D. (1999) An evaluation of management procedures for implementing a precautionary approach in the ICES context for North Sea plaice (*Pleuronectes platessa* L.). *ICES Journal of Marine Science* 56: 834–845.
- Köster, F.W.; Hinrichsen, H.; St. John, M.A.; Schnack, D.; MacKenzie, B.R.; Tomkiewicz, J.; Plikshs, M. (2001). Developing Baltic cod recruitment models. II. Incorporation of environmental variability and species interaction. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 1534–1556.
- McAllister, M.K.; Kirkwood, G.P. (1998). Using Bayesian decision analysis to help achieve a precautionary approach for managing developing fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 2642–2661.
- Philips, G.M.; Taylor, P.J. (1973). Theory and applications of numerical analysis. Academic Press, London. 380 p.
- Polacheck, T.; Klaer, N.L.; Millar, C.; Preece, A.L. (1999). An initial evaluation of management strategies for the southern bluefin tuna fishery. *ICES Journal of Marine Science* 56: 811–826.
- Punt, A.E.; Smith, A.D.M. (1999). Harvest strategy evaluation for the eastern stock of gemfish (*Rexea solandri*). *ICES Journal of Marine Science* 56: 860–875.
- Punt, A.E.; Hilborn, R. (1994). A comparison of fishery models with and without cannibalism with implications for the management of the Cape hake resource off southern Africa. *ICES Journal of Marine Science* 51: 19–29.
- Quinn T.J. II; Fagen, R.; Zheng, J. (1990). Threshold management policies for exploited populations. *Can. J. Fish. Aquat. Sci* 47: 2016–2029.
- Sainsbury, K.J.; Punt, A.E.; Smith, A.D.M. (2000). Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science* 57: 731–741.
- Scott, B.; Marteinsdottir, G.; Wright, P. (1999). Potential effects of maternal factors on spawning stock-recruitment relationships under varying fishing pressure. *Canadian Journal of Fisheries and Aquatic Sciences* 56: 1882–1890.
- Smith, A.D.M.; Sainsbury, K.J.; Stevens, R.A. (1999). Implementing effective fisheries-management systems – management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science* 56: 967–979.
- Sullivan, K.J.; O'Brien, C.J. (comps.) (2002). Report from the Mid-Year Fishery Assessment Plenary, November 2002: stock assessments and yield estimates. 45 p. (Unpublished report held in NIWA library Wellington.)
- Walters, C.J.; Bonfil, R. (1999) Multispecies spatial assessment models for the British Columbia groundfish trawl fishery. *Canadian Journal of Fisheries and Aquatic Sciences* 56: 601–628.

Worthington, D.G.; Blount, C.; Chick, R.C.; Gibson, P.T.; Stewart, B.R. (2001). An assessment of the performance indicators of the Abalone Share Management Plan in 2000. *New South Wales Fishery Resource Assessment Series 11*. 48 p.

**Table 1: New Zealand Fishstocks which are not managed by a “status quo policy”, the associated methods used to estimate MCY and CAY, and an indication of the FPIs estimated.**

| Policy   | Fishstock <sup>1</sup> | MCY <sup>2</sup>   | CAY <sup>3</sup> | FPIs estimated                         |                                    |                 |
|----------|------------------------|--------------------|------------------|--|------------------------------------|-----------------|
|          |                        |                    |                  | Current biomass (tonnage) <sup>4</sup> | Current biomass (%B <sub>0</sub> ) | Other FPIs      |
| Reactive | COC Snake Bank         | $0.5F_{REF}B_{AV}$ | $F_{REF}$        | No                                     | No                                 | No              |
|          | COC Otago Pen.         | $0.25F_{REF}B_0$   | $F_{REF}$        | No                                     | No                                 | No              |
|          | COC Tas. &Gold. Bay    | $0.25F_{REF}B_0$   | $F_{REF}$        | No                                     | No                                 | No              |
|          | OYS 5                  | None               | $F_{REF}$        | No                                     | No                                 | No              |
|          | OYS 7                  | $0.5F_{REF}B_{AV}$ | $F_{REF}$        | No                                     | No                                 | No              |
|          | SKI (all)              | Francis            | Francis          | No                                     | Yes                                | No              |
|          | HAK 1, 4               | Francis            | Francis          | No                                     | Yes                                | No              |
|          | HOK (all)              | Francis            | Francis          | Yes                                    | Yes                                | No              |
|          | LIN 3-7                | Francis            | Francis          | No                                     | Yes                                | No              |
|          | ORH (most)             | Francis            | Francis          | Yes                                    | Yes                                | Yes             |
|          | BOE 3A                 | Francis            | Francis          | Yes                                    | Yes                                | Yes             |
|          | SSO 3A, 4              | Francis            | Francis          | Yes                                    | Yes                                | No              |
|          | PAU 5B, 5D, 7          | None               | None             | Yes                                    | No                                 | Yes             |
|          | RCO 3, 7               | Francis            | Francis          | No                                     | Yes                                | No              |
|          | GUR 1W, 1E             | Francis            | None             | No                                     | Yes                                | No              |
|          | SNA 1, 8               | CSP                | $U_{REF}$        | Yes                                    | No                                 | Yes             |
|          | SNA 2, 7               | None               | None             | Yes                                    | No                                 | Yes             |
|          | SBW Campbell           | Francis            | Francis          | Yes                                    | Yes                                | No <sup>5</sup> |
|          | SBW Bounty             | None               | Francis          | Yes                                    | No                                 | No <sup>5</sup> |
|          | SBW Pukaki             | None               | Francis          | Yes                                    | Yes                                | No              |
|          | TRE 7                  | $0.25F_{REF}B_0$   | None             | Yes                                    | Yes                                | No              |
|          | CRA 1-3                | None               | None             | Yes                                    | No                                 | Yes             |
|          | Active                 | SCA 1, CS, 7       | None             | $F_{REF}$                              | No                                 | No              |
| CRA 7, 8 |                        | None               | None             | No                                     | No                                 | Yes             |
| AMP      | ELE 3, 5               | $cY_{av}$          | None             | No                                     | No                                 | No              |
|          | LIN 1                  | $cY_{av}$          | None             | No                                     | No                                 | No              |
|          | ORH 1 <sup>6</sup>     | None               | None             | No                                     | No                                 | No              |
|          | GUR 3                  | $cY_{av}$          | None             | No                                     | No                                 | No              |
|          | SPO 3, 7               | None               | None             | No                                     | No                                 | No              |
|          | RBV 1                  | None               | None             | No                                     | No                                 | No              |
|          | SPE 3                  | None               | None             | No                                     | No                                 | No              |
|          | SWA 1                  | $cY_{av}$          | None             | No                                     | No                                 | No              |
|          | STA 3, 7               | $cY_{av}$          | None             | No                                     | No                                 | No              |
|          | International          | ALB                | $cY_{av}$        | None                                   | No <sup>7</sup>                    | No              |
| STN      |                        | None               | None             | No <sup>7</sup>                        | No                                 | No              |

1: See Annala et al. (2002) for species codes and stock definitions.

2: See Annala et al. (2002) for definitions of  $F_{REF}$ ,  $B_{AV}$ ,  $B_0$ , and  $cY_{av}$ . “Francis” refers to the risk based definition of MCY in Francis (1992).

3:  $F_{REF}$  designates use of a Baranov type equation with a reference fishing mortality.  $U_{REF}$  designates an exploitation rate definition. “Francis” refers to the risk based definition of CAY in Francis (1992).

4: The question being whether a current biomass estimate is presented in tonnes, excluding any tonnages which are given simply for the purpose of calculating CAY.

5: Some other FPIs were presented in an alternative Industry assessment.

6: Excluding Mercury-Colville box

7: There are no agreed assessments, although biomass and FPIs have been estimated.

Table 2: FPIs estimated for fishstocks which are managed “reactively”.  $B_{cur}$  is current biomass (as at the time of the stock assessment),  $B_{cur+n}$  is biomass  $n$  years in the future,  $U$  denotes exploitation rate, and  $B_{AV}$  is an average biomass over a specified reference period.

| Species code | Stock     | Stock status      | Safety   | Target   | Other   |
|--------------|-----------|-------------------|--|--|---|
| ORH          | East Cape | $B_{cur}/B_0$     | -  | -  | CSP   |
|              | MEC       | $B_{cur}/B_0$     | $P(B_{cur} > 0.2B_0)$<br>$P(B_{cur+5} > 0.2B_0)$ | $P(B_{cur} > B_{msy})$<br>$P(B_{cur+5} > B_{msy})$                           | CSP   |
|              | NW CR     | $B_{cur}/B_0$     | $P(B_{cur} > 0.2B_0)$                            | $P(B_{cur} > B_{msy})$   | -   |
|              | NE CR     | $B_{cur}/B_0$     | $P(B_{cur} > 0.2B_0)$                            | $P(B_{cur} > B_{msy})$   | CSP, catches*   |
| BOE          | 3A        | $B_{cur}/B_0$     | -  | $P(B_{cur+n} > B_{msy})$ $n = 5, 10$<br>$P(B_{cur+n} > B_{msy})$ $n = 5, 10$ | $P(B_{cur+5} > B_{cur})$<br>$P(B_{cur+10} > B_{cur})$                             |
| SNA          | 1         | $B_{cur}/B_{msy}$ | -  | $E(B_{cur+20}/B_{msy})$<br>$P(B_{cur+20} > B_{msy})$                         | $P(B_{cur+20} > B_{cur})$   |
|              | 2         | $B_{cur}/B_{msy}$ | -  | $E(B_{cur+5}/B_{msy})$   | $E(B_{cur+5})$  |
|              | 7         | $B_{cur}/B_{msy}$ | -  | $E(B_{cur+5}/B_{msy})$<br>$P(B_{cur+n} > B_{msy})$ $n = 0, 5$                | $E(B_{cur+5})$  |
|              | 8         | $B_{cur}/B_{msy}$ | -  | -  | Predicted CSP   |
| SBW          | Campbell  | $B_{cur}/B_0$     | $P(B_{cur+n} < B_{1991})$<br>$n = 1, 2, 5$       | -  | -   |
|              | Bounty    | -                 | -  | -  | $P(B_{cur+n} < B_{cur})$ $n=1, 2, 3$  |
|              | Pukaki    | $B_{cur}/B_0$     | -  | -  | -   |
| CRA          | 1, 2, 3   | -                 | -  | $E(B_{cur+n}/B_{av})$ $n = 0, 5$   | $U_{cur}, U_{cur+4}, E(B_{cur+5}/B_{cur})$  |
| PAU          | 5B, 5D    | -                 | -  | $E(B_{cur+n}/B_{av})$ $n = 0, 5$<br>$P(B_{cur+5} < B_{av})$                  | $U_{cur}, U_{cur+5}, B_{cur+5}$<br>$E(B_{cur+5}/B_{cur}), P(B_{cur+5} < B_{cur})$ |
|              | 7         | -                 | -  | $E(B_{cur+n}/B_{av})$ $n = 0, 5$<br>$P(B_{cur+5} < B_{av})$                  | $U_{cur}, U_{cur+5}$<br>$E(B_{cur+5}/B_{cur}), P(B_{cur+5} < B_{cur})$            |

\* Under a 10 year projection, maximum catches which satisfied a “safety” criterion or a “target” criterion were estimated together with the minimum catch satisfying a “moving towards  $B_{MSY}$ ” criterion.

Table 3: Generic FPIs and the associated generic loss functions.  $B_{TAR}$  can take the value of  $B_{MCT}$ ,  $B_{MAT}$ , or  $B_{AV}$  (the average biomass over a specified reference period). See Appendix 3 for definition of loss functions  $Asym$  and  $Sq$ . (Note:  $Asym(x | b)$  has zero loss when  $x=b$ , and  $Sq(x | p)$  has zero loss when  $x=p$ .) Under the loss function column, “P” denotes the associated FPI.

| FPI                      | Loss function   |
|--------------------------|---|
| $B_{cur}/B_0$            | $Asym(B_{cur}   b = 0.5B_0)$  |
| $E(B_{cur+n})/B_0$       | $Asym(E(B_{cur+n})   b = 0.5B_0)$   |
| $B_{cur}/B_{TAR}$        | $Asym(B_{cur}   b = B_{TAR})$   |
| $E(B_{cur+n})/B_{TAR}$   | $Asym(E(B_{cur+n})   b = B_{TAR})$  |
| $P(B_{cur+n} > 0.2B_0)$  | $Sq(P   p = 1)$   |
| $P(B_{cur+n} > B_{TAR})$ | $Sq(P   p = 0.5)$   |
| $P(B_{cur+n} < B_{cur})$ | If $B_{cur} < B_{TAR}$ $Sq(P   p = 0)$ else $Sq(P   p = 1)$   |
| $E(B_{cur+n}/B_{cur})$   | If $B_{cur} < B_{TAR}$ $Asym(E(B_{cur+n})   b = 1.25B_{cur})$ else $Asym(E(B_{cur+n})   b = 0.75B_{cur})$ |

**Table 4: The effect of regime shifts with lower or higher average recruitment (R) on estimates of mean recruitment, unfished biomass ( $B_0$ ), and selected FPIs. It is assumed that the current and historic model estimates are accurate.**

|   | Shift to lower R | Shift to higher R |
|---|------------------|-------------------|
| Mean R                                  | Over-estimated   | Under-estimated   |
| Unfished biomass ( $B_0$ )              | Over-estimated   | Under-estimated   |
| <b>FPI</b>                              |                  |                   |
| $B_{cur} / B_0$                         | Under-estimated  | Over-estimated    |
| $E(B_{cur+n}) / B_0$                    | Indeterminate    | Indeterminate     |
| $B_{cur} / B_{TAR}$ ( $B_0$ based)      | Under-estimated  | Over-estimated    |
| $B_{cur} / B_{av}$                      | Not affected     | Not affected      |
| $E(B_{cur+n}) / B_{TAR}$ ( $B_0$ based) | Indeterminate    | Indeterminate     |
| $E(B_{cur+n}) / B_{av}$                 | Over-estimated   | Under-estimated   |
| $P(B_{cur+n} > 0.2B_0)$                 | Indeterminate    | Indeterminate     |
| $P(B_{cur+n} > B_{TAR})$ ( $B_0$ based) | Indeterminate    | Indeterminate     |
| $P(B_{cur+n} > B_{av})$                 | Over-estimated   | Under-estimated   |
| $P(B_{cur+n} < B_{cur})$                | Under-estimated  | Over-estimated    |
| $E(B_{cur+n} / B_{cur})$                | Over-estimated   | Under-estimated   |

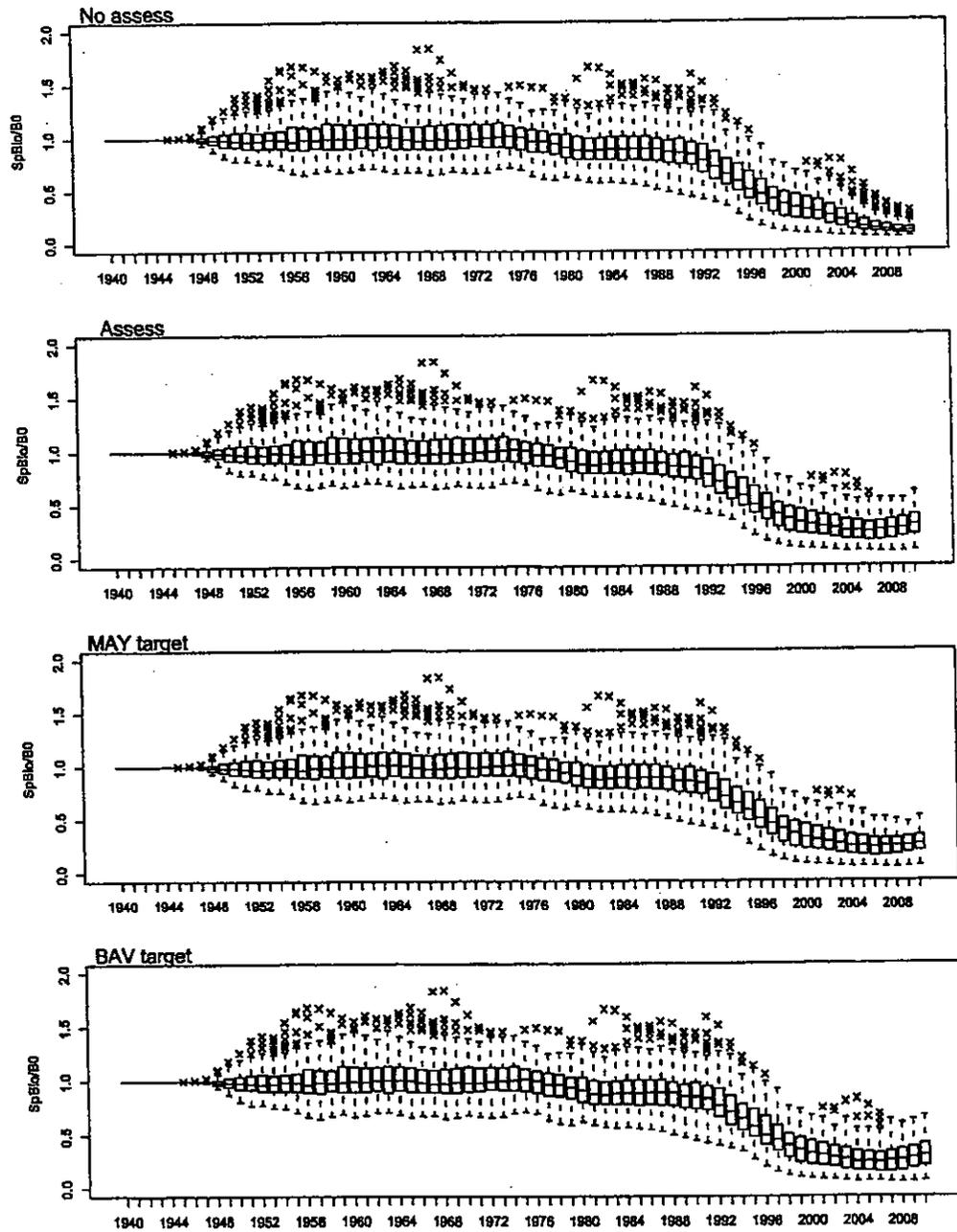


Figure 1: Box and whisker plots of the spawning biomass trajectories for hake ( $B_t$  LOW) under the four management strategies. The horizontal line shows the median and the box shows the 25<sup>th</sup> to 75<sup>th</sup> percentiles ( $B_t/B_0$ ).

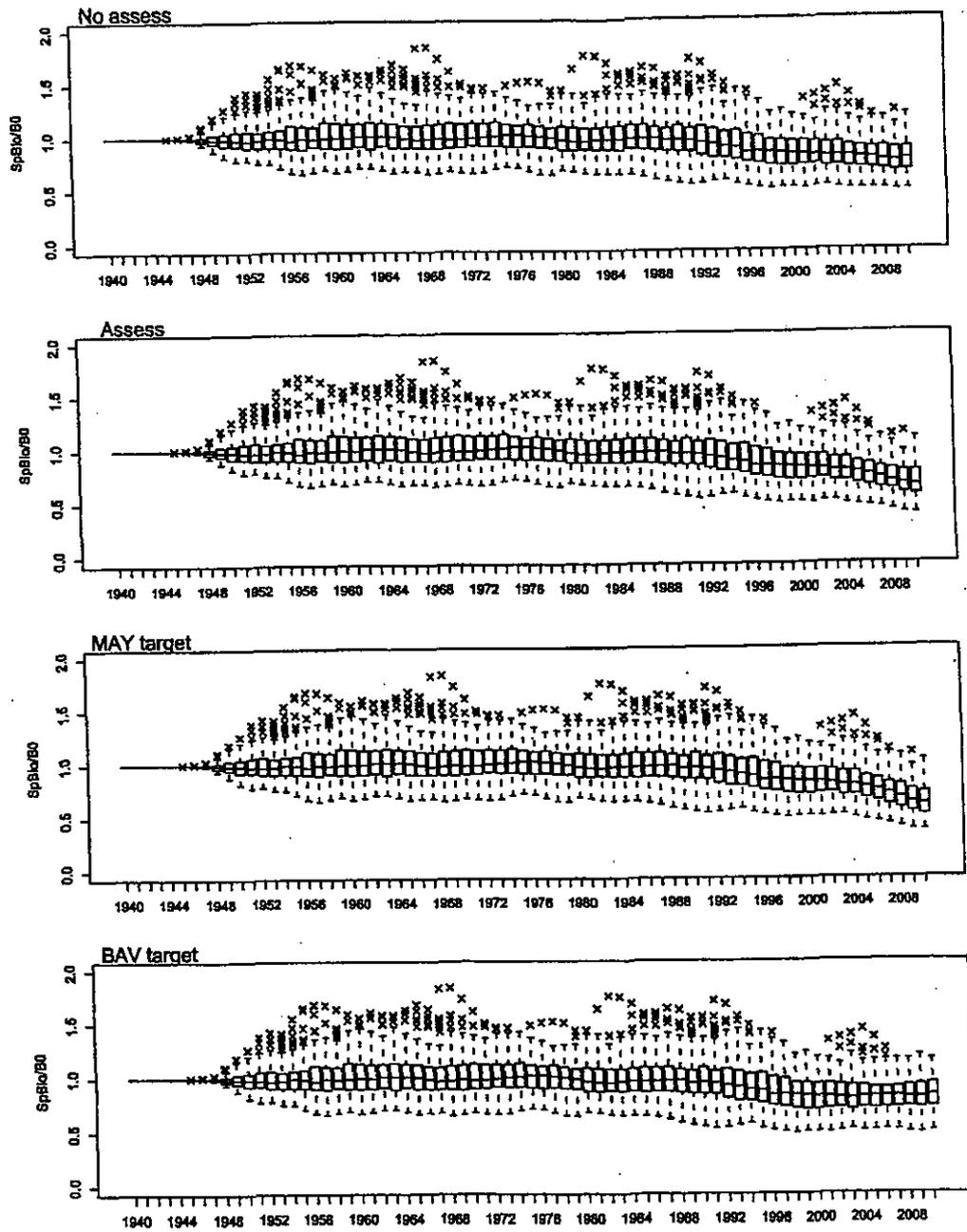


Figure 2: Box and whisker plots of the spawning biomass trajectories for hake ( $B_\theta$  HIGH) under the four management strategies. The horizontal line shows the median and the box shows the 25<sup>th</sup> to 75<sup>th</sup> percentiles ( $B_t/B_\theta$ ).

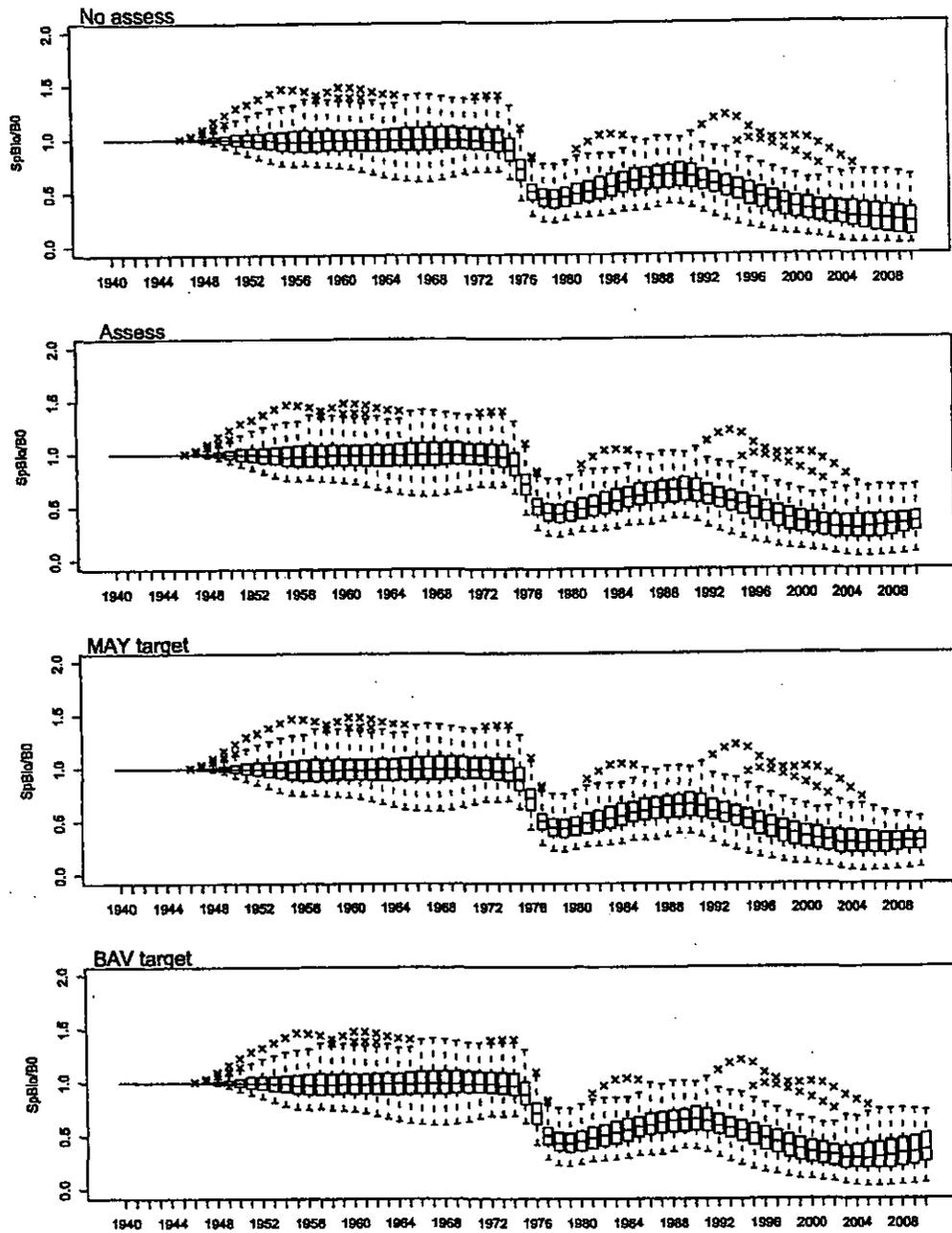


Figure 3: Box and whisker plots of the spawning biomass trajectories for ling ( $B_0$  LOW) under the four management strategies. The horizontal line shows the median and the box shows the 25<sup>th</sup> to 75<sup>th</sup> percentiles ( $B_i/B_0$ ).

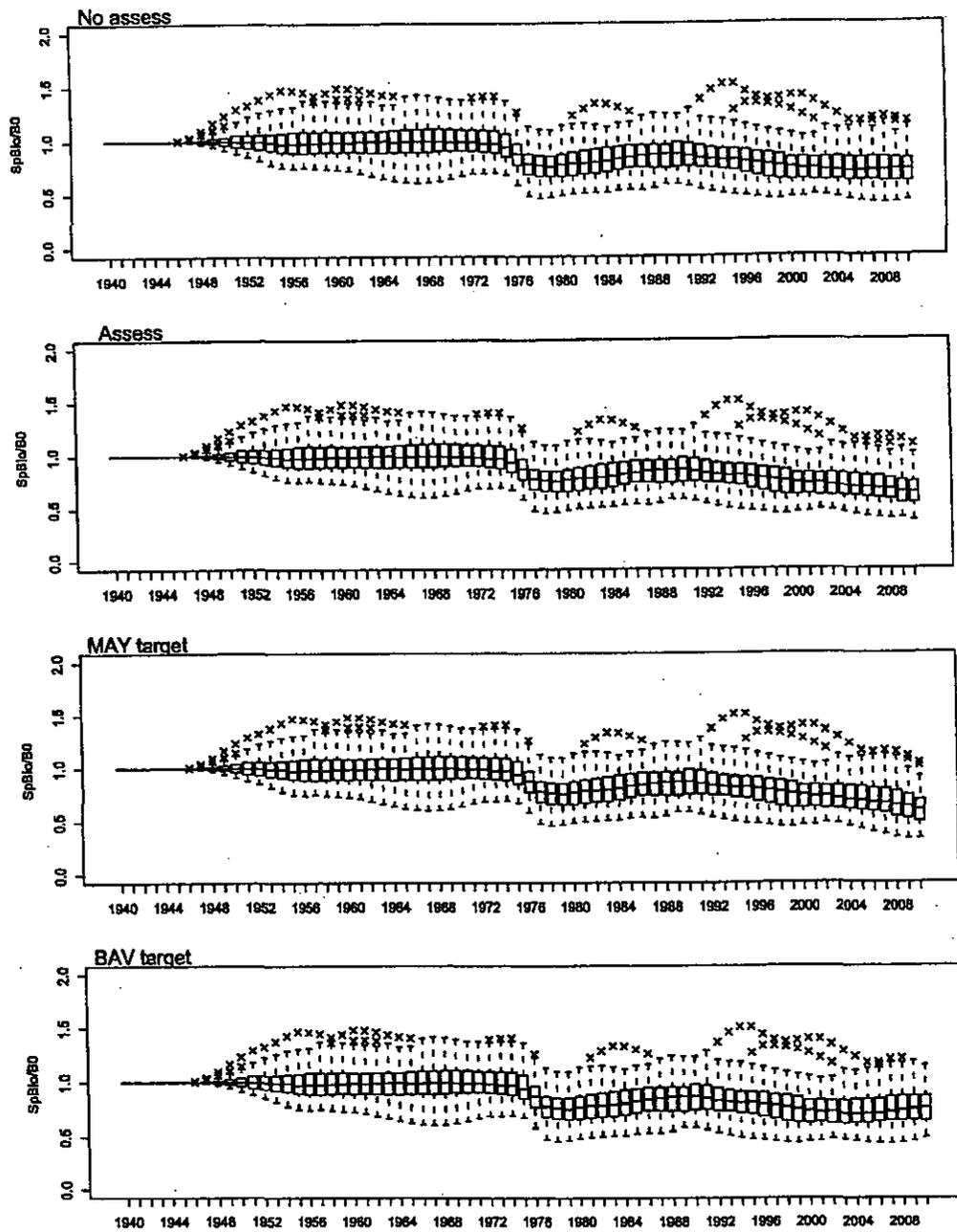


Figure 4: Box and whisker plots of the spawning biomass trajectories for ling ( $B_p$  HIGH) under the four management strategies. The horizontal line shows the median and the box shows the 25<sup>th</sup> to 75<sup>th</sup> percentiles ( $B_t/B_0$ ).

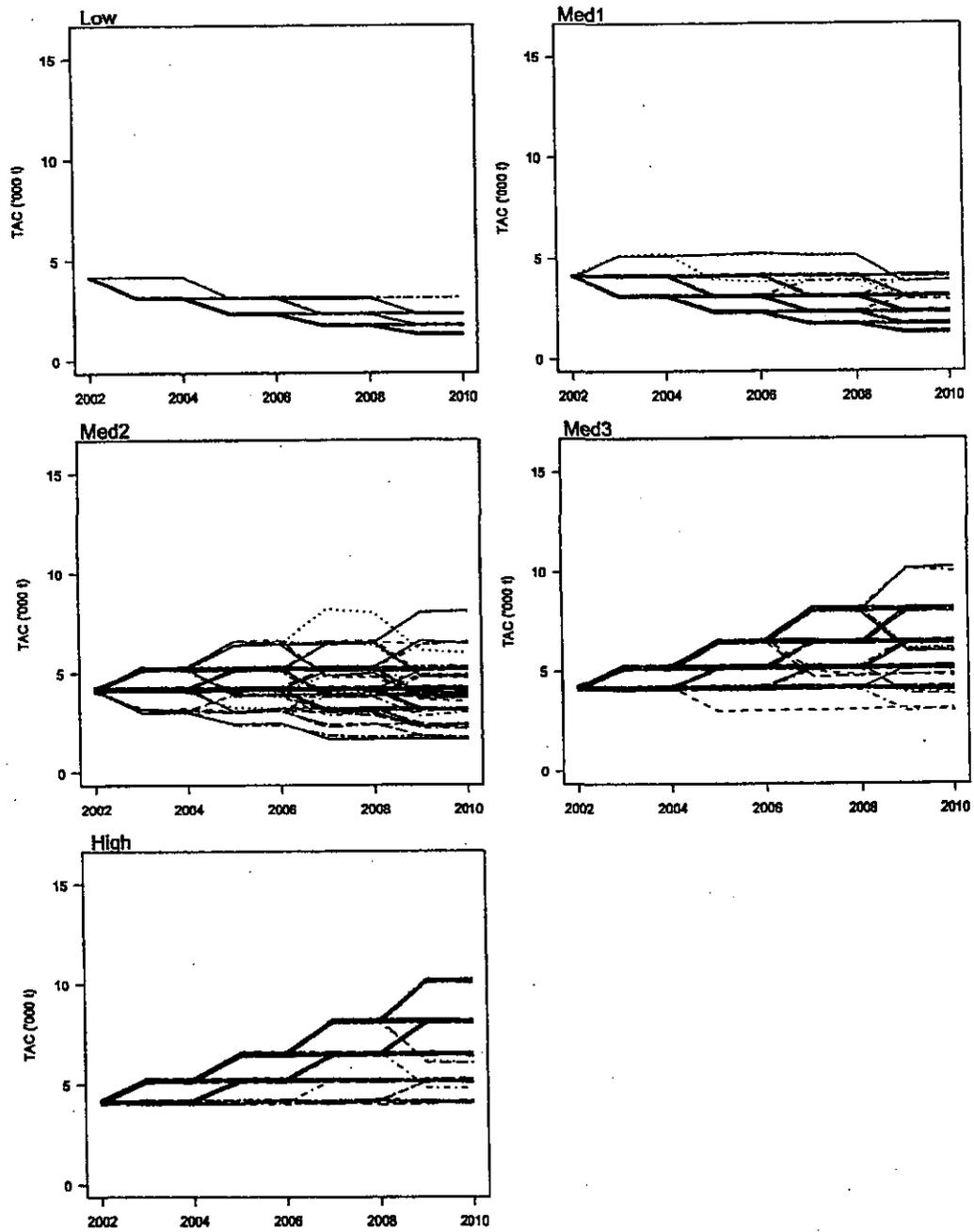
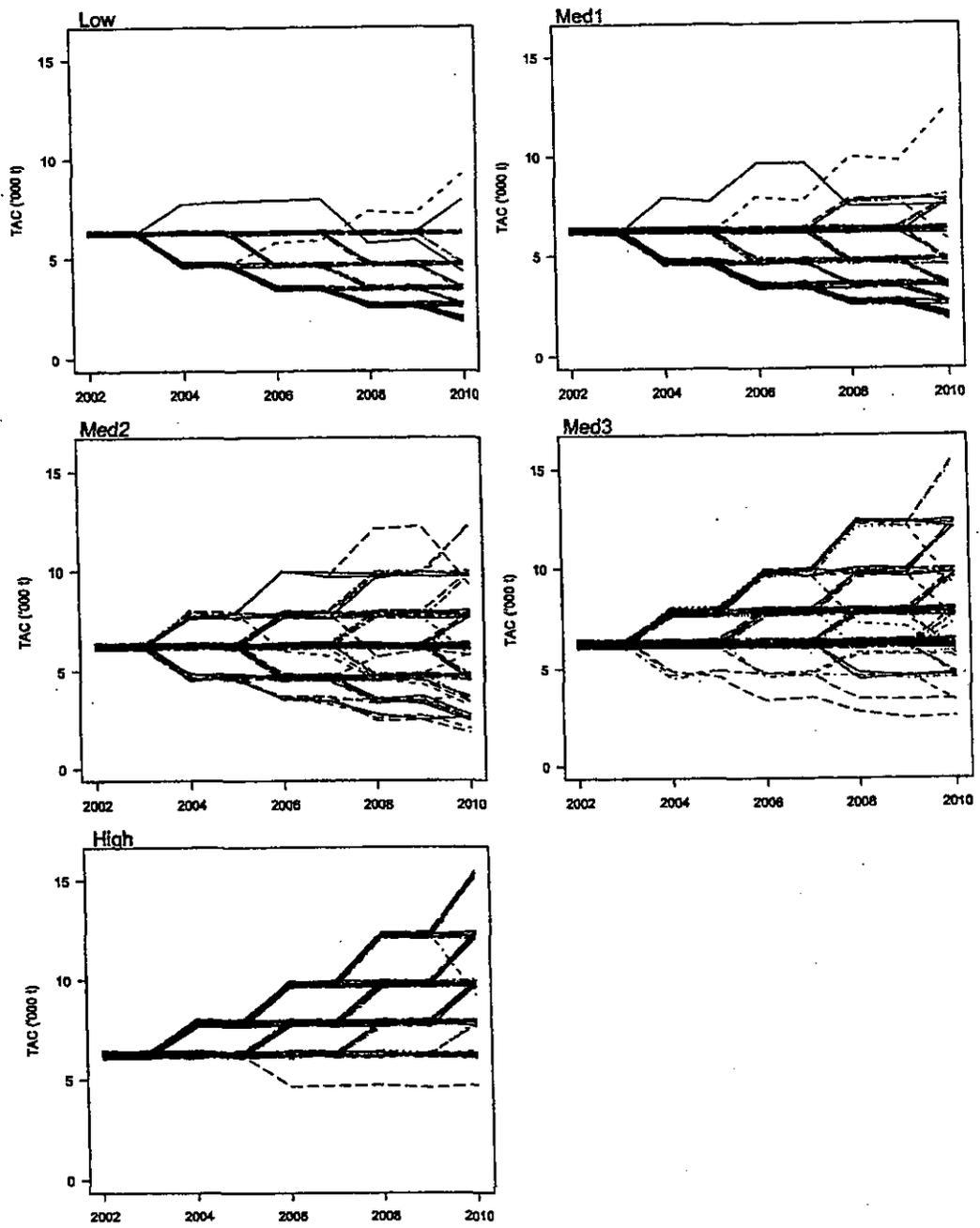


Figure 5: TAC trajectories for hake at the five levels of  $B_0$  when managed under the ASSESS strategy. The y values have been jittered to show the most common trajectories.



**Figure 6: TAC trajectories for ling at the five levels of  $B$ , when managed under the ASSESS strategy. The y values have been jittered to show the most common trajectories.**

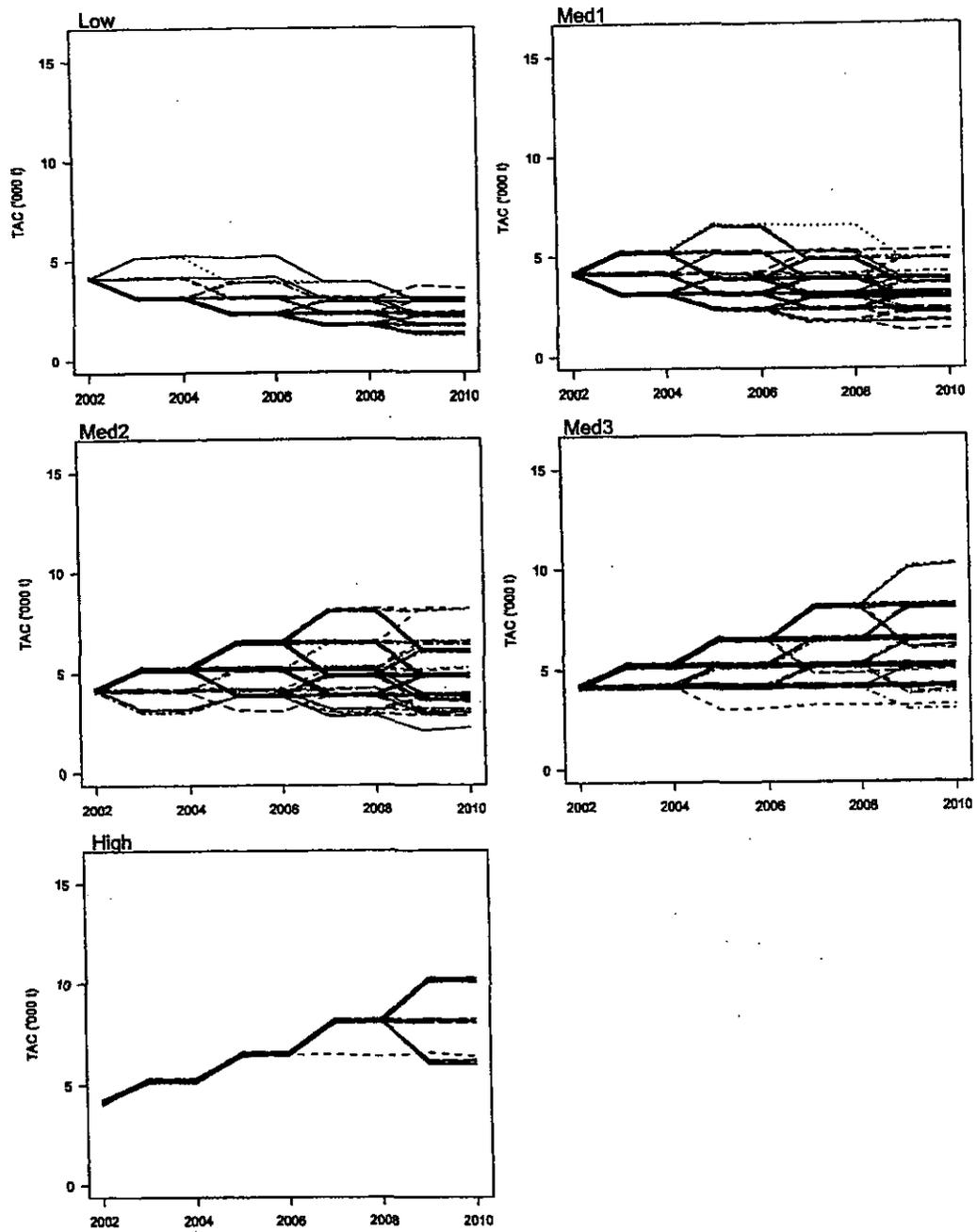


Figure 7: TAC trajectories for hake at the five levels of  $B_0$  when managed under the MAY target strategy. The y values have been jittered to show the most common trajectories.

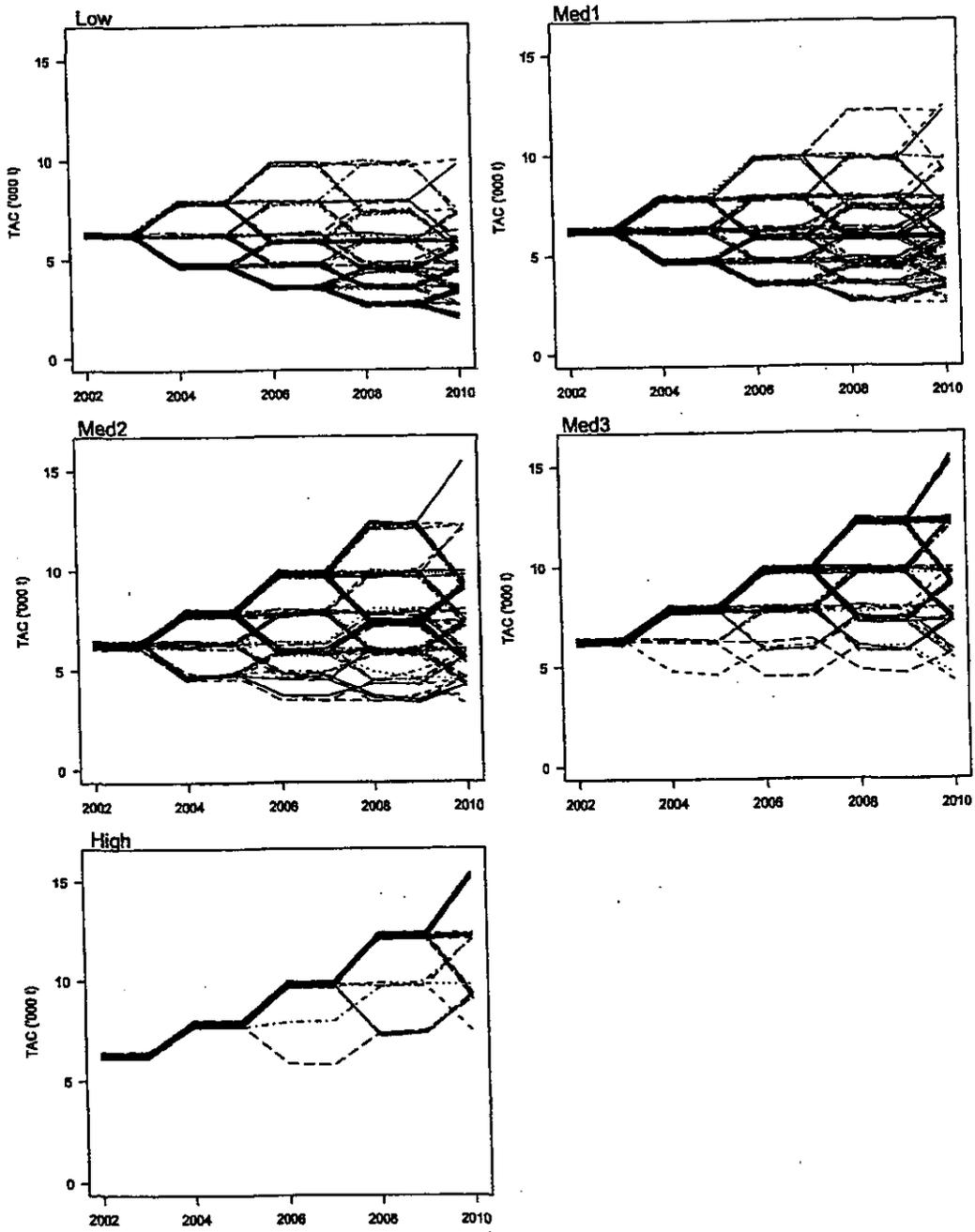
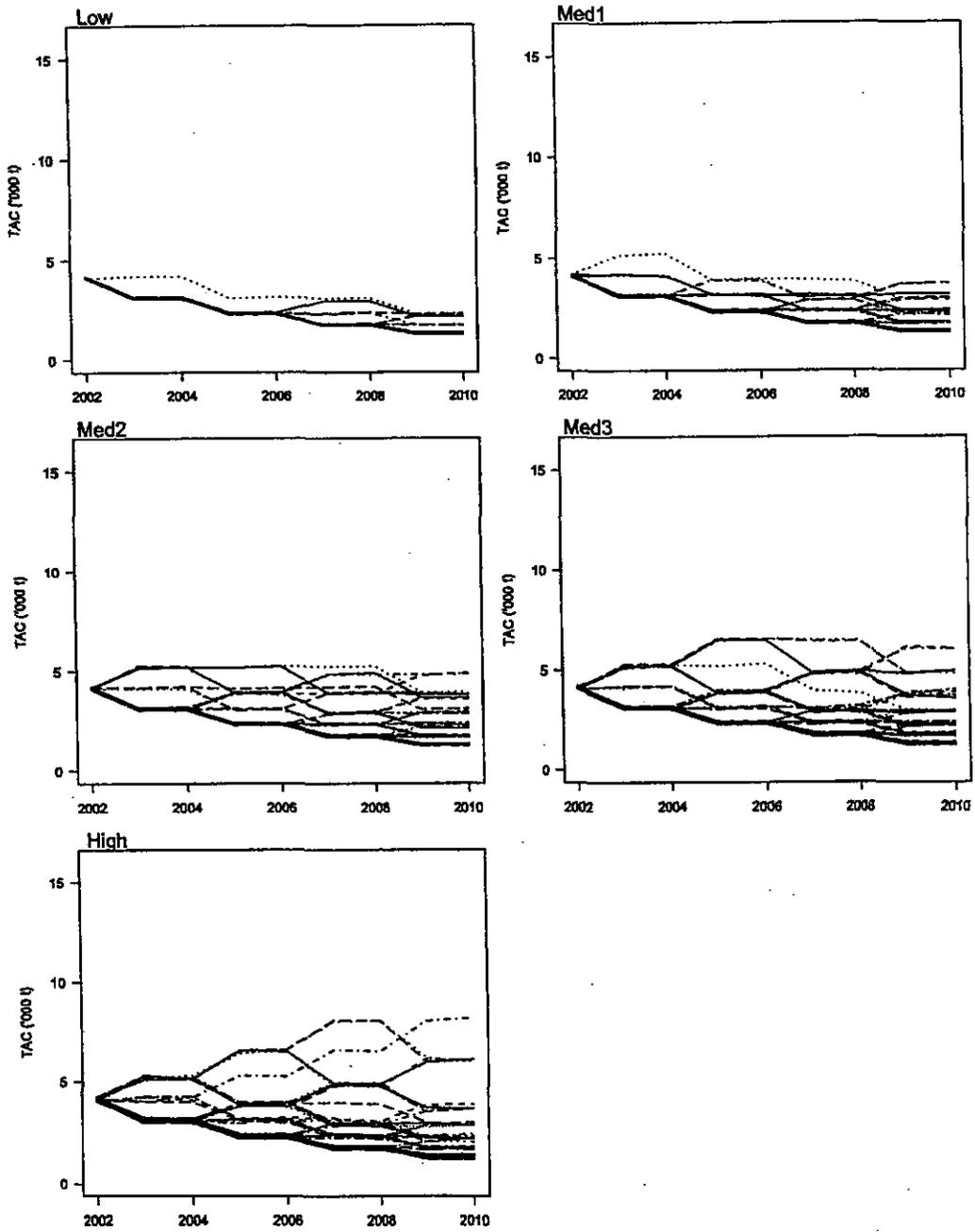


Figure 8: TAC trajectories for ling at the five levels of  $B_0$  when managed under the MAY target strategy. The y values have been jittered to show the most common trajectories.



**Figure 9: TAC trajectories for hake at the five levels of  $B_0$ , when managed under the BAV target strategy. The y values have been jittered to show the most common trajectories.**

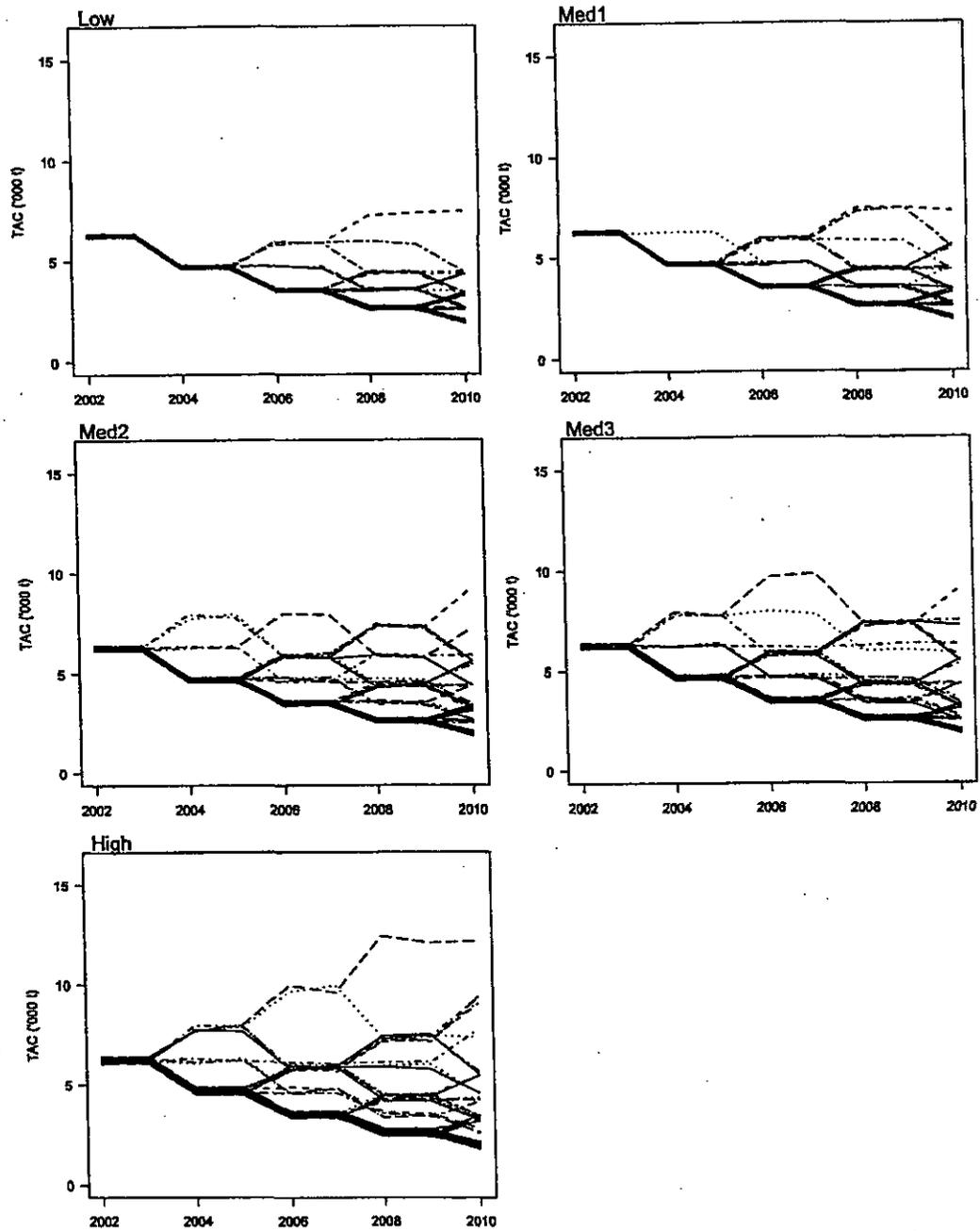


Figure 10: TAC trajectories for ling at the five levels of  $B_0$  when managed under the BAV target strategy. The y values have been jittered to show the most common trajectories.

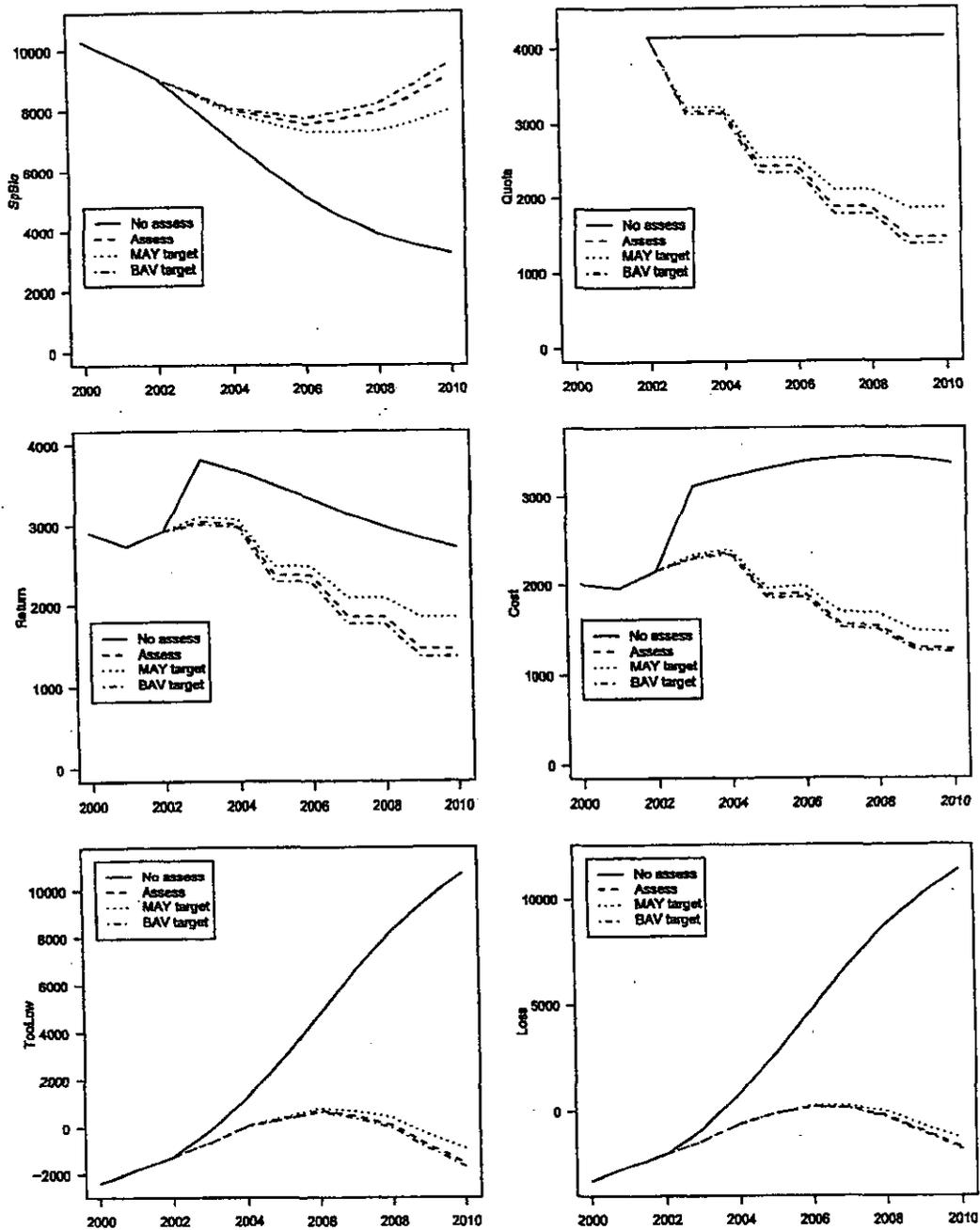


Figure 11: Mean trends in spawning biomass (SpBio), TAC (Quota), fishing return (Return), cost of fishing (cost), biological loss (TooLow), and total loss (loss) for hake ( $B_0$  LOW) under the four management strategies from 2000 to 2010.

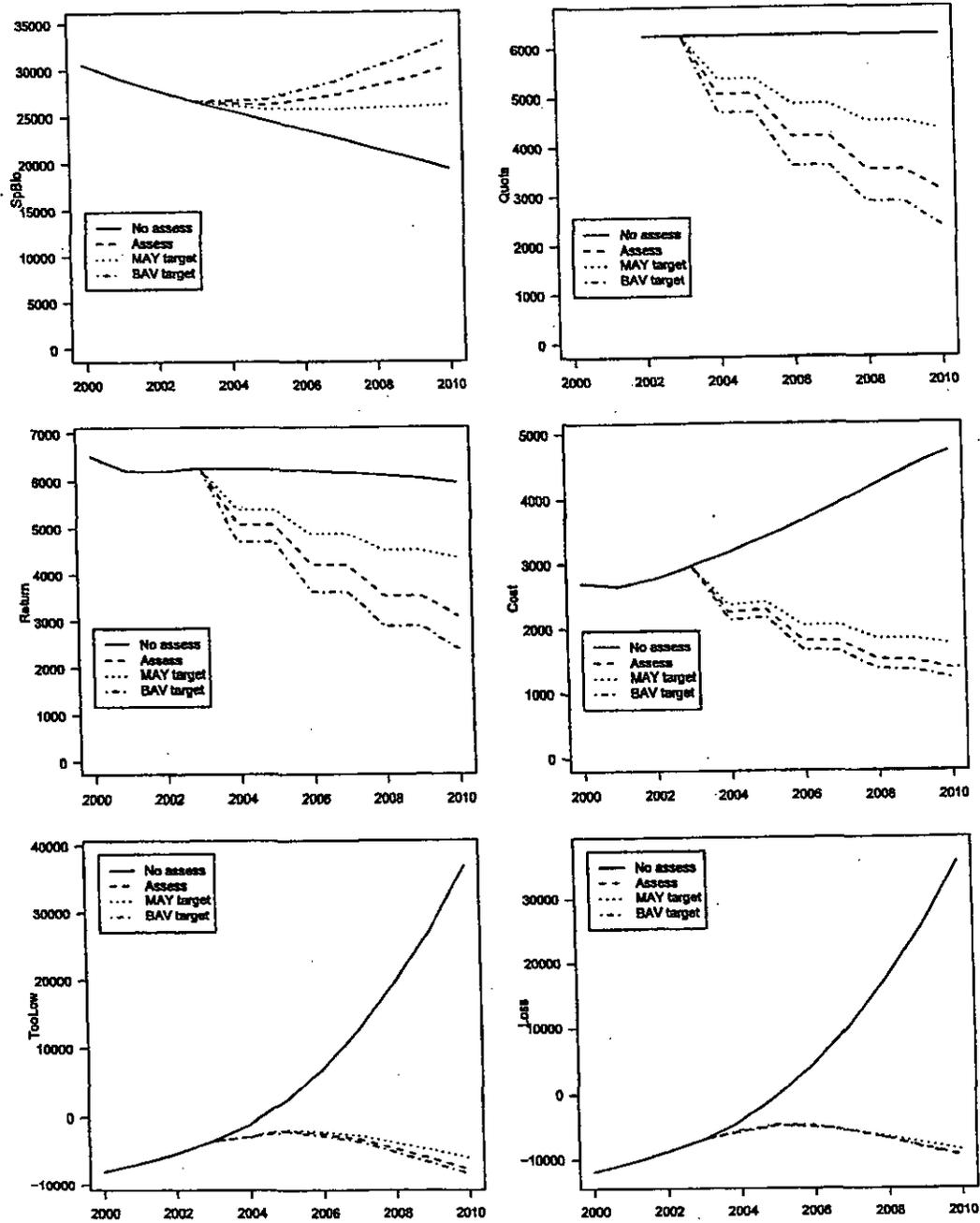


Figure 12: Mean trends in spawning biomass (SpBio), TAC (Quota), fishing return (Return), cost of fishing (cost), biological loss (TooLow), and total loss (loss) for ling ( $B_0$  LOW) under the four management strategies from 2000 to 2010.

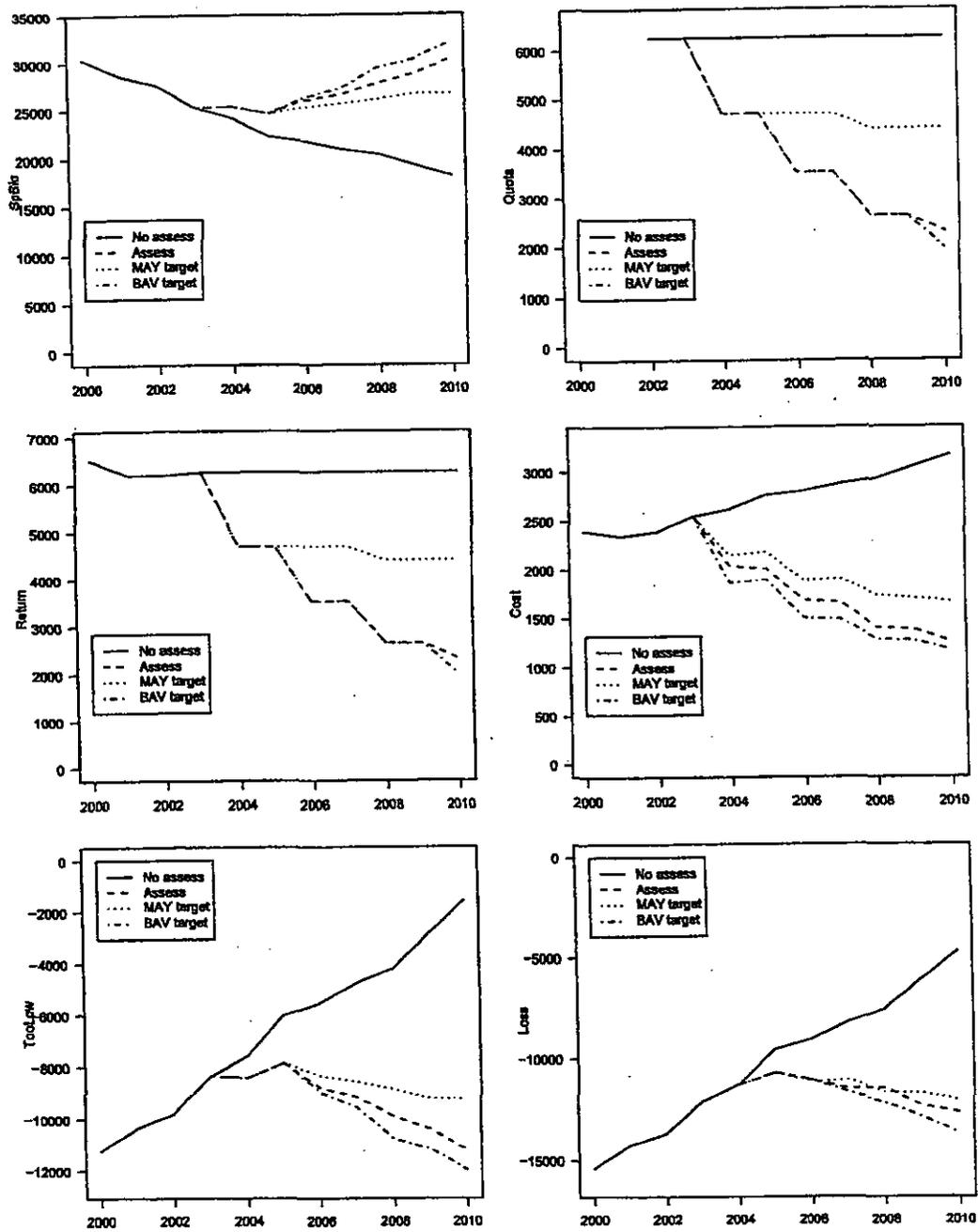


Figure 13: Median trends in spawning biomass (SpBio), TAC (Quota), fishing return (Return), cost of fishing (cost), biological loss (TooLow), and total loss (loss) for ling ( $B_0$  LOW) under the four management strategies from 2000 to 2010.

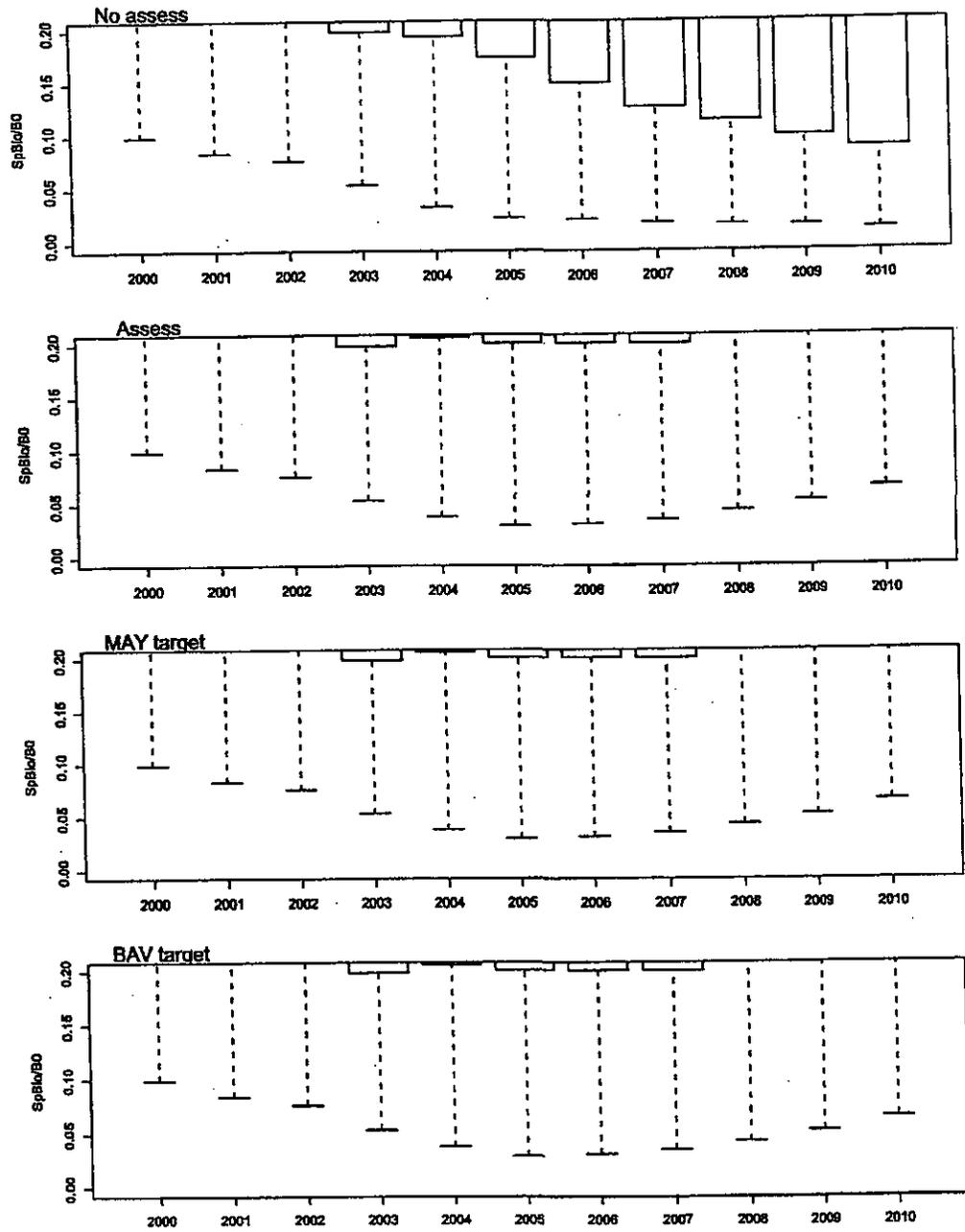


Figure 14: Box and whisker plots of the spawning biomass trajectories for ling ( $B_0$ , LOW) from 2000 to 2010 under the four management strategies. The plot is truncated at the threshold proportion (0.2) and the medians are not visible; the lower bound of the truncated boxes is the 25<sup>th</sup> percentile.

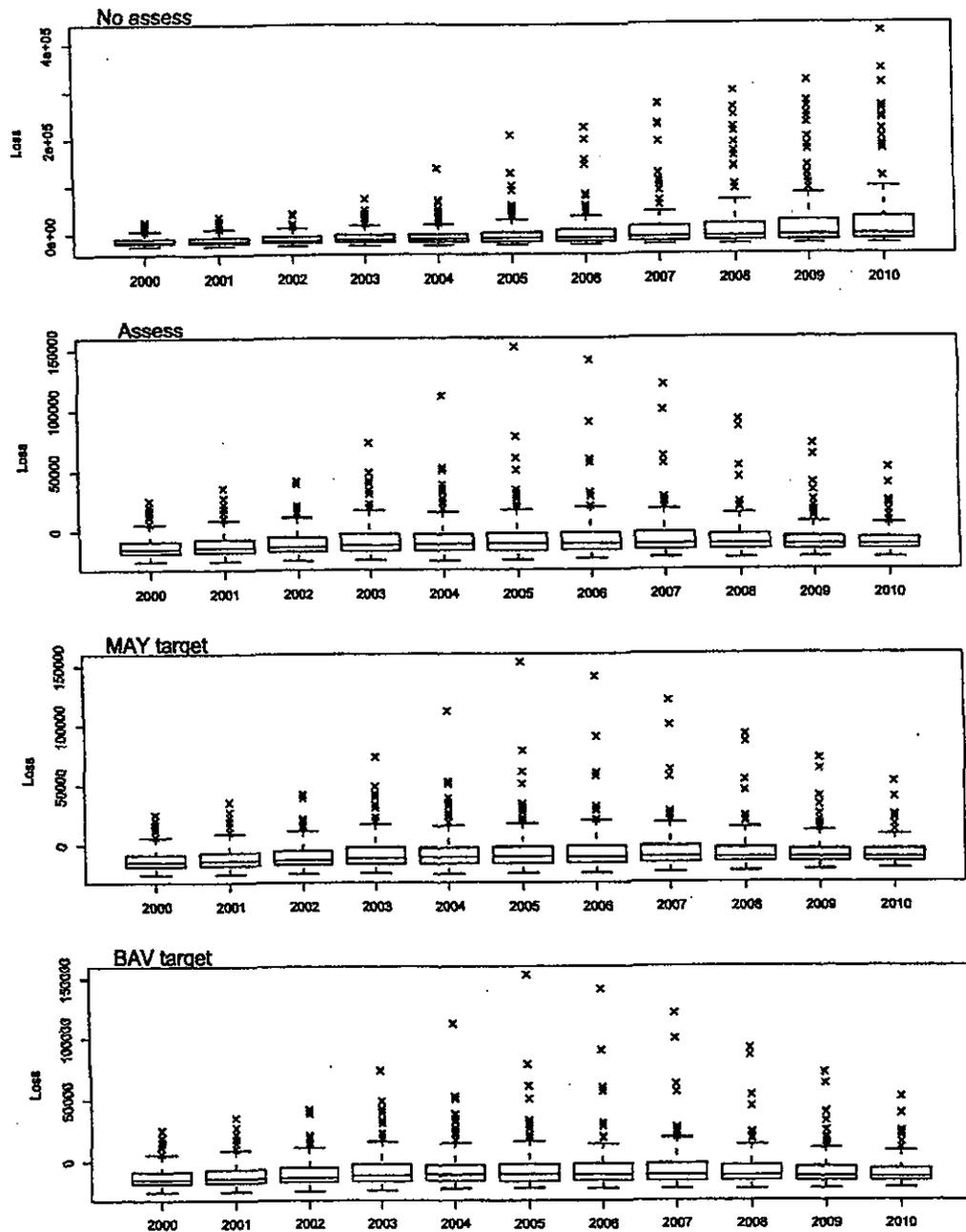


Figure 15: Box and whisker plots of the total loss for ling ( $B_0$  LOW) from 2000 to 2010 under the four management strategies. The horizontal line shows the median and the box shows the 25<sup>th</sup> to 75<sup>th</sup> percentiles.

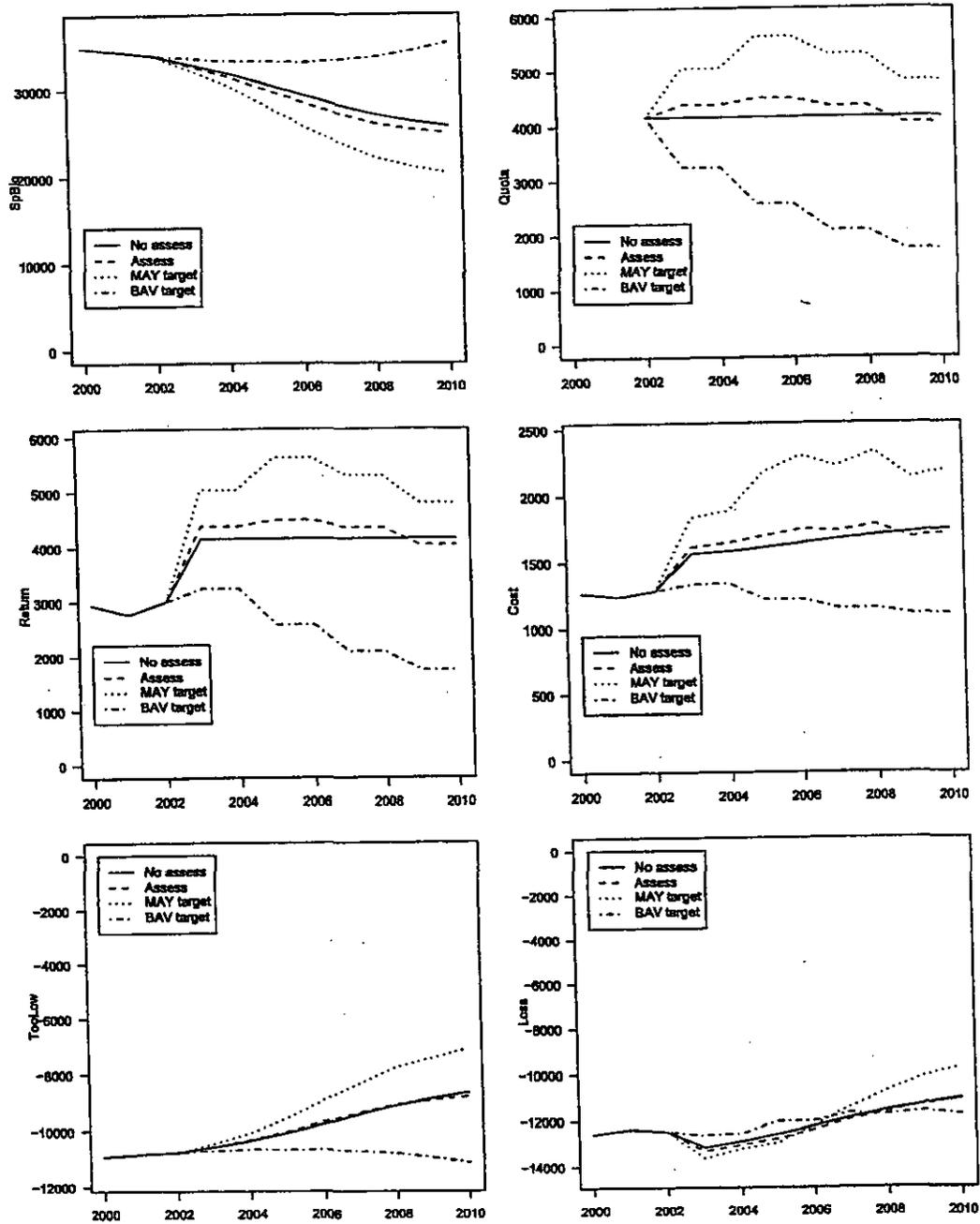


Figure 16: Mean trends in spawning biomass (SpBio), TAC (Quota), fishing return (Return), cost of fishing (cost), biological loss (TooLow), and total loss (loss) for hake ( $B_0$  MED2) under the four management strategies from 2000 to 2010.

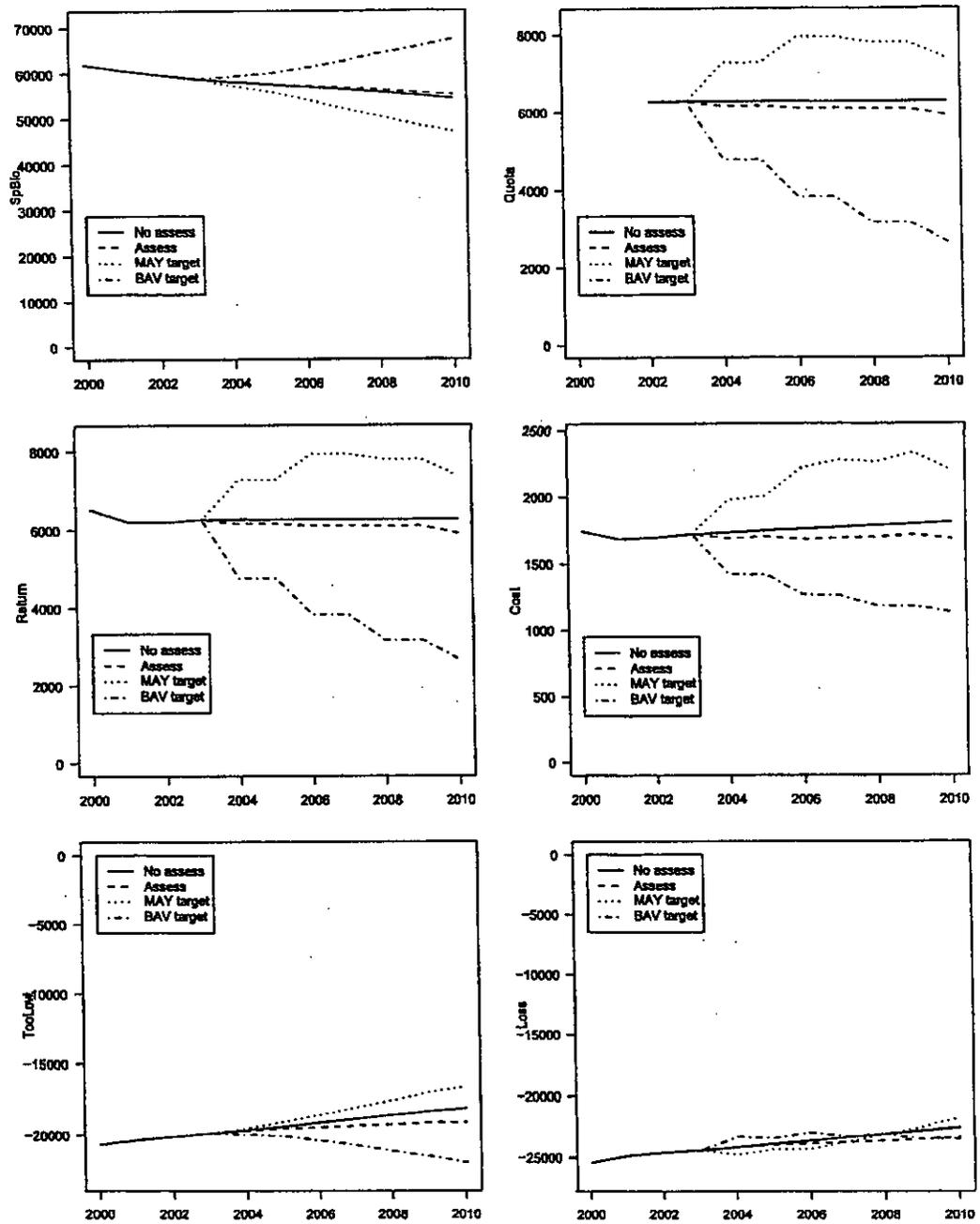


Figure 17: Mean trends in spawning biomass (SpBio), TAC (Quota), fishing return (Return), cost of fishing (cost), biological loss (TooLow), and total loss (loss) for ling ( $B_0$  MED2) under the four management strategies from 2000 to 2010.

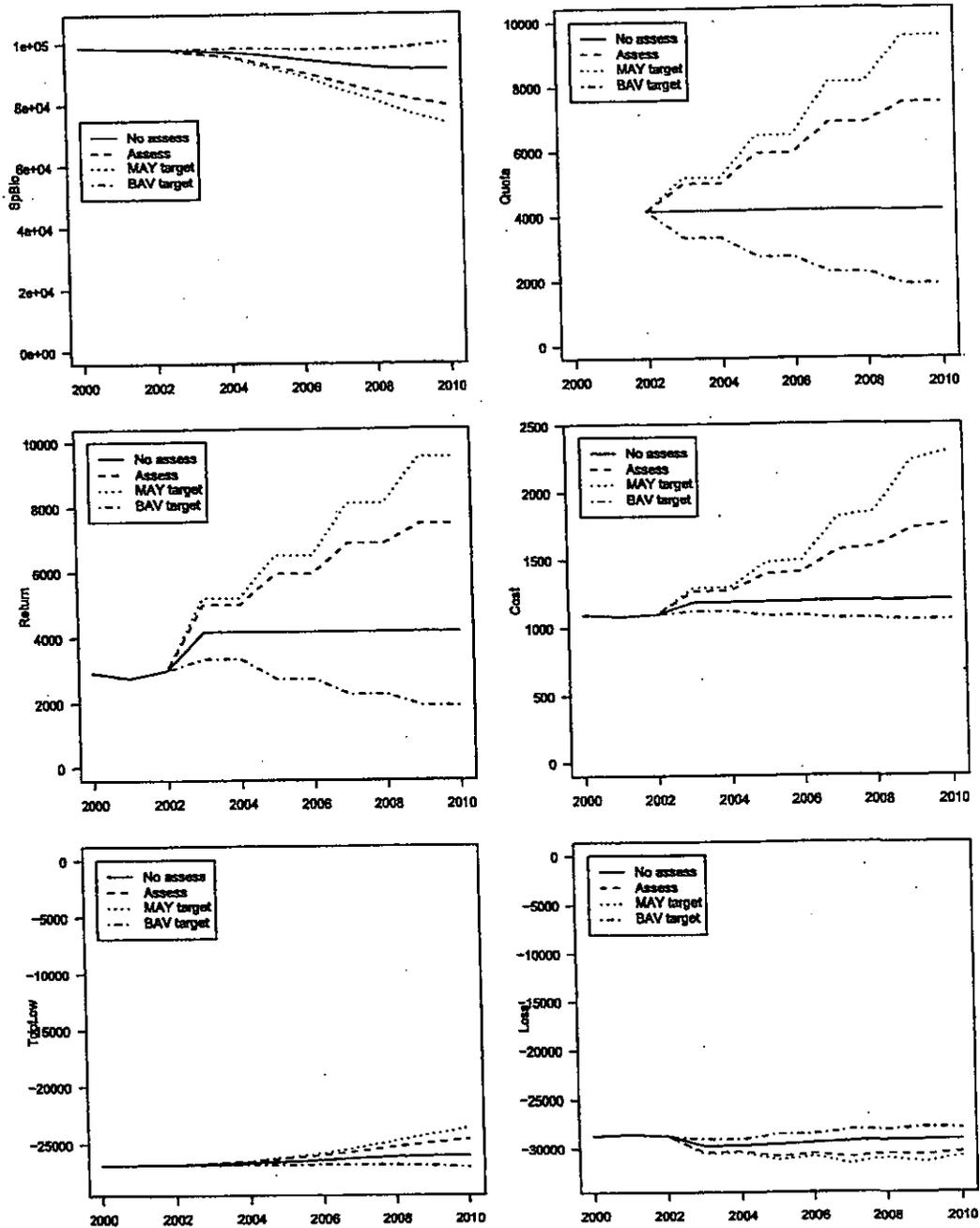


Figure 18: Mean trends in spawning biomass (SpBio), TAC (Quota), fishing return (Return), cost of fishing (cost), biological loss (TooLow), and total loss (loss) for hake ( $B_0$  HIGH) under the four management strategies from 2000 to 2010.

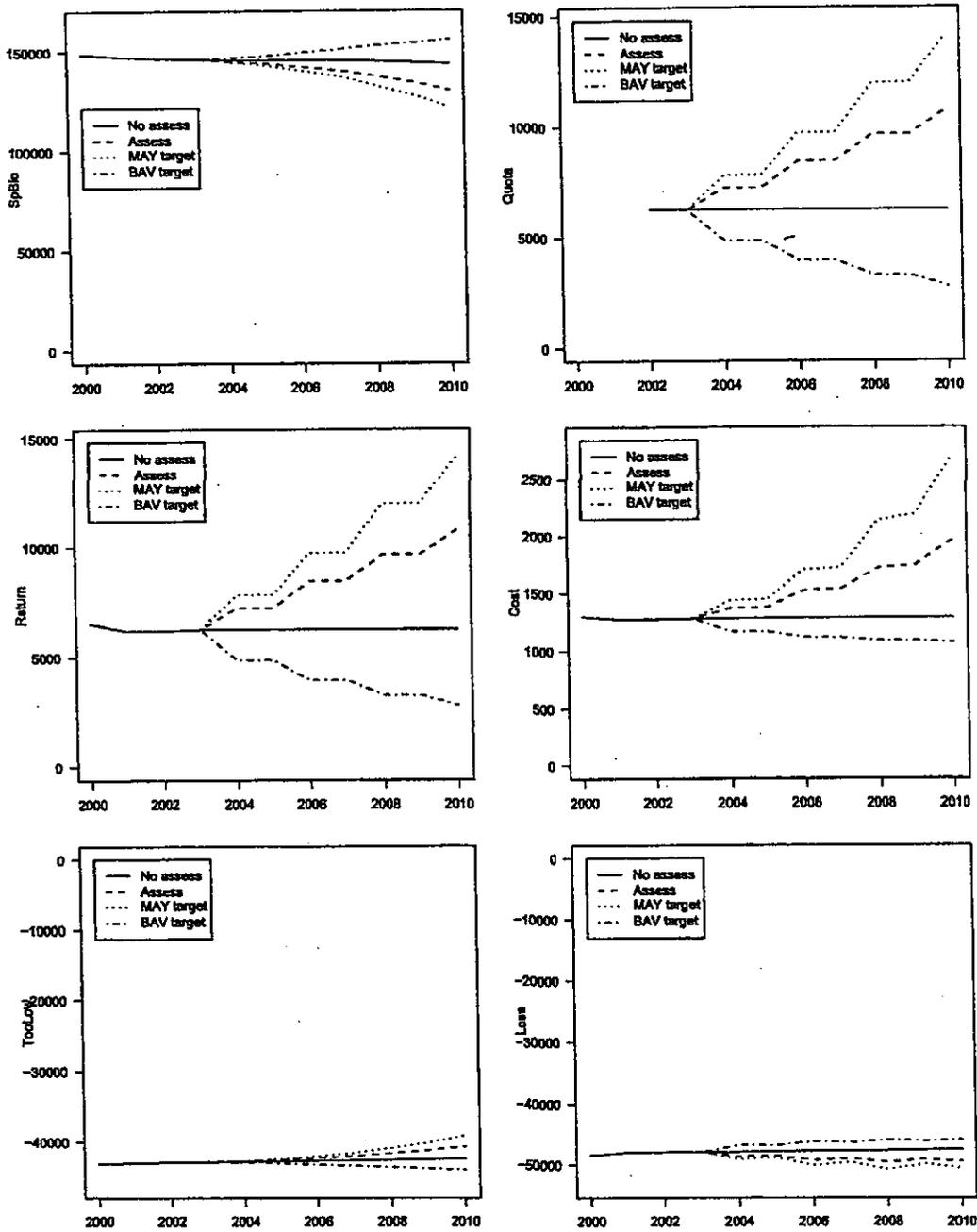


Figure 19: Mean trends in spawning biomass (SpBio), TAC (Quota), fishing return (Return), cost of fishing (cost), biological loss (TooLow), and total loss (loss) for ling ( $B_0$  HIGH) under the four management strategies from 2000 to 2010.

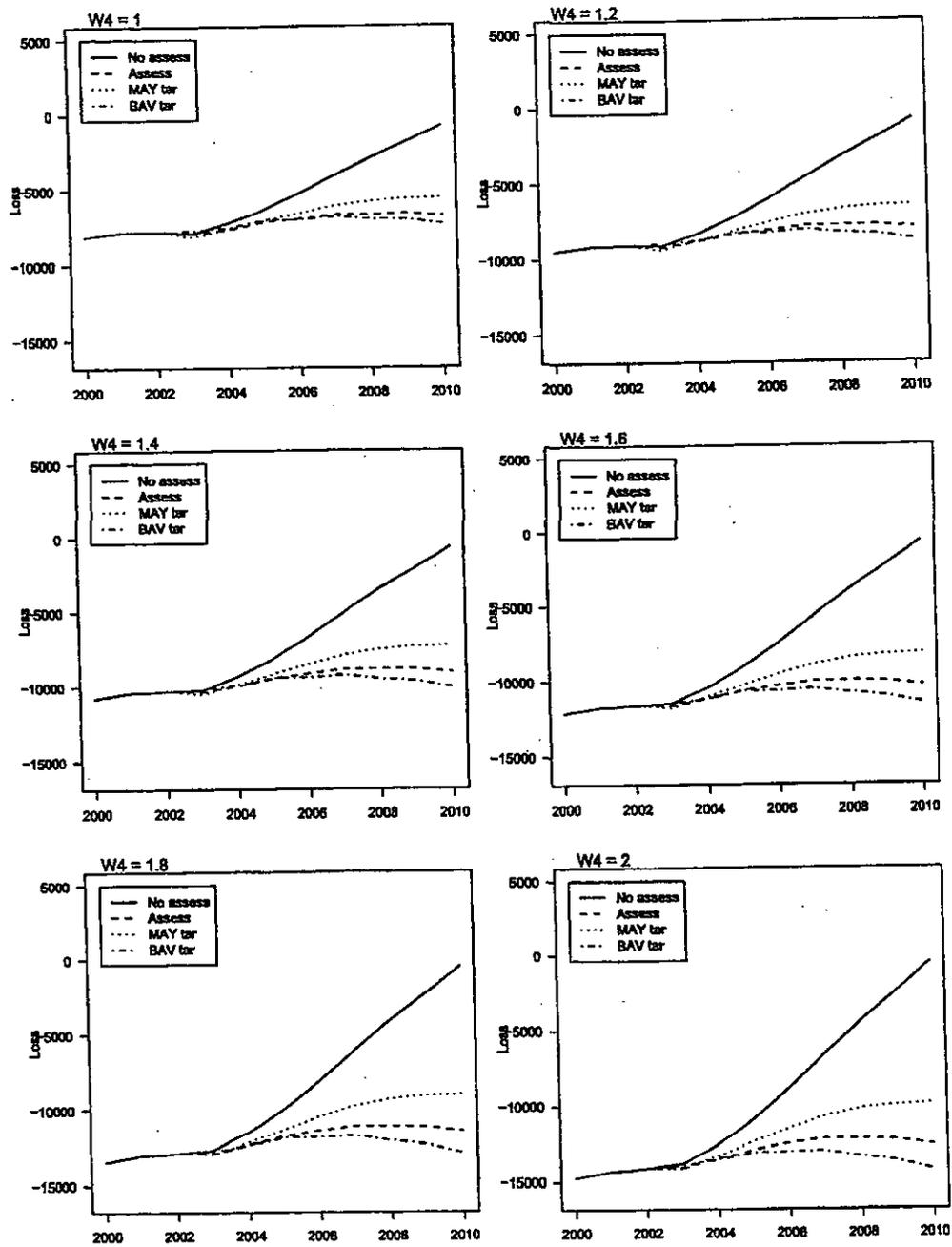


Figure 20: Total loss for hake ( $B_0$ MED1) with six different weightings on biological loss ( $w_4$ ) under the four management strategies from 2000 to 2010.

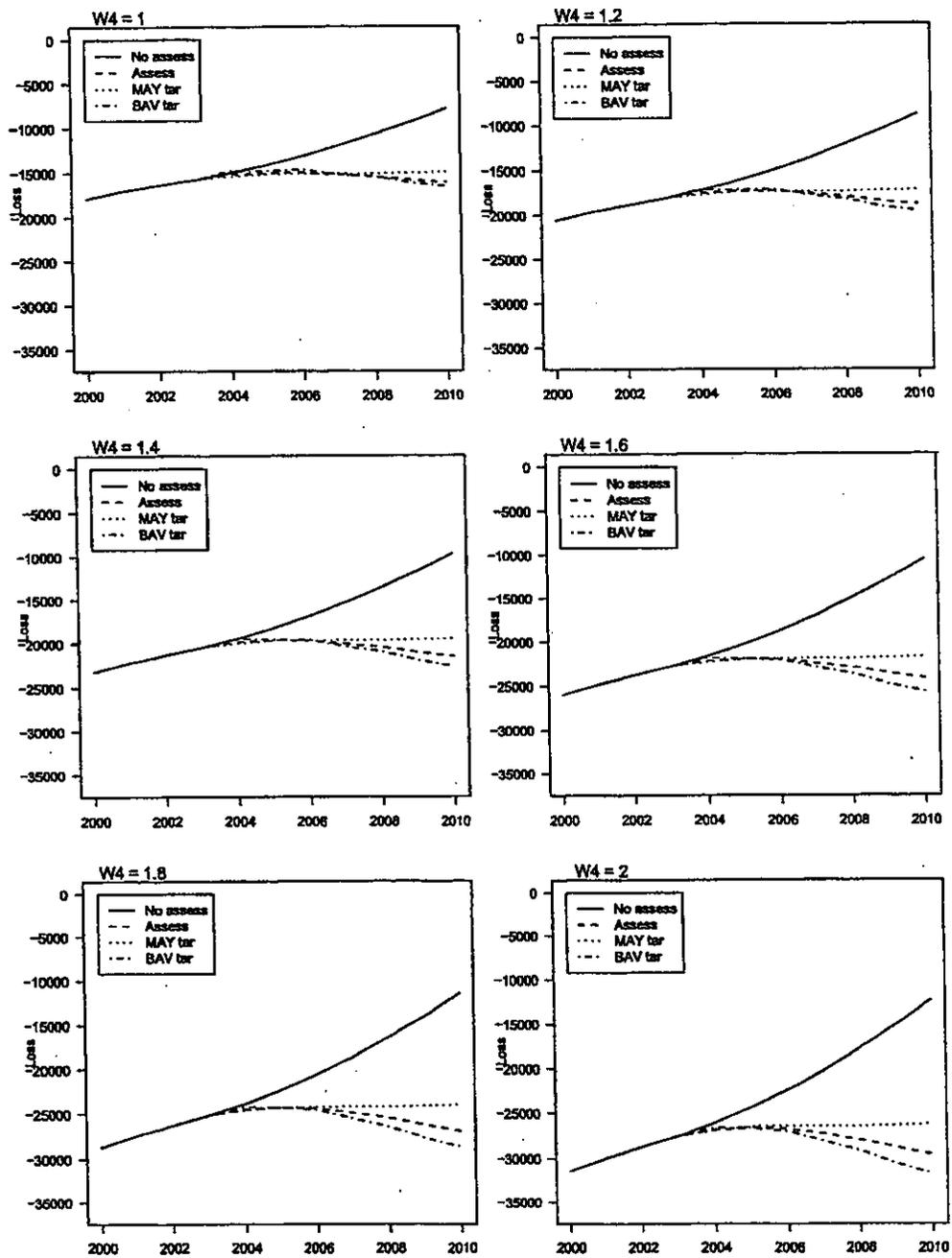
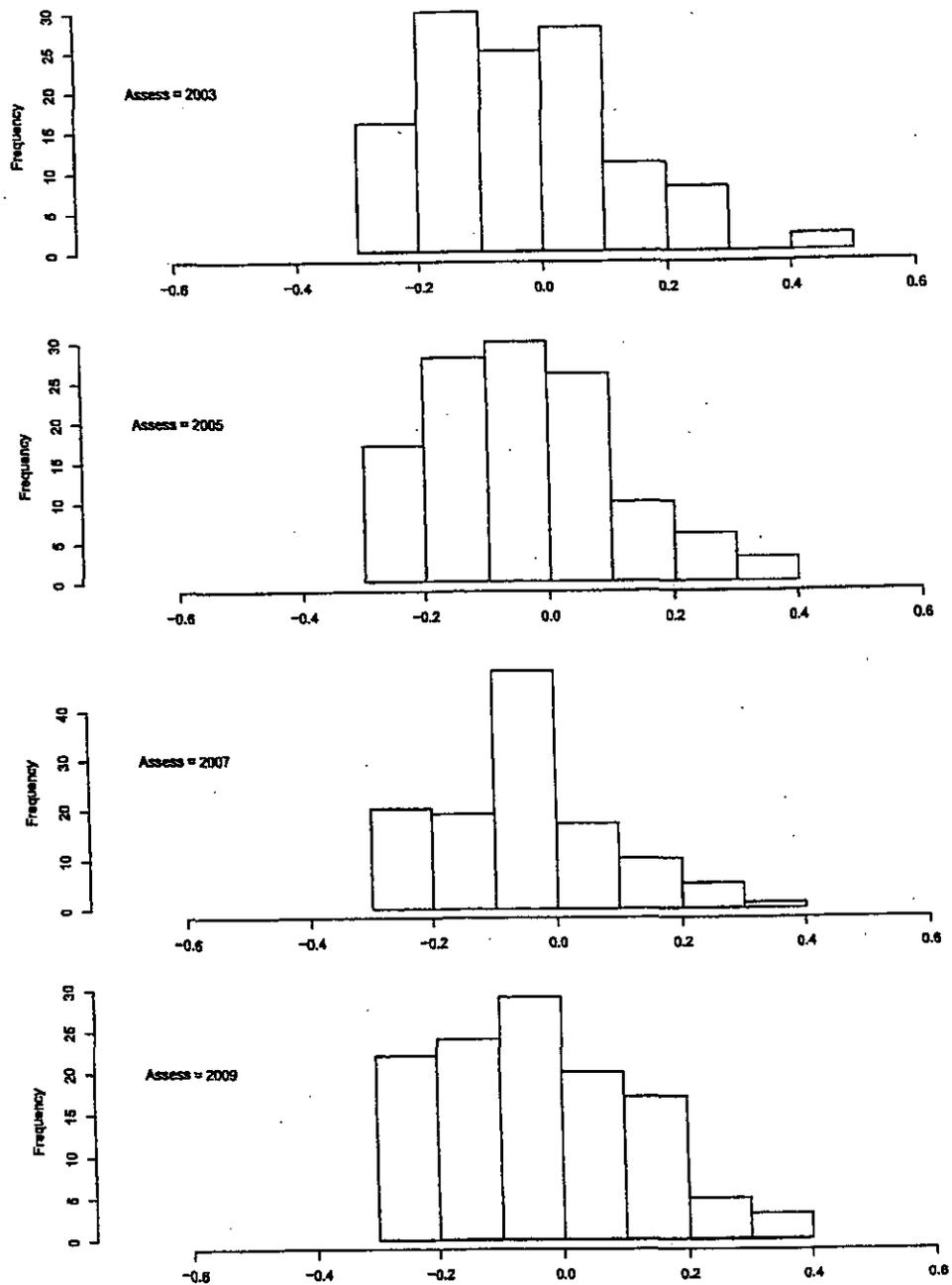
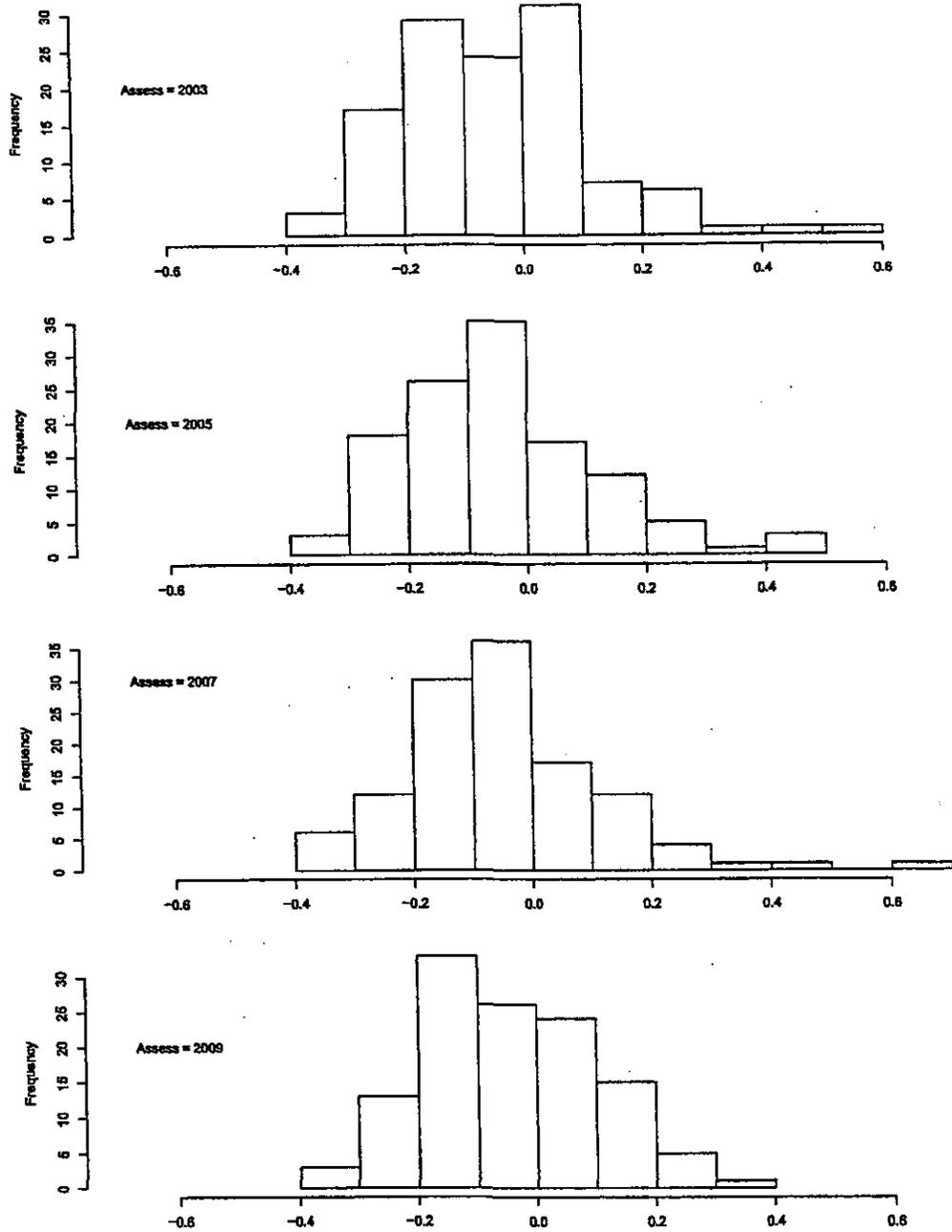


Figure 21: Total loss for ling ( $B_0$  MED1) with six different weightings on biological loss ( $w_b$ ) under the four management strategies from 2000 to 2010.



**Figure 22: Histograms of the relative error of estimating  $B_0$  for ling ( $B_0$  LOW) in each of the four assessment years (2003, 2005, 2007, and 2009).**



**Figure 23: Histograms of the relative error of estimating  $B_0$  for ling ( $B_0$  MED2) in each of the four assessment years (2003, 2005, 2007, and 2009).**

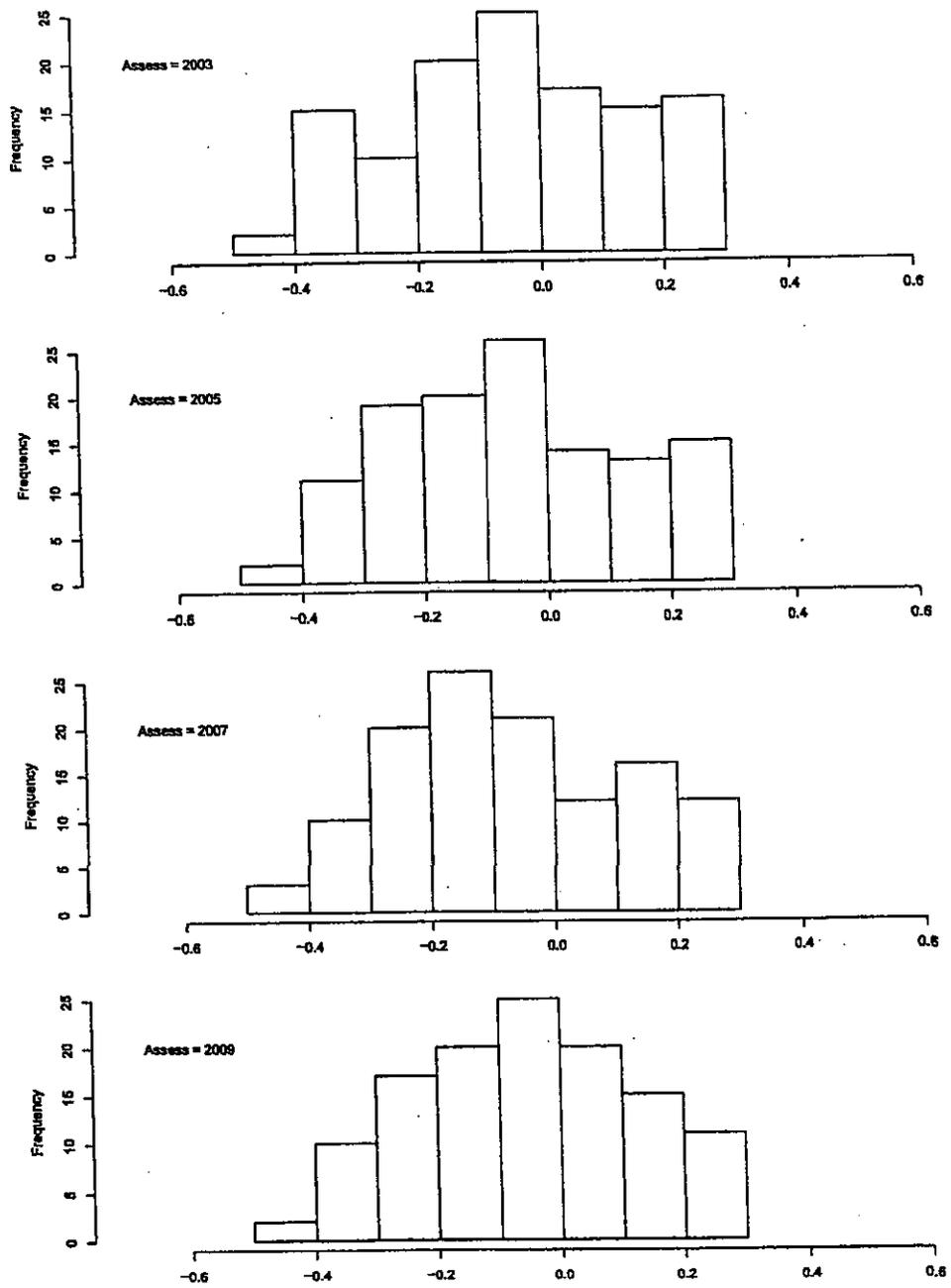
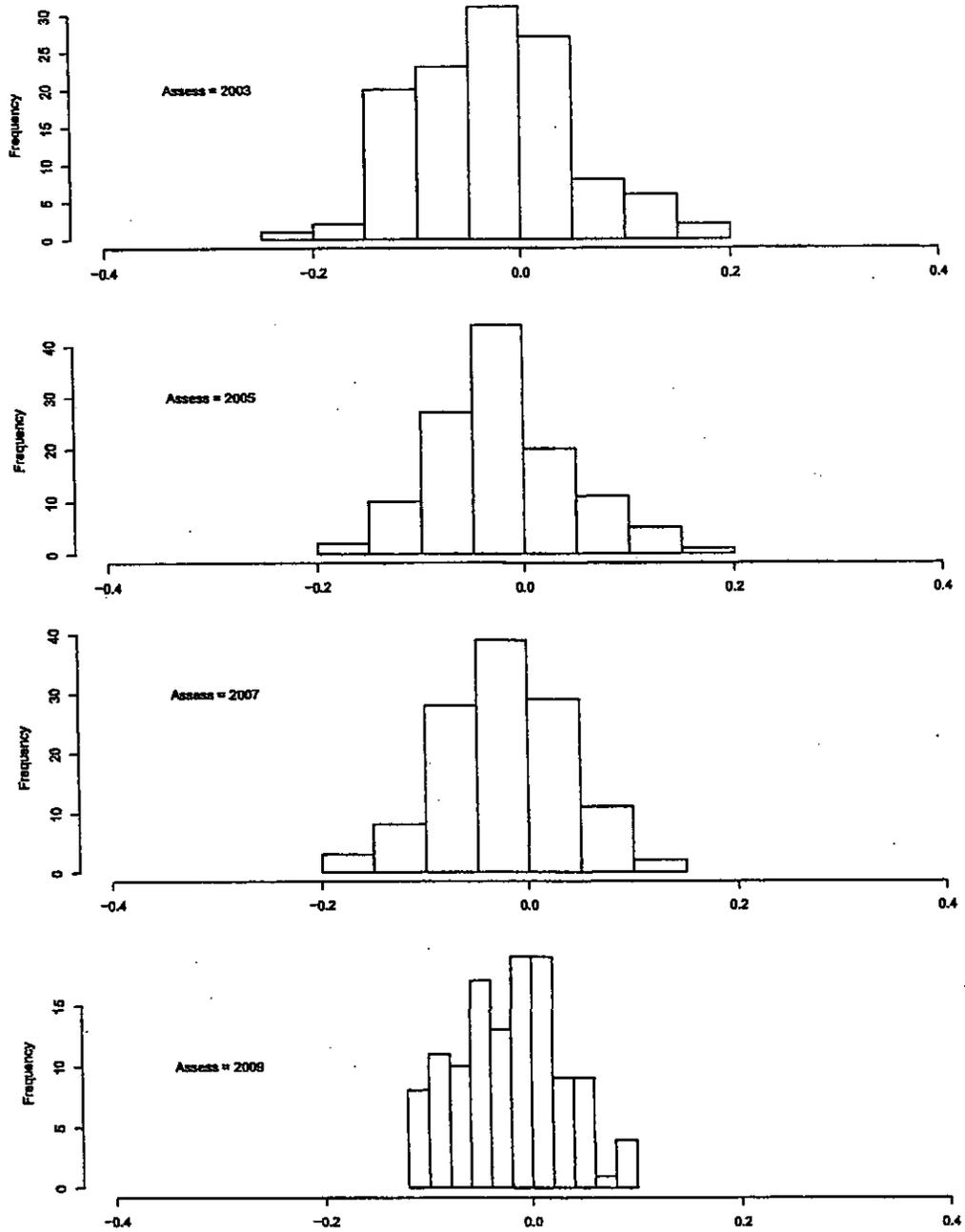
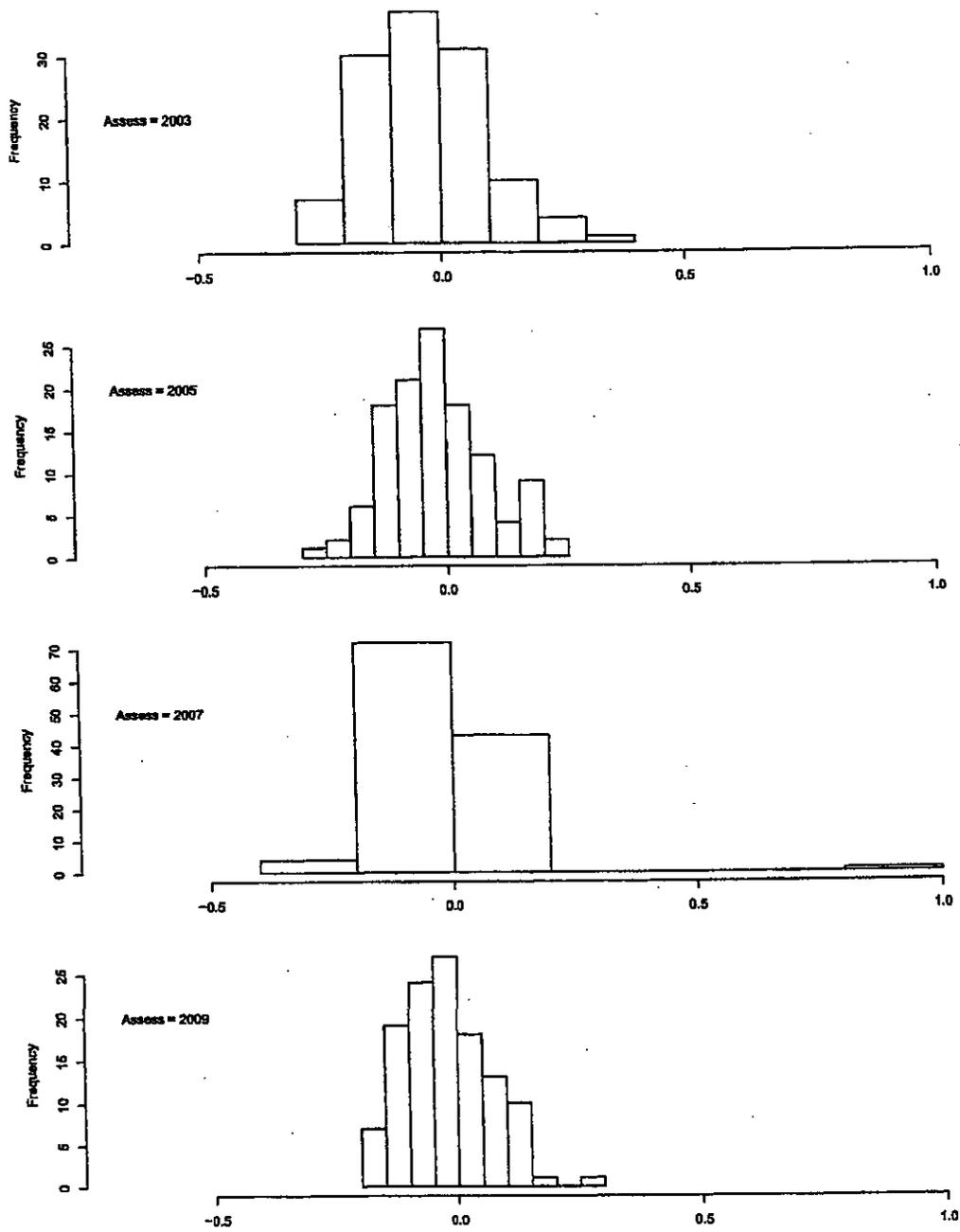


Figure 24: Histograms of the relative error of estimating  $B_0$  for ling ( $B_0$  HIGH) in each of the four assessment years (2003, 2005, 2007, and 2009).



**Figure 25: Histograms of the relative error of estimating  $B_{2002}$  for ling ( $B_{\theta}$  LOW) in each of the four assessment years (2003, 2005, 2007, and 2009).**



**Figure 26: Histograms of the relative error of estimating  $B_{2002}$  for ling ( $B_{\theta}$  MED2) in each of the four assessment years (2003, 2005, 2007, and 2009).**

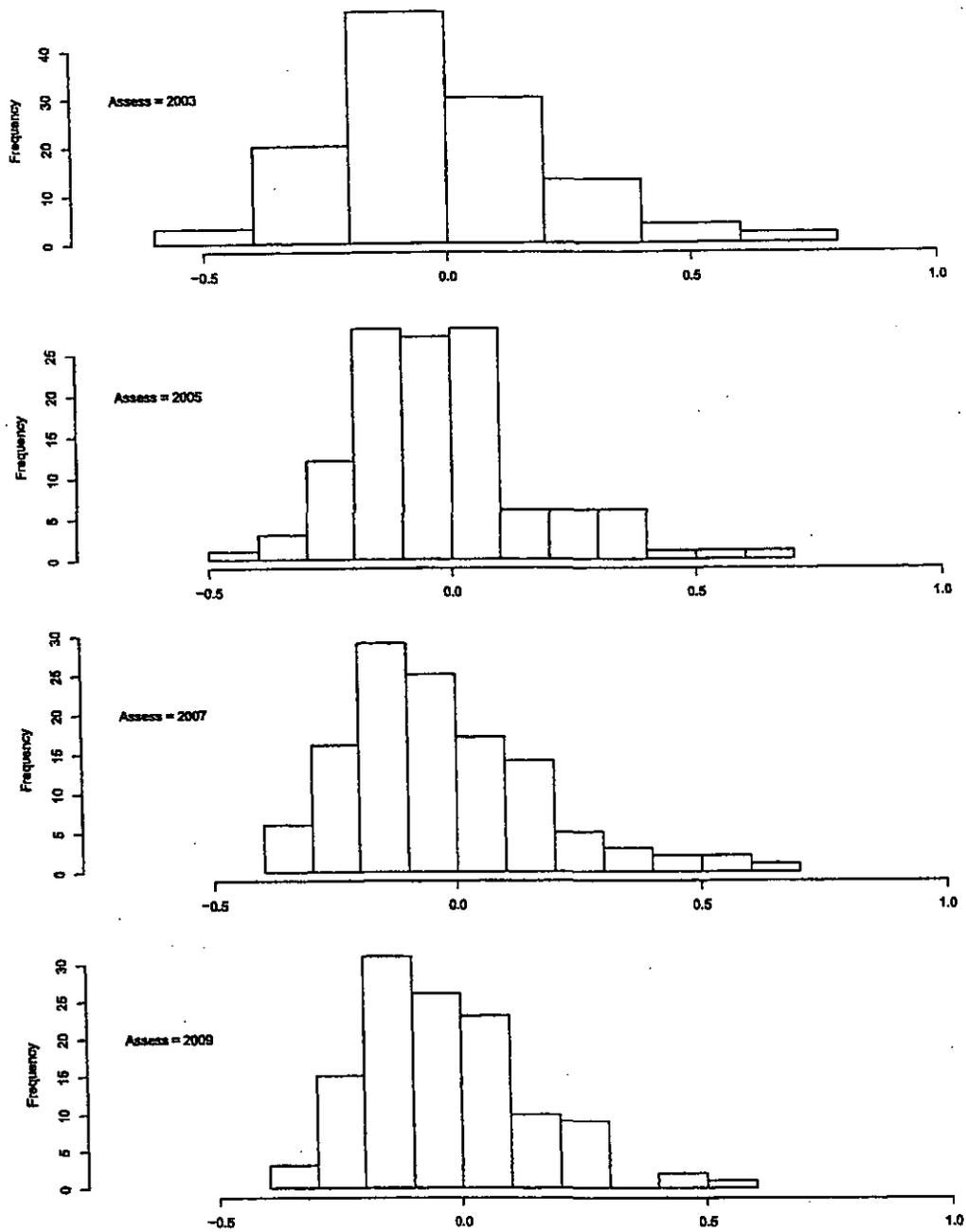


Figure 27: Histograms of the relative error of estimating  $B_{2002}$  for ling ( $B_0$  HIGH) in each of the four assessment years (2003, 2005, 2007, and 2009).

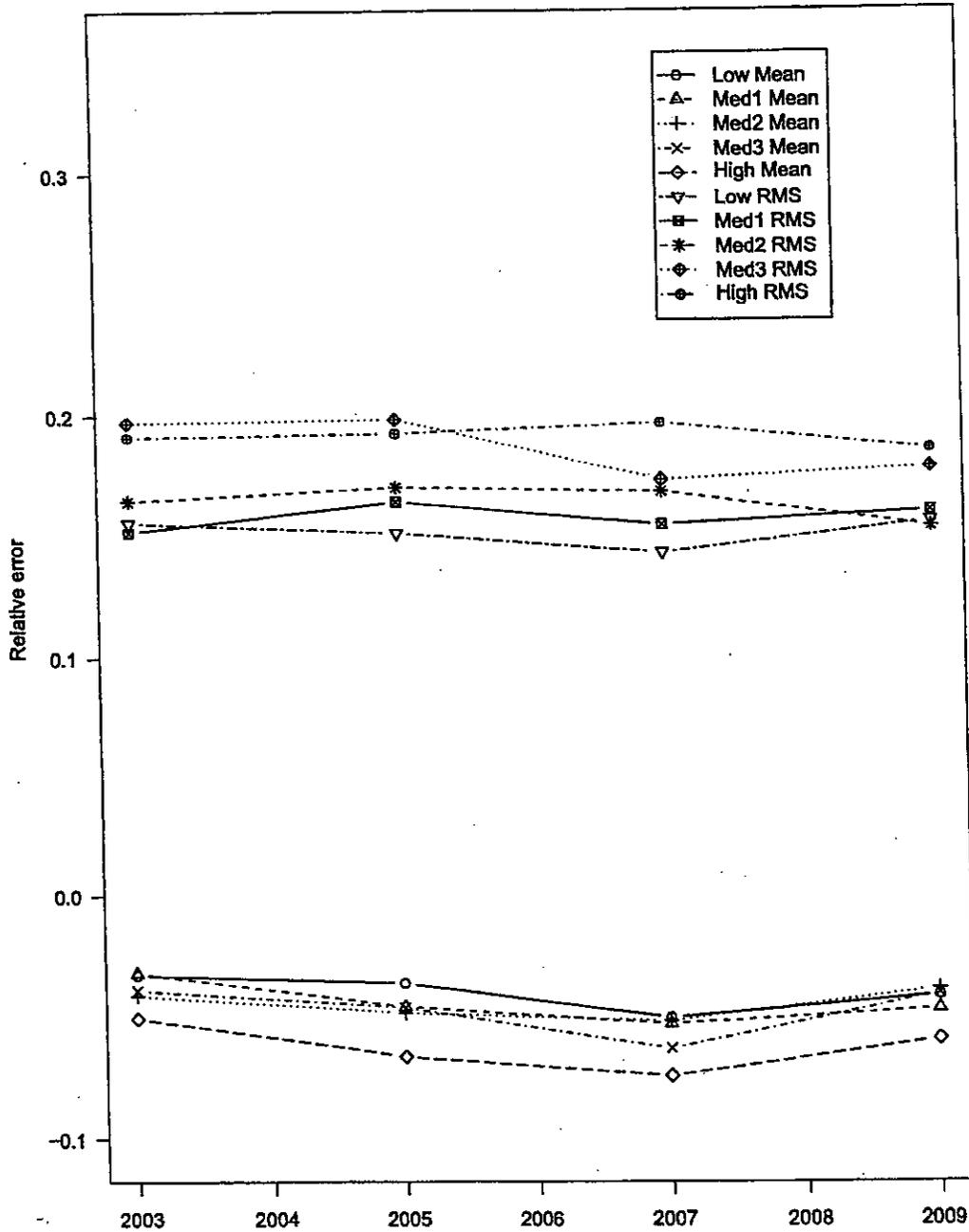


Figure 28: Mean relative error (Mean) and root mean squared relative error (RMS) when estimating  $B_0$  for ling at each biomass level in each assessment year.

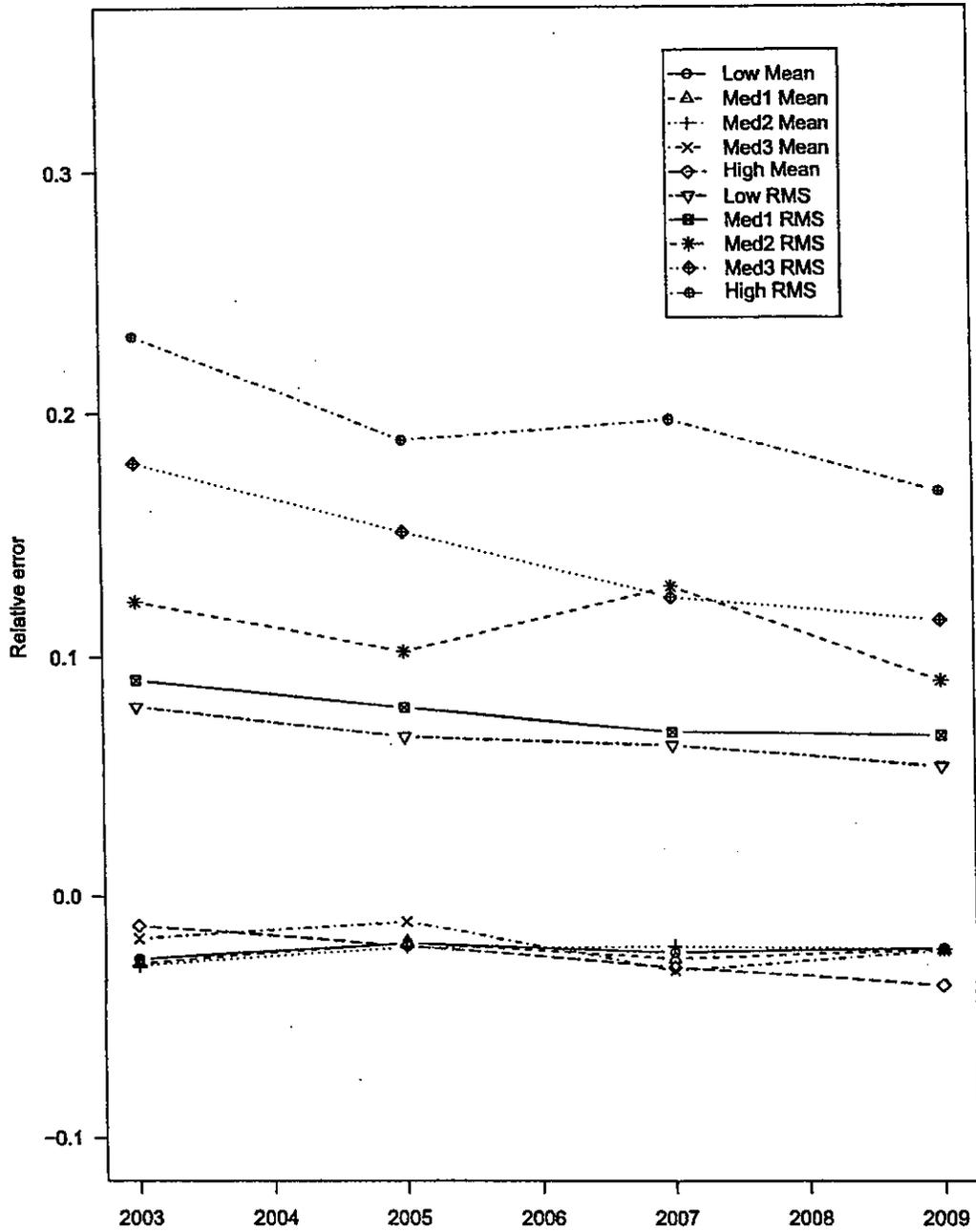


Figure 29: Mean relative error (Mean) and root mean squared relative error (RMS) when estimating  $B_{2002}$  for ling at each biomass level in each assessment year.

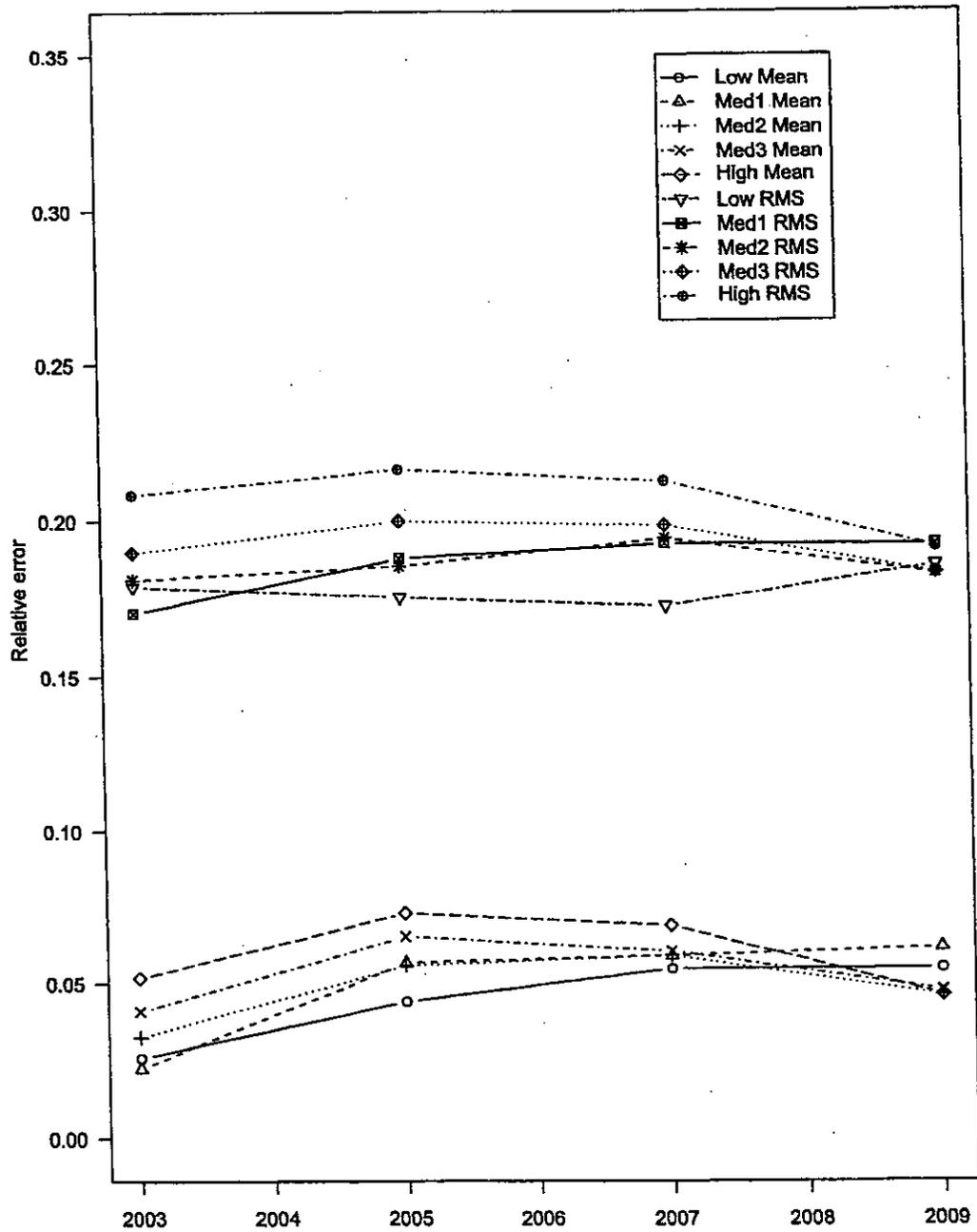


Figure 30: Mean relative error (Mean) and root mean squared relative error (RMS) when estimating  $B_{cur}/B_0$  for ling at each biomass level in each assessment year.

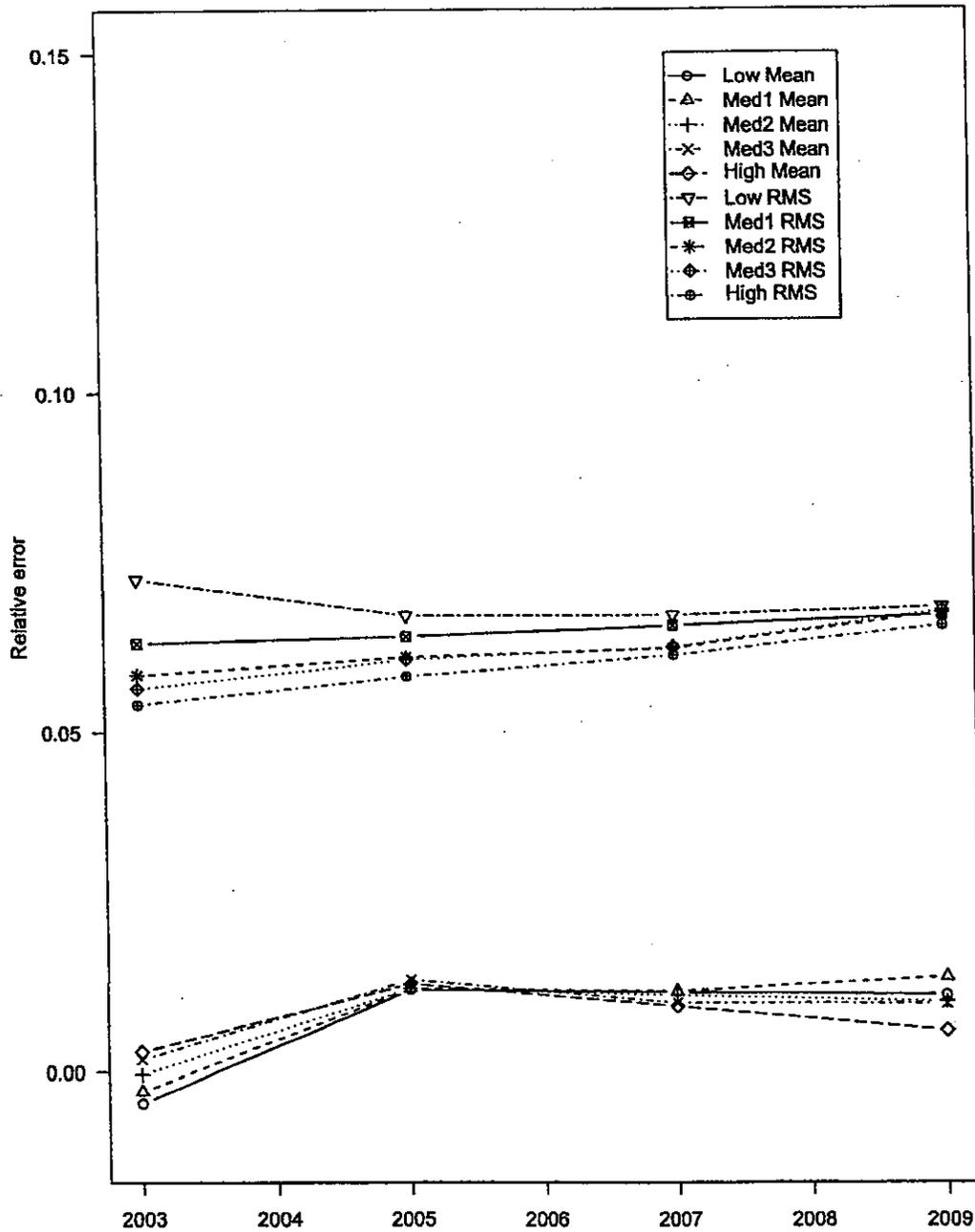


Figure 31: Mean relative error (Mean) and root mean squared relative error (RMS) when estimating  $B_{cur}/B_{AV}$  for ling at each biomass level in each assessment year.

## APPENDIX A: OPERATING MODEL EQUATIONS

This appendix describes the operating model equations in sufficient detail to allow the results of the case study to be replicated. The specification of the model in ISL's general modelling package (Modelling and Simulation System – MASS) is not explicitly described.

### Partition and annual cycle

Fish in the model are classified according their location and several "characteristics" of the fish:

#### Area:

- 1: Chatham Rise (CR)
- 2: Cook Strait (CKST)
- 3: Sub Antarctic (SA)
- 4: west coast South Island (WCSI)

#### Species:

- 1: hoki (HOK)
- 2: hake (HAK)
- 3: ling (LIN)

#### Stock:

- 1: east
- 2: west

#### Sex:

- 1: male
- 2: female

#### Age:

- 0–30 years

#### Status:

- 0: alive
- 1: dead (due to natural mortality)
- 2: dead (due to CR trawl fishery)
- 3: dead (due to CR line fishery)
- 4: dead (due to CR HAK fishery)
- 5: dead (due to CKST fishery)
- 6: dead (due to SA fishery)
- 7: dead (due to WCSI fishery)

The cross product of each of the six properties constitutes the "partition" (a multi-dimensional array, within which the numbers of fish in each cell can be stored). It should be noted that any "fish" will fall

within a cell of the partition, but not all cells will contain a positive number of fish. In the operating model, many of the cells were not used due to the following conditions:

- Single stocks of HAK and LIN (eastern only) which never leave the CR.
- Eastern HOK spawn in CKST and reside on the CR.
- Western HOK spawn in WCSI and reside on SA.

The "dead" cells in the Status dimension of the partition are only temporarily occupied: before each fishing operation the relevant cells are zeroed and those fish killed during the fishing operation are accounted for (allowing, at that time, the calculation of catch tonnages for each or any fishing mortality).

The annual cycle of the model consists of a number of "operations" which are conducted in succession on the fish in the partition. Each operation has a date associated with it, which is used to calculate duration of time where appropriate. The operating model cycle and the names of the operations are:

|              |   |
|--------------|---|
| 1 Oct:       | Start   |
| 1 April:     | CR.Z<br>SA.Z<br>HOKw.recruit                                |
| 1 June:      | CR.Z<br>SA.Z<br>HOK.spawn                                   |
| 1 August:    | CKST.Z<br>WCSLZ<br>CR.Z<br>SA.Z<br>HOK.ageing<br>HOK.births |
| 1 September: | CKST.Z<br>WCSLZ<br>CR.Z<br>SA.Z<br>HOK.home<br>HOKw.CR      |
| 1 October:   | CR1.Z<br>SA.Z<br>HAKLIN.ageing<br>HAKLIN.births<br>Finish   |

The operations are described below in sections where like operations are grouped. Prior to describing the operations, relevant parameters are defined.

### Operating model parameters

There are several types of model parameters: recruitment, biological and migration, and selection.

### Recruitment

Fish recruit into the partition at age 0. The average level of recruitment is given by the "births" parameter which was varied according to the level of  $B_0$  required (Table A1). The "births" are split into equal proportions of males and females. The actual recruitment in any year depends on the mean level of recruitment, the year class strength, and the stock recruitment relationship.

For a given stock and species, in year  $i$ , the total number of recruits is:

$$R_i = Y_i s(S_i | S_0, \Delta) N_0$$

where  $Y_i$  is the year class strength,  $N_0$  is the average number of births,  $S_i$  is the female spawning biomass, and  $s(S_i | S_0, \Delta)$  is the scalar from the Beverton-Holt stock recruit relationship (given virgin female spawning biomass  $S_0$  and steepness  $\Delta$ ). The  $Y_i$  are independent lognormal random variables with mean 1 and specified c.v.s (Table A1).

### Biological and migration

The biological parameters used are taken mainly from the 2002 Plenary report and associated assessment FARs. Natural mortality depends on species and sex (Table A2.a), as do the length-weight parameters (Table A2.b). The growth parameters depend on species, stock, and sex (Table A2.c). Proportion spawning (product of percent spawning and proportion mature) are dependent on species, stock, sex, and age (Table A3)

There are several explicit migrations in the annual cycle (in addition to spawning – which involves a migration for hoki but not for hake or ling). In each case a specific stock of hoki is involved in the migration but the parameters are trivial (0 or 1) for each migration, except the recruitment of western hoki from the CR to the SA (see Table A3).

### Selection

Selection patterns are needed for the various fisheries and for the CR trawl survey. In the case of the trawl fishery ("CR.trawl") and the trawl survey on the CR ("CR.survey") the parameters depend on species, sex, and age (Table A4.a). For the target hake fishery ("CR.HAK") and the ling line fishery ("CR.LIN"), the species are given and the parameters depend on sex and age (Table A4.b). For the hoki fisheries, in areas other than the CR ("CKST.HOK", "WCSLHOK", "SA.HOK"), the species and stock are given and the selection parameters are age specific (Table A4).

### Operating model operations

The various operations have been grouped into categories: structural, fishing, migrations, ageing, and births.

#### Structural

This is used to describe "Start" and "Finish". No operation occurs at "Start" and at "Finish" the only operation is incrementing the fishing year label (*year*) by 1. (In all the runs, the full cycle was executed 1941 to 2010 – with an equilibrium age structure in 1940.)

### Fishing

Each "fishing" operation is associated with a  $Z$ . Each  $Z$  is associated with a set of instantaneous fishing mortalities ( $F_i$ ). Each  $F_i$  has an associated selection pattern for every *cell* in the partition ( $S_{i,cell}$ ). A "fishing" operation occurs for a specified time  $t$  and numbers in the partition are adjusted according to the Baranov catch equation. Let the number of live fish in each *cell* be  $N_{cell}$  at the start of the "fishing" operation, then the number of "dead" from each *cell* due to  $F_i$  is:

$$C_{cell,t} = \frac{S_{i,cell} F_i}{Z_{cell}} (1 - e^{-Z_{cell} t}) N_{cell}$$

where

$$Z_{cell} = \sum_{i=0}^{i=n} S_{i,cell} F_i$$

and

$$S_{0,cell} = M_{cell}$$

$$F_0 = 1$$

Thus the partition numbers can be adjusted for specified  $F_i$ . When specified catches are given the above equations need to be solved iteratively for the  $F_i$  using the given mean fish weights (to equate catch biomass with the given catches).

The "fishing" operations and their associated fishing mortalities and selection patterns (in parentheses) for the operating model are:

|         |   |
|---------|---|
| CR.Z:   | mixed trawl (CR.trawl), ling line (CRLIN)                       |
| CR1.Z:  | mixed trawl (CR.trawl), ling line (CRLIN), target hake (CR.HAK) |
| SA.Z:   | hoki trawl (SA.HOK)   |
| CKST.Z: | hoki trawl (CKST.HOK)   |
| WCSL.Z: | hoki trawl (WCSL.HOK)   |

The catch histories were specified by species, area, and year (Table A5.a) and partitioned across the five time periods according to the length of each period and considerations with regard to known fleet movements (e.g., movement to the hoki spawning grounds in winter, Table A5.b).

Maximum exploitation rates were specified for each fishing period for each  $F_i$  (catch over selected biomass at the start of the period). These maximums were the same each year and independent of species (Table A6).

### Migration

Migrations in the operating model all involve hoki. The migration names, the areas migrated to and from, and the patterns of migration are:

|               |  |
|---------------|--|
| HOKw.recruit: | CR to SA, age dependent (see Table A3)                               |
| HOK.spawn:    | Home ground to spawning ground, age and sex dependent (see Table A3) |
| HOK.home:     | Spawning ground to home ground (all fish except age 0 on WCSI)       |
| HOKw.CR:      | Age 0 fish from WCSI to CR   |

### Ageing

An "ageing" operation involves only live fish (Status = 0) and is essentially a "migration" within the age dimension, with special treatment for the plus group at age 30, and the youngest fish at age 0:

$$\begin{aligned}N_{cell,age=30} &= N_{cell,age=30} + N_{cell,age=29} \\N_{cell,age} &= N_{cell,age-1} \quad age = 29, \dots, 1 \\N_{cell,age=0} &= 0\end{aligned}$$

Where *cell* subscripts the non-age dimensions for the cells specified in the ageing operation.

In the annual cycle for the operating model, ageing occurs at the same time for hake and ling (HAKLIN.ageing), but at an earlier time for both hoki stocks (HOK.ageing).

### Births

The fish recruit to the partition at age 0 into their spawning ground, equal numbers for each sex. The number of recruits each year is determined by the "births" parameter (giving the average recruitment), the stock recruit relationship, and the year class strength (see Recruitment above).

In the annual cycle for the operating model, births occur at the same time for hake and ling (HAKLIN.births), but at an earlier time for both hoki stocks (HOK.ageing).

**Table A1: Mean virgin recruitment ( $N_0$ , millions) and associated unfished biomass ( $B_0$ , '000 t) used in the main operating model runs for each species and stock. The steepness of the Beverton-Holt stock-recruit relationship and the c.v.s of the lognormal recruitment variability are also given (following Annala et al. 2002).**

| Run                 | HOK east |       | HOK west |       | HAK   |       | LIN   |       |
|---------------------|----------|-------|----------|-------|-------|-------|-------|-------|
|                     | $N_0$    | $B_0$ | $N_0$    | $B_0$ | $N_0$ | $B_0$ | $N_0$ | $B_0$ |
| LOW                 | 584      | 500   | 1037     | 1000  | 3.22  | 30    | 13.95 | 85    |
| MED1                | 584      | 500   | 1037     | 1000  | 4.30  | 40    | 15.59 | 95    |
| MED2                | 584      | 500   | 1037     | 1000  | 5.91  | 55    | 18.87 | 115   |
| MED3                | 584      | 500   | 1037     | 1000  | 8.60  | 80    | 22.97 | 140   |
| HIGH                | 584      | 500   | 1037     | 1000  | 12.90 | 120   | 32.82 | 200   |
| Recruitment c.v.    |          | 1.31  |          | 1.31  |       | 0.658 |       | 0.658 |
| Beverton-Holt steep |          | 0.90  |          | 0.90  |       | 0.90  |       | 0.90  |

**Table A2: Biological parameters used for species in the operating model.**

**a: Natural mortality (from Annala et al. 2002)**

| Species | Male | Female |
|---------|------|--------|
| HOK     | 0.34 | 0.26   |
| HAK     | 0.20 | 0.18   |
| LIN     | 0.18 | 0.18   |

**b: Weight =  $a(\text{length})^b$  (weight in g, length in cm)**

| Species | Male   |      | Female |      | Identifier within Annala et al. 2002 |
|---------|--------|------|--------|------|--------------------------------------|
|         | a      | b    | a      | b    |                                      |
| HOK     | 0.0048 | 2.89 | 0.0048 | 2.89 | HOK 1                                |
| HAK     | 0.0025 | 3.23 | 0.0017 | 3.33 | HAK 4                                |
| LIN     | 0.0010 | 3.35 | 0.0011 | 3.32 | LIN 3&4                              |

**c: von Bertalanffy growth parameters**

| Species | Male  |       |            | Female |       |            | Identifier within Annala et al. 2002 |
|---------|-------|-------|------------|--------|-------|------------|--------------------------------------|
|         | K     | $t_0$ | $L_\infty$ | K      | $t_0$ | $L_\infty$ |                                      |
| HOK     | 0.261 | -0.50 | 92.6       | 0.213  | -0.60 | 104.0      | Western stock                        |
| HOK     | 0.232 | -1.23 | 89.5       | 0.161  | -2.18 | 101.8      | Eastern stock                        |
| HAK     | 0.277 | -0.11 | 90.3       | 0.202  | -0.20 | 113.4      | HAK 4                                |
| LIN     | 0.108 | -1.24 | 119.0      | 0.076  | -1.05 | 160.1      | LIN 3&4                              |

**Table A3: Proportion spawning at age and sex for each species and stock in the operating model and the SA migration proportions for the western hoki stock (hake and ling derived from Annala et al. 2002; hoki proportions based on results in Francis et al. 2003).**

| Species      | Sex  | Age  |     |     |     |        |       |       |       |       |     |
|--------------|------|------|-----|-----|-----|--------|-------|-------|-------|-------|-----|
|              |      | 1    | 2   | 3   | 4   | 5      | 6     | 7     | 8     | 9     | 10  |
| HOK<br>east  | Male | .05  | 0.1 | 0.4 | 0.7 | 0.7    | 0.7   | 0.7   | 0.7   | 0.7   | 0.7 |
|              | Fem. | 0.0  | .05 | 0.1 | 0.4 | 0.4    | 0.4   | 0.5   | 0.6   | .65   | .65 |
| HOK<br>west  | Male | 0.6  | 0.6 | 0.6 | 0.6 | 0.6    | 0.6   | 0.6   | 0.6   | 0.6   | 0.6 |
|              | Fem. | 0.1  | 0.2 | 0.4 | 0.6 | .65    | .65   | .65   | .65   | .65   | .65 |
| HAK          | Male | 0.0  | 0.0 | 0.0 | .02 | .07    | .31   | .78   | 1.0   | 1.0   | 1.0 |
|              | Fem. | 0.0  | 0.0 | 0.0 | .02 | .04    | .07   | .45   | .86   | 1.0   | 1.0 |
| LIN          | Male | 0.0  | 0.0 | 0.0 | 0.0 | 0.090  | 0.252 | 0.477 | 0.693 | 0.855 | 0.9 |
|              | Fem. | 0.0  | 0.0 | 0.0 | 0.0 | 0.0009 | 0.090 | 0.252 | 0.477 | 0.693 | 0.9 |
| HOK<br>to SA | Male | 0.05 | 0.1 | 0.3 | 0.5 | 0.5    | 0.8   | 1.0   | 1.0   | 1.0   | 1.0 |
|              | Fem. | 0.05 | 0.1 | 0.3 | 0.5 | 0.5    | 0.8   | 1.0   | 1.0   | 1.0   | 1.0 |

**Table A4: Proportion selected at age and sex for each species and stock in the operating model for the various fisheries and the CR trawl survey (proportions based on results in Francis et al. 2003, Horn 2002, Dunn 2003).**

**a: CR trawl survey**

| Species | Sex  | Age |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|---------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|         |      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  |
| HOK     | Male | 0.1 | 0.3 | 0.6 | 0.8 | 0.9 | 1.0 | 1.0 | 1.0 | 0.9 | .85 | .80 | .78 | .76 | .74 | .73 | .72 | .71 | .70 |
|         | Fem. | 0.1 | 0.3 | 0.6 | 0.8 | 0.9 | 1.0 | 1.0 | 1.0 | 0.9 | .85 | .80 | .78 | .76 | .74 | .73 | .72 | .71 | .70 |
| HAK     | Male | .05 | 0.1 | .15 | .25 | .35 | 0.4 | 0.5 | .55 | 0.6 | .65 | .75 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |     |
|         | Fem. | .05 | 0.1 | .12 | .15 | .20 | .25 | .35 | 0.4 | .45 | 0.5 | .55 | 0.6 | 0.6 | .55 | 0.5 | 0.5 | 0.5 |     |
| LIN     | Male | .05 | 0.1 | .15 | 0.2 | 0.4 | .65 | 0.8 | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |     |
|         | Fem. | .05 | 0.1 | .15 | 0.4 | 0.6 | .75 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |     |

**b: CR trawl fishery**

| Species | Sex  | Age |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|---------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|         |      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  |
| HOK     | Male | 0.1 | 0.3 | 0.6 | 0.8 | 0.9 | 1.0 | 1.0 | 1.0 | 0.9 | .85 | .80 | .78 | .76 | .74 | .73 | .72 | .71 | .70 |
|         | Fem. | 0.1 | 0.3 | 0.6 | 0.8 | 0.9 | 1.0 | 1.0 | 1.0 | 0.9 | .85 | .80 | .78 | .76 | .74 | .73 | .72 | .71 | .70 |
| HAK     | Male | .05 | 0.1 | .15 | .25 | .35 | 0.4 | 0.5 | .55 | 0.6 | .65 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |     |
|         | Fem. | .05 | 0.1 | .12 | .15 | .20 | .25 | .35 | 0.4 | .45 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |     |
| LIN     | Male | .05 | 0.1 | .15 | 0.2 | 0.3 | .35 | 0.5 | 0.6 | .75 | 0.8 | 0.8 | .75 | 0.7 | .65 | .62 | 0.6 | 0.6 |     |
|         | Fem. | .05 | 0.1 | .15 | 0.2 | 0.3 | .35 | 0.5 | 0.6 | .75 | 0.8 | 0.8 | .75 | 0.7 | .65 | .62 | 0.6 | 0.6 |     |

**c: Target fisheries for ling and hake**

|      | Age |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  |
| LIN  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Male | 0.0 | .05 | 0.1 | .15 | .25 | 0.4 | 0.6 | 0.7 | .75 | 0.8 | .85 | .87 | .88 | .89 | 0.9 | .89 | .87 | .85 | 0.8 | .75 | 0.7 | 0.7 | 0.7 |
| Fem. | 0.0 | .05 | 0.1 | .15 | .25 | 0.4 | 0.6 | .75 | .85 | 0.9 | .94 | .97 | .99 | 1.0 | 1.0 | .98 | .95 | .93 | 0.9 | .85 | 0.8 | .75 | 0.7 |
| HAK  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Male | .05 | 0.1 | .15 | .25 | .35 | .43 | 0.5 | .55 | 0.6 | .65 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |     |
| Fem. | .05 | 0.1 | .12 | .15 | .20 | .29 | .35 | 0.4 | .45 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |     |

**d: Hoki only fisheries (same selectivity, WCSI and CKST; selectivity depends on age only).**

| Fishery  | Age |    |    |    |    |    |    |     |     |    |
|----------|-----|----|----|----|----|----|----|-----|-----|----|
|          | 1   | 2  | 3  | 4  | 5  | 6  | 7  | 8   | 9   | 10 |
| Spawning | 0   | .1 | .3 | .5 | .7 | .8 | .9 | .95 | .98 | 1  |
| SA trawl | 0   | .1 | .4 | 1  | 1  | .9 | .7 | .6  | .6  | .6 |

**Table A5: Catch histories used in the operating model and how they were partitioned across the five time periods.**

**a: Catch histories used in recent stock assessments (from Annala et al. 2003, Dunn 2003, Horn 2002).**

| Year | HOK    |        |        |        |        | HAK     |       | LIN      |         |
|------|--------|--------|--------|--------|--------|---------|-------|----------|---------|
|      | CR1    | CR2    | SA1    | SA2    | CKST   | WCSI    | CR    | CR trawl | CR line |
| 1971 | 0      | 0      | 0      | 0      | 0      | 0       | 0     | 0        | 0       |
| 1972 | 1 500  | 2 500  | 0      | 0      | 0      | 5 000   | 0     | 0        | 0       |
| 1973 | 1 500  | 2 500  | 0      | 0      | 0      | 5 000   | 0     | 250      | 0       |
| 1974 | 2 200  | 3 800  | 0      | 0      | 0      | 5 000   | 0     | 382      | 0       |
| 1975 | 13 100 | 22 900 | 0      | 0      | 0      | 10 000  | 191   | 953      | 8 439   |
| 1976 | 13 500 | 23 500 | 0      | 0      | 0      | 30 000  | 488   | 2 100    | 17 436  |
| 1977 | 13 900 | 24 100 | 0      | 0      | 0      | 60 000  | 1 288 | 2 055    | 23 994  |
| 1978 | 1 100  | 1 900  | 0      | 0      | 0      | 5 000   | 34    | 1 400    | 7 577   |
| 1979 | 2 200  | 3 800  | 0      | 0      | 0      | 18 000  | 609   | 2 380    | 821     |
| 1980 | 2 900  | 5 100  | 0      | 0      | 0      | 20 000  | 750   | 1 340    | 360     |
| 1981 | 2 900  | 5 100  | 0      | 0      | 0      | 25 000  | 997   | 673      | 160     |
| 1982 | 2 600  | 4 400  | 0      | 0      | 0      | 25 000  | 596   | 1 183    | 339     |
| 1983 | 1 500  | 8 500  | 3 200  | 3 500  | 0      | 23 300  | 302   | 1 210    | 326     |
| 1984 | 3 200  | 6 800  | 6 700  | 5 400  | 0      | 27 900  | 344   | 1 366    | 406     |
| 1985 | 6 200  | 3 800  | 3 000  | 6 100  | 0      | 24 900  | 544   | 1 351    | 401     |
| 1986 | 3 700  | 13 300 | 7 200  | 3 300  | 0      | 71 500  | 362   | 1 494    | 375     |
| 1987 | 8 800  | 8 200  | 5 900  | 5 400  | 0      | 146 700 | 509   | 1 313    | 306     |
| 1988 | 9 000  | 6 000  | 5 400  | 7 600  | 600    | 227 000 | 574   | 1 636    | 290     |
| 1989 | 2 300  | 2 700  | 700    | 4 900  | 7 000  | 185 900 | 804   | 1 397    | 488     |
| 1990 | 3 300  | 9 700  | 900    | 9 100  | 14 000 | 173 000 | 950   | 1 934    | 529     |
| 1991 | 17 400 | 14 900 | 4 400  | 12 700 | 29 700 | 135 900 | 907   | 2 563    | 2 228   |
| 1992 | 33 400 | 17 500 | 14 000 | 17 400 | 25 600 | 107 200 | 2 417 | 3 451    | 3 695   |
| 1993 | 27 400 | 19 700 | 14 700 | 10 900 | 22 200 | 100 100 | 2 758 | 2 375    | 3 971   |
| 1994 | 16 000 | 10 600 | 5 800  | 5 500  | 35 900 | 117 200 | 2 933 | 1 933    | 4 159   |
| 1995 | 29 600 | 16 500 | 5 900  | 7 500  | 34 400 | 80 100  | 3 385 | 2 222    | 5 530   |
| 1996 | 37 900 | 23 900 | 5 700  | 6 800  | 59 700 | 75 900  | 3 760 | 2 725    | 4 863   |
| 1997 | 42 400 | 28 200 | 6 900  | 15 100 | 56 500 | 96 900  | 3 695 | 3 003    | 4 047   |
| 1998 | 55 600 | 34 200 | 10 900 | 14 600 | 46 700 | 107 100 | 3 941 | 4 707    | 3 227   |
| 1999 | 59 200 | 23 600 | 8 800  | 14 900 | 40 500 | 97 500  | 3 374 | 3 282    | 3 818   |
| 2000 | 43 100 | 20 500 | 14 300 | 19 500 | 39 000 | 105 600 | 2 942 | 3 739    | 2 779   |
| 2001 | 36 300 | 20 700 | 13 200 | 16 900 | 33 700 | 109 200 | 2 767 | 3 400    | 2 800   |
| 2002 | 24 700 | 18 800 | 16 900 | 13 400 | 24 000 | 98 300  | 3 000 | 3 400    | 2 800   |

**b: Percentage of catch (from a: above) used in each time period of the operating model.**

| Species   | 1 Oct – 1 Apr  | 1 Apr – 1 Jun | 1 Jun – 1 Aug | 1 Aug – 1 Sep | 1 Sep – 1 Oct  |
|-----------|----------------|---------------|---------------|---------------|----------------|
| HOK CR    | 100 % CR1, SA1 | 60% CR2, SA2  | 10% CR2, SA2  | 5% CR2, SA2   | 25% CR2, SA2   |
| HOK spawn |                |               | 50% spawn     | 50% spawn     |                |
| HAK       | 58%            | 19%           | 6%            | 2%            | 10%, 5% target |
| LIN trawl | 60%            | 20%           | 7%            | 3%            | 10%            |
| LIN line  | 60%            | 20%           | 7%            | 3%            | 10%            |

**Table A6: Maximum exploitation rates (catch over biomass) for each area, fishery, and time period in the operating model (same maximum for each species). “-” denotes no fishing in that area at that time.**

| Area/fishery | 1 Oct – 1 Apr | 1 Apr – 1 Jun | 1 Jun – 1 Aug | 1 Aug – 1 Sep | 1 Sep – 1 Oct |
|--------------|---------------|---------------|---------------|---------------|---------------|
| CR trawl     | 0.3           | 0.15          | 0.1           | 0.05          | 0.05          |
| CR LIN       | 0.2           | 0.10          | 0.1           | 0.05          | 0.05          |
| CR HAK       | -             | -             | -             | -             | 0.10          |
| SA           | 0.3           | 0.15          | 0.1           | 0.05          | 0.05          |
| CKST         | -             | -             | 0.4           | 0.4           | -             |
| WCSI         | -             | -             | 0.4           | 0.4           | -             |

## APPENDIX B: ESTIMATION MODELS

This appendix describes the estimation models in sufficient detail to allow the results of the case study to be replicated. The specification of the models in ISL's general modelling package (Modelling and Simulation System – MASS) is not explicitly described.

There are two estimation models, one for hake and one for ling. These are virtually identical in structure and mainly differ in the value of specified parameters, available data, and the number of year class strengths which are estimated.

### Partition and annual cycle

The partitions for the two models are almost the same but the ling model has a line fishery in addition to a trawl fishery. There are just three dimensions:

Sex:

- 1: male
- 2: female

Age:

0–30 years

Status:

- 0: alive
- 1: dead (due to natural mortality)
- 2: dead (due to CR trawl fishery)
- 3: dead (due to CR line fishery) (LIN model only)

The annual cycle of the two models is much simpler than that of the operating model, with the five fishing periods being combined into three periods:

|        |        |
|--------|--------|
| 1 Oct: | Start  |
| 1 Jun: | CR.Z   |
| 1 Sep: | CR.Z   |
| 1 Oct: | CR.Z   |
|        | Ageing |
|        | Births |
|        | Finish |

The equations governing the operations are the same as in the operating model. However, it should be noted that "CR.Z" differs between the hake and ling models. Hake has a single trawl fishery, but ling has trawl and line fisheries.

## Estimation model parameters

There are the same types of parameters as those found in the operating model: recruitment, biological and migration, and selection. The nature of the parameters has already been described, but for the estimation models it is necessary to know which parameters were estimated, and which were not. Also, for those which were estimated, initial values (and perhaps bounds) must be specified, and for those which were not, constant values must be specified.

### Recruitment

The average level of recruitment, given by the "births" parameter, was estimated with the following starting value and bounds:

|      | Initial ('000 t) | Bounds ('000 t) |
|------|------------------|-----------------|
| HAK: | 3.6              | 2, 15           |
| LIN: | 18               | 10, 40          |

The bounds encompass the full range of values used in the operating model (HAK: 3.22–12.9, LIN: 13.95–32.82).

The Beverton-Holt steepness parameters were fixed at 0.9 as in the operating model. The estimated year class strengths had bounds 0.1–1.0 and initial values (in the 2008 and 2009 assessments respectively):

|                  |   |
|------------------|---|
| HAK (1974–2002): | 1.0 1.0 1.0 1.5 1.5 1.5 0.5 0.5 0.5 1.0 1.0 1.0 1.5<br>1.5 1.5 0.5 0.5 0.5 1.0 1.0 1.0 1.5 1.5 1.5 0.5 0.5<br>0.5 1.0 1.0         |
| LIN (1973–2003): | 1.0 1.0 1.0 1.5 1.5 1.5 0.5 0.5 0.5 1.0 1.0 1.0 1.5<br>1.5 1.5 0.5 0.5 0.5 1.0 1.0 1.0 1.5 1.5 1.5 0.5 0.5<br>0.5 1.0 1.0 1.5 0.5 |

This pattern of initial values encourages better mapping of the estimation model space by the minimizer (and hopefully gives faster convergence) than starting with all values equal to 1. For assessments in earlier years (HAK: 2002, 2004, 2006; LIN: 2003, 2005, 2007), fewer year class strengths were estimated (the last cohort estimated, is given by the assessment year minus 6).

### Biological and migration

There are no migration parameters in the estimation models. The biological parameters were all fixed in the estimation models and set equal to the values in the operating model (see Tables A2 and A3).

### Selection

No data relevant to the ling longline fishery were available to the estimation model, so the selection pattern for this fishery was fixed and set equal to the value in the operating model (see Table A4).

In each estimation model there are catch at age (and sex) data from the commercial trawl fishery and from the CR trawl survey. Therefore, these selection patterns were estimated. The same lower and upper bounds were used at each sex and age for all selection patterns (Table B1). It should be noted that the value at the maximum male age was essentially fixed (see Likelihood and penalties section below).

## Catch history

The catch histories from the operating model were also used in the estimation models (simply a mapping from the five time periods of the operating model to the three time periods of the estimation models).

Maximum exploitation rates were defined in the estimation models:

|     |       | 1 Oct-1 Jun | 1 Jun-1 Sep | 1 Sep-1 Oct |
|-----|-------|-------------|-------------|-------------|
| HAK | trawl | 0.4         | 0.15        | 0.10        |
| LIN | trawl | 0.3         | 0.15        | 0.05        |
|     | line  | 0.3         | 0.15        | 0.05        |

## Likelihood and penalties

Maximum likelihood estimation was used. To derive the likelihood, all observations from a given time series ( $X_i$ ) were taken to have independent lognormal errors ( $\varepsilon_i$ ) and to be related to the true values ( $T_i$ ) by a scalar  $q$ :

$$X_i = qT_i\varepsilon_i$$

$$\text{where } \ln(\varepsilon_i) \sim N\left(\frac{-\sigma_i^2}{2}, \sigma_i^2\right)$$

Commercial catch at age (and sex) data were used as proportions (sex ratio preserved), with  $q = 1$ . For all other time series a  $q$  was estimated. The c.v.s of the observations were set equal to the c.v.s used in the operating model to generate the simulated data (that is, the estimation models have the correct c.v.s, except in the case of catch at age proportions where the c.v.s in the estimation model are used with the proportions, whereas in the operating model they are applied to numbers).

Three types of penalties were added to the negative log likelihood in the minimisation to achieve the following: average year class strength estimates approximately equal to 1, cubic smoothing of the selection patterns, and stabilisation of the selection value for males at the maximum age.

The year class strength penalty was of the form:

$$100 \ln(Y)^2$$

where  $Y$  is the mean estimated year class strength.

The smoothing of the selectivities to achieve approximate 3<sup>rd</sup> order polynomials was done by imposing penalties on non-zero 4<sup>th</sup> differences:

$$10 \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} [\Delta^4 s_{ij}(k)]^2$$

where  $i$  indexes the commercial and survey selectivities,  $j$  indexes the sexes,  $k$  indexes age (in years), and  $\Delta$  is the forward difference operator for a spacing of  $h = 1$  (see, for example, Philips & Taylor 1973).

The "fixing" of the selection value for males at the maximum age for each selection pattern was done by imposing a penalty on differences between the initial value and the estimated value:

$$1000 \sum_{i=1} (s_i - v_i)^2$$

where  $i$  indexes the commercial and survey selectivities and  $s_i$  and  $v_i$  are respectively the estimated and initial selection values for males at the maximum age.

### Projections

To evaluate the loss associated with particular TACs, projections were done using each estimation model for 5 years beyond the assessment year. Projections were done using the estimation model with the estimated values of mean recruitment, year class strength, and selection patterns, with lognormal errors applied to cohort numbers beginning with the cohort spawned 5 years before the assessment year.

**Table B1: Initial values and bounds for the commercial trawl fishery and CR trawl survey selectivities for hake and ling used in the estimation models.**

**a: hake**

|                 |      | Age |     |     |     |     |     |     |     |     |     |     |
|-----------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                 |      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  |
| Low bound       | Male | .01 | .01 | .05 | .05 | .10 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
|                 | Fem. | .01 | .01 | .05 | .05 | .10 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Initial Fishery | Male | .05 | 0.1 | .15 | .25 | .35 | 0.4 | 0.5 | .55 | 0.6 | .65 | 0.7 |
|                 | Fem. | .05 | 0.1 | .12 | .15 | .20 | .25 | .35 | 0.4 | .45 | 0.5 | 0.5 |
| Survey          | Male | .05 | 0.1 | .15 | .25 | .35 | 0.4 | 0.5 | .55 | 0.6 | .65 | 0.7 |
|                 | Fem. | .05 | 0.1 | .12 | .15 | .20 | .25 | .35 | 0.4 | .45 | 0.5 | 0.5 |
| High bound      | Male | 0.5 | 0.5 | 0.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
|                 | Fem. | 0.5 | 0.5 | 0.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

**b: ling**

|                 |      | Age |     |     |     |     |     |     |     |     |     |     |     |     |     |
|-----------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                 |      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  |
| Low bound       | Male | .01 | .01 | .05 | .05 | .10 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
|                 | Fem. | .01 | .01 | .05 | .05 | .10 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Initial Fishery | Male | .05 | 0.1 | .15 | 0.2 | 0.3 | .35 | 0.5 | 0.6 | .75 | 0.8 | 0.8 | .75 | .72 | 0.7 |
|                 | Fem. | .05 | 0.1 | .15 | 0.2 | 0.3 | .35 | 0.5 | 0.6 | .75 | 0.8 | 0.8 | .75 | .72 | 0.7 |
| Survey          | Male | .05 | 0.1 | .15 | 0.2 | 0.3 | 0.5 | 0.6 | 0.7 | 0.7 | 0.7 | -   | -   | -   | -   |
|                 | Fem. | .05 | 0.1 | .15 | 0.2 | 0.3 | 0.5 | 0.6 | 0.7 | 0.7 | 0.7 | -   | -   | -   | -   |
| High bound      | Male | 0.5 | 0.5 | 0.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
|                 | Fem. | 0.5 | 0.5 | 0.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

## APPENDIX C: GENERIC LOSS FUNCTIONS

Two generic forms are used for loss functions in this report:

ASYM(x, b): a function with two asymptotes  
 SQ(x): a simple quadratic function.

The two functions and their properties are described further below.

### Asymptotic loss function

A form of this function is used when the FPI is a biomass ratio (hence taking values from 0 to  $\infty$ ) and there is a "target" value of  $x = b$  (where the "loss" is zero). It is defined as,

$$ASYM(x|a,b,c) = a \left( 1 - \frac{b+c}{x+c} \right)^2 = a \left( \frac{x-b}{x+c} \right)^2$$

It has  $x$  and  $y$  asymptotes:

$$ASYM(-c) = \infty \text{ and } ASYM(\infty) = a.$$

There is a single minimum at  $x = b$  and a single turning point at  $x = (3b + c)/2$ . This function has increasing loss with increasing distance from  $b$  provided that  $c > -b$ . In order for it to be a sensible loss function we need  $c > 0$  (otherwise there is a discontinuity at a valid value of  $x$ ).

Specific function values are:

$$\begin{aligned} ASYM(-c) &= \infty \\ ASYM(0) &= ab^2/c^2 \\ ASYM(b-c) &= ac^2/b^2 \\ ASYM(b) &= 0 \\ ASYM(2b+c) &= a/4 \\ ASYM(3b+2c) &= 4a/9 \\ ASYM(\infty) &= a. \end{aligned}$$

The constant  $a$  is used for scaling the function when it is a component of a composite loss function (being the sum of various ASYM() and SQ() loss functions). The constant  $b$  is a "target value" as the loss is zero when  $x = b$ . The constant  $c$  is used to control the relative value of the function across some specified range of  $x$ . For example, if it is desired to have the same loss at  $x_1 = b/n_1$  and  $x_2 = n_2 b$  then the constant  $c$  should be set:

$$c = b \left[ 1 - \frac{2(n_2 - n_1)}{n_1(n_2 - n_1) + 1} \right]$$

A sufficient condition for  $c$  to be positive is  $n_2 \geq n_1$  and  $n_1 \geq 2$ , in which case  $c \leq b$ . For example, equal losses at  $b/2$  and  $2b$  are achieved by setting  $c = b$ , and equal losses at  $b/2$  and  $4b$  are achieved by setting  $c = b/5$ .

## Square loss function

This is a simple quadratic used for probabilistic FPIs where there is a “target” probability of  $x = p$  (when the loss equals zero). It is defined as,

$$SQ(x|a, p) = a(p - x)^2$$

It has a single minimum at  $x = p$  and has no turning points. It is a symmetric function about  $x = p$ . Specific values of interest are:

$$\begin{aligned} SQ(0) &= ap^2 \\ SQ(p) &= 0 \\ SQ(2p) &= ap^2 \\ SQ(1) &= a(1 - p)^2 \end{aligned}$$

## APPENDIX D: RETROSPECTIVE ANALYSIS

In this appendix “retrospective analysis” is formally defined and two simple examples are given. In the first example it is demonstrated that “good” estimators can, and often will, produce a “bad” retrospective pattern. The second example demonstrates that “bad” estimators can produce a “good” retrospective pattern. The conclusion is that retrospective analysis is not useful for inferring or concluding anything about the properties of an estimator.

In a retrospective analysis the estimates of an item of interest are compared over a number of data sets for a particular estimation procedure. The data sets considered are a “current data set” and successively smaller data sets created by removing the most recent data (e.g., new data may be accumulated on an annual basis; successive data sets might be those available in 2003 (the current data set), 2002, then 2001 only, then 2000 only, and 1999 only, etc).

Let us denote the  $i$ th data set by  $S_i$  and suppose that the current data set is  $S_{n+k}$ . Let the estimator be denoted by  $Y$  and let  $Y_i = Y(S_i)$ . Suppose that the retrospective analysis considers  $k+1$  data sets, then the analysis will consider a *single realisation* of the random variables:  $\{ Y_n, Y_{n+1}, \dots, Y_{n+k} \}$ . It is noteworthy that the  $Y_i$  are almost certainly correlated random variables because of the overlap in the data from which they are derived. Also, in general, it would be expected that the variance of successive  $Y_i$  would be decreasing as more data are added. Also, if  $Y$  has the property of “consistency” (which essentially means that as  $i$  increases  $Y_i$  gets ever closer to the true value of the item of interest) then because of the correlations, it is likely that there will be trend in the  $Y_i$  (i.e., if the early estimates are above the true value, they will eventually trend down towards it; similarly, if the early estimates are below the true value, they must eventually trend upwards to it).

Consider the example where  $S_i = \{ X_j | j = 1 \dots i \}$  where the  $X_j$  are independent and identically distributed random variables with mean  $\mu$  and variance  $\sigma^2$ . Let the estimator  $Y$  be the arithmetic mean:

$$Y_i = Y(S_i) = \bar{X}_i = \frac{1}{i} \sum_{j=1}^i X_j$$

Then  $E(Y_i) = \mu$  and  $\text{Var}(Y_i) = \sigma^2/i$ . In a retrospective analysis, we consider differences between estimates for the current data set and earlier data sets. So, we are interested in  $Y_{n+j} - Y_n$  for a particular  $n$  and various values of  $j$ . It is easy to show in this example that,

$$Y_{n+j} - Y_n = \frac{1}{n+j} \sum_{i=n+1}^{n+j} X_i - \frac{j}{n+j} \bar{X}_n$$

It then follows that,

$$E(Y_{n+j} - Y_n) = 0$$

and

$$\text{Var}(Y_{n+j} - Y_n) = \frac{j\sigma^2}{n(n+j)}$$

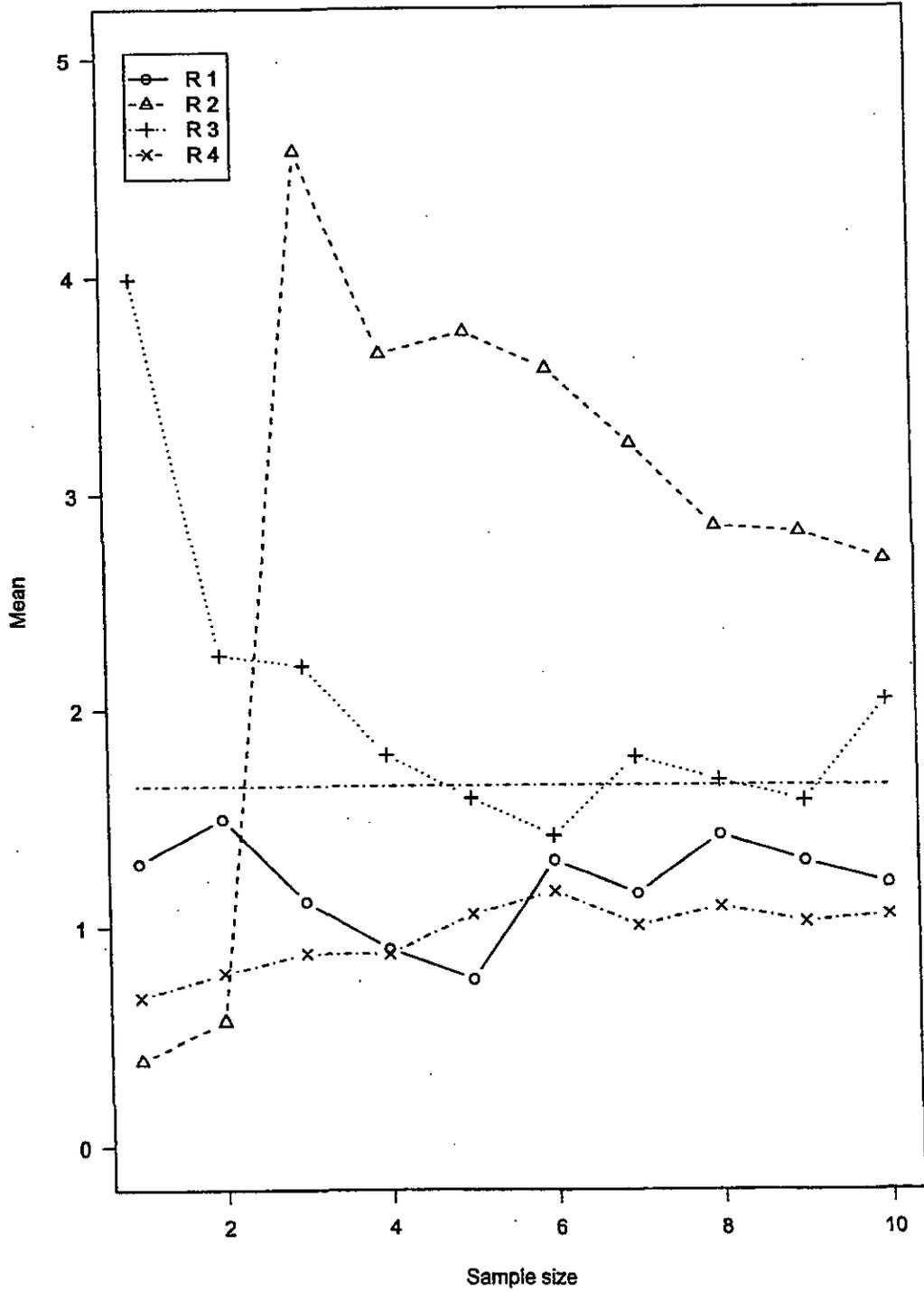
So, while the expected value of the differences between the estimators is zero, the variance of the differences increases with increasing differences in the data sets (i.e., as  $j$  increases). Large differences can be expected if the underlying variance is high.

It can also be shown that the  $Y_i$  are highly correlated:

$$\text{Cor}(Y_{n+j}, Y_n) = \sqrt{\frac{n}{n+j}}$$

Since,  $Y$  is a consistent estimator of  $\mu$  it follows that a retrospective analysis is likely to show a trend. Figure A1 shows four realisations where an underlying lognormal distribution is used. Three of the four realisations show overall trends or trends in a large part of their trajectory. Any attempt to draw conclusions about properties of the estimator or how well the item of interest is being estimated are seen to be highly problematic. For example, from realisations 2 and 3, the "high" variance of the estimator is apparent, but realisations 1 and 4 suggest a relatively "low" variance for the estimator. In these "low" variance cases, one might conclude that the estimator is "performing well", but the closest current estimate occurs for realisation 3 (one of the realisations exhibiting "high" variance). The arithmetic mean of independent identically distributed random variables is a perfectly "good" estimator of the mean of the underlying distribution. It would be wrong to conclude otherwise from a retrospective analysis.

Let us very briefly consider a second example to illustrate the point that a "good" retrospective pattern does not imply a "good" estimator (as we have already seen, a "bad" pattern does not imply a "bad" estimator). Take the estimator from the first example and add a large constant to it. This will be a very poor estimator of the underlying population mean, but will exhibit a near "perfect" retrospective pattern: low variance and no trend.



**Figure D1: Four realisations of the arithmetic mean of a random sample from a lognormal distribution. The population mean is shown by the dot-dashed line ( $\exp(0.5)$ ).**