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Evaluation of interim harvest strategies for sablefish (*Anoplopoma fimbria*)
in British Columbia, Canada for 2008/09

by

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## Abstract

This paper applies a management strategy evaluation (MSE) approach toward identifying an *interim* management procedure for setting sablefish (*Anoplopoma fimbria*) quotas in 2008/2009 and beyond. We employ the MSE methodology developed by Cox et al. (2008) to evaluate the likely performance of data-based and model-based management procedures under four simulation scenarios for sablefish stock dynamics. Conservation, catch variability, and catch performance are compared to four management objectives that were developed through consultations with industry stakeholders and managers. Our simulations indicate that 70-80% of the management procedures examined would likely fail to meet specified conservation objectives under some scenarios for sablefish population dynamics. These failures occurred despite the fact that most procedures rebuild the sablefish stock over 40 years. The remaining "admissible" management procedures show the capability to improve stock status within 3-7 years with 90% certainty even under the most pessimistic scenario for stock productivity and current status. TAC levels for 2008 under these admissible procedures range from 1,500 to 2,700 tonnes; however, most will decrease TACs by up to 50% between 2009 and 2014 if the current stock decline continues. The simulated time required to maintain the spawning stock above 2007 levels with 90% certainty ranged from 4 to 7 years when the 2008 TACs were combined with the highest performing data-based management procedure. Advice in this paper is subject to several limitations based on our current representation of sablefish population dynamics in the operating model scenarios. High discard rates in all fisheries are of greatest concern at the moment because (*i*) our operating model estimates of stock status would be optimistic and (*ii*) failing to account for discard mortality in future projections means that actual recovery rates will be slower.

## Résumé

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# 1 Introduction

## 1.1 Background

Canadian national fisheries policy prescribes that harvest strategies comply with the Precautionary Approach to Capture Fisheries (DFO 2006, FAO 1995). In addition, an emerging fisheries management framework (March 2007, http://www.dfo-mpo.gc.ca/communic/fish_man ) endorsed the national harvest policy and outlined expectations for communicating the risk of resource decline under proposed management actions. The framework also identifies the need to involve stakeholders in the development of fishery objectives consistent with achieving the requirements of various eco-certification programs.

At the time sablefish (*Anoplopoma fimbria*) was last assessed in 2004 (Haist et al. 2005), stock abundance indices had increased relative to historically low levels observed in 2000 and 2001 (Appendix A). Since 2003, declines in these indices suggest that the stock may be approaching conditions experienced in 2001 to 2002 when a quota reduction from 4,000 t to 2,450 t was implemented (Fisheries and Oceans Canada 2002). Subsequent to this reduction, the quota was increased to 3,000 t for the directed sablefish 2003/2004 fishing year (Aug 1-Jul 31) and reached 4,600 t for the 2005/2006 fishing year as trap fishery and survey catch rates increased. As a result of pre-season consultation with the Sablefish Advisory Committee, the quota for the 2006/07 fishing year was reduced to 3,900 t and was similarly reduced to 3,300 t for the 2007/08 fishing year mainly as a result of declining survey indices of abundance and tagging estimates of exploitable biomass. Since 2006, the Science Committee under the DFO-CSA Joint Project Agreement has been developing a management strategy evaluation (MSE) approach aimed at identifying a consistent procedure for setting annual quotas. This process recently culminated in a methodology paper by Cox et al. (2008) that was endorsed by the Pacific Science Advise Review Committee.

This paper applies the MSE approach toward identifying an *interim* procedure for setting sablefish quotas in 2008 and beyond. Our presentation is organised into three main sections describing (*i*) the MSE approach, operating models, and candidate management procedures, (*ii*) detailed results comparing performance of alternative procedures against objectives, and (*iii*) management advice including the specific effects of alternative 2008 TACs on conservation and future yield. We show that 70-80% of procedures examined fail to meet specified conservation objectives. However, of the "admissible" management procedures, several show the capability to halt the current stock decline within 3-7 years with 90% certainty even under the most pessimistic scenario for the stock. TAC levels for 2008 under these admissible procedures range from 1,500 to 2,700 tonnes, however, most will decrease TACs rapidly between 2009 and 2014 if the current stock decline continues.

## 1.2 Fishery objectives

Recent consultations between sablefish industry stakeholders and fishery managers, as well as scientific review processes, have helped to establish two primary conservation objectives for B.C. sablefish fishery. In particular, fishery stakeholders developed an initial conservation objective to prevent further decline in the B.C. sablefish stock below the 2007 level of spawning biomass. This objective was subsequently refined by industry stakeholders and DFO managers to: increase the B.C. spawning stock above the 2007 level within 10 years with 90% certainty.

The second conservation objective, which was originally developed as a placeholder during the MSE process, was to maintain the B.C. spawning stock biomass above 20% of the unfished level. A conservation reference point of 20% of unfished spawning biomass was recently supported in the PSARC review of Cox et al. (2008). The difficulty with this particular objective, however, is that spawning biomass depletion is less than 20% of unfished when some scenario projections begin (e.g., scenario S1 below). Therefore, we developed an operational objective to rebuild spawning biomass above 20% of unfished within 1.5 sablefish generations.

Simulation analyses were performed to evaluate management procedure performance against the following operational objectives:

1. Rebuild B.C. spawning stock biomass to at least 20% of unfished within 1.5 generations (22.5 years assuming $M = 0.08$ and 50% maturity at age-5) with a minimum of 90% certainty;
2. Rebuild B.C. spawning stock biomass above the 2007 level within 10 years or less with a minimum of 90% certainty;
3. Maintain less than 20 % interannual variation in catch;
4. Maximize the median average annual catch over 1-10 years subject to the constraints imposed by Objectives 1-3.

Section 3.2 below provides a specific approach to using these objectives for choosing a management procedure.

## 1.3 Management strategy evaluation

Fishery management requested that evaluation of candidate management procedures against the above objectives utilize the management strategy evaluation (MSE) approach for sablefish developed in Cox et al. (2008). The methodology is a simulation-based framework for comparing the likely future consequences of applying candidate management procedures to alternative scenarios regarding the fish stock (Punt et al. 2001; Sainsbury et al. 2000). Scenarios represent structural hypotheses about the fish stock and/or fishery dynamics that are not currently resolved by the available data or those that may never be resolved. Development and evaluation of management procedures using a closed-loop simulation approach (Walters 1986, de la Mare 1986, 1996, 1998) addresses the requirements of the precautionary approach to fisheries management as well as DFO's decision-making framework. In particular, the approach: (*i*) considers alternative approaches for identifying stock status; (*ii*) evaluates alternative forms of decision rules that specify how harvest levels should be adjusted based on differences between stock status and operational targets; and (*iii*) demonstrates, via computer simulation, whether whole management procedures are likely to meet fishery management objectives.

At this early stage of sablefish MSE development, a specific management procedure has not been formally adopted by fishery managers or endorsed by the sablefish industry. Thus, we tested candidate *interim* procedures to illustrate their likely performance against various scenarios for the sablefish stock. Two specific modifications to procedures suggested through consultations with industry and managers were evaluated in addition to a subset of procedures examined by Cox et al. (2008). For the first modification, we introduced new procedures that set the 2008 TAC to either 1,500, 1,900, 2,300 or 2,700 tonnes, and then applied a particular data-based or catch-age model-based procedure thereafter. The second modification eliminated the necessity to constrain TAC changes between years to 15% or less during the first five years of management procedure implementation. However, as noted above, we retained the objective to limit interannual catch variability to less than 20% (i.e., it is now a lower priority objective than conservation rather than an absolute necessity). Note that we include results from the original constrained procedures for comparison with newly created alternatives.

## 1.4 Operating model

Candidate management procedures for sablefish were tested against scenarios S1 through S4 of the age-structured population dynamics operating model specified by Cox et al. (2008). Changes and updates to the management strategy evaluation between this paper and Cox et al. (2008) are given in Table 1. The main update is that the scenarios were parameterized by fitting the operating model to landings, standardized survey, trap fishery, and catch-age data updated to 2007. Scenarios S1-S4 are defined by combinations of stock productivity and spawning stock depletion as of 2007, namely: S1 - low productivity/low depletion; S2 - low productivity/moderate depletion; S3 - high productivity/moderate depletion; and S4 - high productivity/optimal depletion (Table 2).

It is important to note that the four operating model scenarios are not easily distinguished from the historical data based on commonly accepted statistical tests such as Akaike's information criterion. Such similarity implies that we should simply use the average results across scenarios to provide advice on an interim management procedure for sablefish. However, there exist potentially serious conservation and economic consequences should the future of sablefish turn out like scenario S1. Therefore, we judged conservation performance mainly against scenario S1 when conducting the evaluation.

## 1.5 Candidate interim management procedures

Cox et al. (2008) compared two general types of management procedure that both incorporated variable harvest rate control rules as required by DFO policy (2006). The two types are defined as:

1. Data-based (DB) procedures that set annual TACs by averaging the preceding year’s total catch with a multiple of the three-year running average of fishery-independent surveys, (Table 3) and;
2. Model-based procedures that set annual catch limits using constant exploitation rate policies and estimates of stock biomass from catch-age (CA) models (Table 3).

We do not consider the most aggressive procedures evaluated by Cox et al. (2008) in light of (*i*) the requirement that the removal rate reference not exceed the removal rate at maximum sustainable yield (DFO 2006), and (*ii*) the objective to prevent decline of the spawning biomass below the 2007 level. These requirements eliminated model-based procedures with $U^{ref} = 0.10$ and data-based procedures with $\lambda_2 = \{210, 240\}$ based on their relatively poor conservation performance in Cox et al. (2008). It is possible, however, that an appropriately tuned catch-age procedure with $U^{ref} = 0.08$ might be adequate, so we retained these procedures for this evaluation. Note also that, in the simulation projections, allocation of catch among trap, longline, trawl, and survey gear types was done using the catch proportions from 2007.

### 1.5.1 Data-based procedures

For data-based procedures, we examined survey multipliers of $\lambda_2 = \{120,150, 180\}$ with lower limit and upper stock reference values of $I_{low}$ = 4 kg/trap and $I_{high}$ = 15 kg/trap, respectively (Table 4). As described in Cox et al. (2008), the standardized survey is used for data-based procedures. Alternative tunings of the data-based procedure were also evaluated with lower limit $I_{low}$ = 6 kg/trap and upper $I_{high}$ = 18 kg/trap reference points to determine whether such procedures were capable of providing better catch-conservation trade-off performance. Presumably, increasing the lower limit reference point would increase the probability of avoiding high-risk situations associated with low stock biomass.

Most procedures set the smoothing parameter $\lambda_1 = 0.5$, however, in an attempt to evaluate procedures that allow more rapid TAC changes (increases or decreases) in response to changes in the survey average, we investigated selected tunings with $\lambda_1 = 0.2$.

Combining the above data-based configurations results in 3 general data-based procedure classes. For example, the data-based procedures with $\lambda_2 = 150$ can be grouped using the following notation (Table 4):

1. $DB_{150}$ - a variable harvest rate data-based procedure as defined and evaluated by Cox et al. (2008);

2. $DB_{150,\ 1900t}$ - identical to (1) above except that the TAC in 2008 is set to 1,900 t, or any other desired *catch* value;
3. $DB_{150,\ 15\%}$ - change in catch is limited to a maximum of 15% of the previous year's catch for the first 5 years only. This strategy represents a hard constraint on changes in quotas that overrides management procedure recommendations. Such a constraint implies that slow reduction in quotas is a higher priority objective than any other, including conservation of the stock.

Each of these $DB_{150}$ variants can then be combined with particular choices of $\lambda_1$ or harvest rule reference points $I_{low}$ and $I_{high}$ to better meet specific objectives provided by stakeholders and managers. Data-based combinations from Table 4 result in a total of 28 candidate procedures.

### 1.5.2 Catch-age procedures

The CA model-based procedures were evaluated at reference removal rates $U^{ref}$={0.04, 0.06, 0.08} (Table 4). Lower limit reference and upper stock reference limits of $D_{low} = 0.25$ and $D_{low} = 1.0$ were developed specifically in reference to 1992 spawning biomass; that is, when estimated biomass is at the 1992 level, the above $U^{ref}$ values are used and when estimated spawning biomass is 25% of the 1992 level, the removal rate is zero (Table 3). The risk adjustment $Q = 0.40$ seemed to have a minor effect on the results of Cox et al. (2008) and was omitted from model-based procedures evaluated here.

Combinations of CA model-based procedures fall into two general classes. For example, catch-age procedures with $U^{ref} = 0.06$ can be grouped using the following notation (Table 4):

1. $CA_{0.06,\ 1900t}$ - a variable harvest rate CA model-based procedure with $U^{ref} = 0.06$ and 2008 TAC set to 1900 t, or any other desired *catch* value;
2. $CA_{0.06,\ 15\%}$ - change in catch is limited to a maximum of 15% of the previous year's catch for the first 5 years only. As for the data-based procedures, this strategy imposes slow reduction in quotas as a higher priority objective than conservation.

Catch-age combinations from Table 4 result in a total of 15 candidate procedures.

## 1.6 Performance measures

Quantitative evaluation of management procedure performance requires that fishery objectives specify the following five main components: (*i*) a performance statistic value or range of acceptable values, (*ii*) a method of calculating performance statistics from simulation output, (*iii*) a specific time point or time-period over which to compute the statistics, (*iv*) an acceptable probability that performance occurs within the target range, and (*v*) a scheme for weighting the results arising from different operating model scenarios. The major objectives categories we consider include catch, inter-annual stability of catch, and conservation, although each of these may have several sub-categories and performance statistics. For example, a fishery manager may wish to achieve a target stock size such as $B_{\mathrm{MSY}}$ with 50% certainty, but place a more stringent requirement (e.g., 90% probability) on staying above a lower limit reference point such as $B_{20\%}$. Performance statistics and calculation methods are described in Table 5. Although each statistic may be computed over an arbitrary time period (i.e., $t_1$ - $t_2$), we provide 1 – 5, 6 – 10, 11 – 20, and 21 – 40 year summaries to reflect short-, medium-, and long-term planning horizons. Performance statistics are summarized across 100 simulation replicates and, where appropriate, we use medians of the above statistics to reduce the effects of extreme values.

We developed two new performance statistics to evaluate procedures against conservation Objectives 1 and 2. The first, $T_{0.2}$, is the projected number of years until the spawning biomass exceeded 20% of the unfished spawning biomass, $0.2B_0$, with 90% certainty. The target range for $T_{0.2}$ is 22.5 years (i.e., 1.5 sablefish generations) or less. The second additional performance measure, $T_{init}$, was added to this evaluation to measure the number of years until spawning biomass exceeds the initial spawning stock depletion in 2007 with 90% certainty. The target value for $T_{init}$ is 10 years or less. Both conservation performance statistics, $T_{0.2}$ and $T_{init}$, were computed as the number of years until the $10^{\mathrm{th}}$ percentile of the annual distribution of spawning biomass depletion values exceeded the limit reference point spawning biomass depletion values (i.e., 20% of $B_0$ and depletion in 2007 ($D_{init}$), respectively). It is important to note that these performance statistics relate to the overall distribution of simulated depletion values in any given year of the projection. In contrast, any particular replicate trajectory might increase above, say $0.2B_0$, sooner, go above/below $0.2B_0$ more than once during the projection, or may never actually exceed $0.2B_0$. The minimum possible values for both conservation measures is 1 year because, for example, the 2008 catch will not be implemented in the simulations until beginning-of-year spawning biomass is computed for 2009.

We illustrate performance differences among certain procedures using scenarios S1 and S2 because these are most relevant to current conservation concerns. The complete set of tabular results and graphical counterparts for scenarios S3 and S4 may be found in Appendix B. In general, all procedures perform relatively well for the more optimistic scenarios S3 and S4.

# 2 Results

## 2.1 Data-based procedures

Of the 28 data-based procedures we examined, only 8 passed the first conservation objective to rebuild the spawning stock above $B_{20\%}$ within 22.5 years or less with 90% certainty based on scenario S1 (Table 6). These admissible procedures fell exclusively within the $DB_{120}$ and $DB_{150}$ classes. Although median depletion of most $DB_{180}$ procedures increased beyond 20% within 11-20 years (Figure 1), none were able to provide the required 90% certainty within 22.5 years. All 8 of the admissible procedures also met the second conservation objective to rebuild the spawning stock above the initial level within 10 years or less with at least 90% certainty. In fact, these procedures required only 3 to 7 years to accomplish the objective. Three of these procedures, which involved combining $DB_{150}$ with the "conservation-based" harvest control rule references points $I_{low}$ = 6 kg/trap and $I_{high}$ = 18 kg/trap, did well in terms of conservation performance, but also increased interannual variability in catch because the $\lambda_2$ multiplier was adjusted more frequently. Other procedures obtained lower interannual variability in catch and greater average yields while providing similar conservation performance. Therefore, we did not consider these "conservation-based' procedures further.

Median depletion levels by year 10 of scenario S1 projections ranged from 0.183 to 0.193 for the 8 admissible data-based procedures. Meeting conservation objectives under scenario S1 involved 2008 quota levels ranging from 1,500 to 2,700 tonnes (Table 6); however, relatively low median annual average catches, ranging from 905 to 1,126 tonnes over years 1-10 resulted from applying the procedures over the remaining years. The procedure meeting all conservation and catch variability objectives while maximising the median average annual catch over years 1-10 was the $DB_{120,\,2700}$ $\lambda_1$ = 0.5, {4,15} (Table 6).

Under scenario S2, all data-based procedures met Objective (1) because the spawning stock biomass was initially well above 20% of the unfished level. We did not eliminate procedures based on the observation that only 4 procedures met Objective (2) because the stock is maintained quite close to its maximum sustainable yield level under this scenario (Table 7). The top-ranked procedure under scenario S1 obtained median depletion levels under S2 that were close to the MSY level by 11-20 years, and above MSY levels by 21-40 years (Figure 2).

For both scenarios S1 and S2, the "constrained" data-based procedures that limited interannual changes in catch to 15% or less performed the worst within their class in terms of both conservation and catch (note outlier points in Figures 1 and 2). A constant catch procedure that applies the 2007/2008 fishing year TAC of 3,300 t to every future year is included in Table 6 and Figures 1 and 2 to illustrate the consequences of not adjusting catches in proportion to abundance. For scenario S1, the median depletion is reduced to 0.074 at 10 years under this constant catch procedure and the stock collapses soon after. Under scenario 2, the median stock increases slightly above 20% of unfished by years 11-20; however, in the long-term (21-40 years), the stock fails to recover to the MSY level and the $10^{th}$ percentile of spawning biomass depletion remains below 0.10 (Figure 2). Therefore, both the constrained and constant catch procedures fail to meet conservation objectives and are not considered further (this has already been recognized by industry and managers as part of Cox et al. (2008) evaluation).

## 2.2 Catch-age model procedures

Of the 15 catch-age procedures we examined, only 3 passed the first conservation objective to rebuild the spawning stock above $B_{20\%}$ within 22.5 years with at least 90% certainty based on scenario S1 (Table 8). These admissible procedures fell exclusively within the $CA_{0.04,catch}$ class, which is not particularly surprising because the removal rate reference $U^{ref} = 0.04$ is slightly less than the exploitation rate at MSY ($U_{MSY} = 0.045$). Meeting conservation objectives under scenario S1 using $CA_{0.06,catch}$ procedures involved 2008 quota levels ranging of 1,500, 1,900, or 2,300 tonnes. These procedures all met the $T_{0.2}$ objective while also providing 90% certainty that the stock would recover above the 2007 level within 3-4 years (Table 8, $T_{init}$). Although median depletion of the $CA_{0.06}$ and $CA_{0.06,\,catch}$ classes increased to approximately 20% within 11-20 years (Figure 3), none were able to provide the required 90% certainty within 22.5 years or less under scenario S1.

Median spawning biomass depletion levels by year 10 of the scenario S1 projections ranged from 0.184 to 0.186 for the 3 admissible catch-age procedures. Similar to the data-based procedure results, meeting conservation objectives under scenario S1 involved relatively low median annual average catches over years 1-10 ranging from 1,121 to 1,163 tonnes. The procedure meeting all conservation and catch variability objectives while maximising the median average annual catch over years 1-10 was the $CA_{0.04,\,2300}$ {0.25,1.0} (Table 8).

Under scenario S2, all catch-age procedures met Objective (1) because the spawning stock biomass is well above 20% of unfished biomass initially. Like the data-based situation described above, we did not eliminate procedures based on the observation that none met Objective (2) under scenario S2. We made this choice because the stock is maintained on average quite close to its maximum sustainable yield level for all $CA_{0.04}$ procedures that were admissible under scenario S1 (Table 8). Note that all other CA procedures failed to rebuild or maintain the stock above the initial level with 90% certainty, so $T_{init}$ could not be calculated. Again, because the stock begins near the MSY level, failure to meet this objective is not critical in the short term. Procedures within the $CA_{0.08}$ class do increase the stock above the initial level by 21-40 years, however, there remains a high probability that the stock will be maintained below $B_{20\%}$ for scenario S1 and a small probability for S2 (Figures 3 and 4). Thus, we did not consider the $CA_{0.08}$ procedures further here, although future work should evaluate this class with alternative reference points. Also, like their data-based counterparts, procedures using the 15% constraint on year-to-year changes in TAC performed the worst in their respective classes in terms of both conservation and catch (Figures 3 and 4).

## 3 Advice to managers

This section provides a detailed description of the effects of 2008 TAC choices on the ability to meet conservation objectives. We then invoke a relatively straightforward strategy for selecting a management procedure from among the 33 possible candidates while explicitly taking fishery objectives into account. Finally, we describe some of the limitations of our advice; in particular, the potential sensitivity of our approach to current uncertainties.

## 3.1 Effects of 2008 quota on fishery performance

Procedures within the $DB_{120}$ class performed similarly (using S1) in terms of average annual catch, but differed substantially in short-term conservation performance depending upon the 2008 quota. For example, although the $DB_{120, 2700}$ (note: other rule parameters are omitted to reduce clutter) procedure results in a median average catch of 1,126 t over 10 years, the $DB_{120, 1900}$ procedure obtained 1,012 t per year on average while increasing the spawning stock above 2007 levels within 4 years instead of 7. Figure 5 shows four variations of $DB_{120}$. Although all of these candidates provide similar long-term depletion and catch performance (recall that long-term performance is determined mainly by $\lambda_2 = 120$, which is common to all these procedures), lower 2008 quotas decrease the immediate rate of stock decline and thereby increase the rate of recovery. Ultimately, by year 10 the $DB_{120, 1900}$ procedure provides almost 100 t greater expected average catch (Table 5; Catch (t=10)) and 40 t greater expected minimum catch (Table 5; Min. catch (1-10 years)). Differences between these four procedures are less pronounced under scenario S2 (Figure 6).

Procedures in the catch-age $CA_{0.04}$ class show similar short-term differences under scenario S1 as those observed for the $DB_{120}$ class; that is, a 2008 quota of 1,900 t compared to 2,700 shortens the time required to increase the stock above the initial level by half (i.e., from 5 years to 3), while differing by only 42 t in expected 10-year average catch (Figure 7). Under scenario S2, the 2008 quota has no noticeable effect on conservation performance because the stock begins at a higher level. Thus, there is actually not as much "room for growth" compared to scenario S1, where there is a wide gap between the 2007 level and the MSY level.

## 3.2 Choosing a management procedure

We applied the hierarchical strategy for choosing among candidate management procedures that was described by Cox et al. (2008). The approach orders fishery management objectives linearly according to their level of priority under a precautionary fishery management policy in which conservation objectives predominate over volatility and yield considerations. Treatment of uncertainty is accomplished by stating specific operational objectives in probabilistic terms while being equally specific about the time frames over which objectives should be achieved. Management procedures failing to meet an objective at any level are discarded as not being effective at generating desirable outcomes.

Table 9 provides a decision-making strategy that evaluates management procedure performance against the four objectives identified in the Introduction to this document. The final column of Table 9 shows the number of data-based (DB) and catch-age (CA) procedures capable of meeting the objectives at each level of the hierarchy. It is clear that the first conservation objective dominates the others because it eliminated approximately 70% and 80% of data-based and catch-age procedures, respectively. The second and third objectives did not eliminate any procedures that had already passed Objective 1. Despite this lack of sensitivity, performance under Objective 2 important to decision-making because it provides an immediate goal to be achieved compared to the goal of Objective 1, which may not be achieved for up to two decades in some cases. In particular, our analysis has revealed that shortening the time horizon for Objective 2 to, say, 3-5 years as opposed to 10 years may allow faster progress toward conservation objectives while sacrificing little in terms of average annual yield. Faster progress under the top-ranked data-based procedure (i.e., $DB_{120,\,catch}$ ) is achieved as the sole result of the 2008 quota. **Under the $DB_{120,\,catch}$ procedure, 2008 TACs of 2,700, 2,300, and 1,900 t are associated with times of 7, 6, and 4 years, respectively to maintain spawning stock biomass above the 2007 level with 90% certainty.** It is important to note that these timeframes are predicated on following the particular management procedure for the full duration of the period. Also, given that we only simulated 100 replicate trajectories, differences in rebuilding performance of 1-year should essentially be ignored.

## 3.3 Limitations of advice

The operating model scenarios for B.C. sablefish were determined using structural assumptions and methods typical of fisheries stock assessment and each therefore contains the inherent uncertainties found in most fisheries models. However, unlike the traditional single "best assessment" approach, we evaluated the sensitivity of proposed management procedures over a range of stock scenarios that we think encompass several plausible alternatives. The reader may have noticed that we downplayed the importance of optimistic scenarios S3 and S4 in this assessment. We did this for two reasons. First, almost all procedures performed well under these scenarios in both the short- and long-term. Thus, it is reassuring that if the stock is actually better off than we anticipate, conservation and catch performance will improve relatively rapidly based on advice derived from this type of assessment. Second, we did not feel justified in treating scenarios S3 and S4 equally with S1 and S2 despite similarities based on statistical grounds. Scenarios S3 and S4 contain highly optimistic productivity and linear fishery CPUE assumptions that have both been rightly criticized in the fisheries literature (Hilborn and Walters 1992).

Scenarios considered in this paper focused on B.C. sablefish stock productivity and the present level of spawning biomass depletion. Although these two uncertainties are amongst the most critical to evaluate in management strategy simulations, these scenarios do not capture the broader range of uncertainties associated with the B.C. sablefish stock and fishery (Table 10). Cox et al. (2008) provided a list of key uncertainties that could cause failure of the sablefish management procedures evaluated in this document. High discard rates in all fisheries are of particular concern because (*i*) our operating model estimates of stock status would be optimistic and (*ii*) failing to account for discard mortality in future projections means that actual recovery rates will be slower.

Simulated performance of management procedures also assumes that data collection programs required to support those procedures are in place in the future. Some of these data collection programs are currently in doubt. For example, the commercial catch sampling program that would provide fishery catch-at-age is being re-introduced and may be fully in place by mid-2008. If re-introduction of this program is unsuccessful, then management planning on the basis of catch-age model-based procedures is moot. On the basis of statistical principles and industry desires, the standardized trap survey program is likely to be replaced by the existing stratified random trap survey, which began in 2003. Regardless of the fate of the standardised survey program, industry stakeholders have expressed a preference for using the stratified random survey in data-based management procedures. Thus, MSE development will necessarily have to begin work on a succession procedure for the future using an index derived from the stratified random survey.

## 3.4 Conclusions

The purpose of management strategy evaluation is to identify a fishery management procedure that, when followed over time, adequately meets objectives that are agreed upon by industry stakeholders and fishery managers. This paper demonstrated that embedding different 2008 quota choices into several candidate management procedures mainly affected short-term performance relative to conservation objectives. Although the full range of 2008 TAC options (1,500 - 2,700 t) was included in the admissible management procedures, we expect that quotas in the range 2,000-2,400 t will achieve conservation objectives more rapidly and with greater certainty, while potentially buffering against known uncertainties such as discarding. Importantly, similar average annual catch is expected over 10-years for all quota levels considered. It should also be noted that improved conservation performance also improves profitability because fishery catch-per-unit effort is also expected to be higher.

For both data-based and CA model-based procedures, the long-term performance does not vary widely within scenarios because a single TAC value within the range tested cannot dominate the long-term properties of the procedures. All admissible data-based procedures indicate a significant decline in median catch to at least the 2,000 t level (scenario S4) and as low as ~1000 t (scenario S1) during the first 10 years of the projection with the minimum occurring about 5 years into the projection period. This outcome mainly reflects the apparent lack of significant sablefish recruitment as suggested by recent data (e.g., stock indices, age proportions). The management procedures we evaluated attempt to deal with declining stock abundance indices by reducing directed catch, and thus are expected to maintain stock sizes at reasonable levels despite such poor recruitment. Ultimately, use of variable harvest rate decision rules as required by national fisheries policy is intended to encourage stock growth towards their most productive levels. Based on the simulation results, the costs of not reducing catches according to a consistent procedure are longer times to meet conservation objectives and increased risks associated with depletion levels lower than the 2007 level.

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Table 1 Differences between this document and Cox et al. (2008).

| Topic | Change | Location |
|---|---|---|
| Objectives | • Revised for FY2008/2009 to emphasize conservation objectives determined from consultations<br>• Added objective to prevent decline of the spawning biomass below the current level with 90% certainty<br>• Added objective to rebuild stock above $B_{20\%}$<br>• Lowered priority of objective to limit year-to-year changes to 15% or less during the first 5 projection years | Section 1.2 |
| Operating model | • Removed Japanese longline CPUE series<br>• Removed tagging biomass index<br>• Set growth parameter $L_1$=35 cm and re-estimated $k$ and $L_\infty$<br>• Added 2006 standardized survey age proportions | Section 1.4<br>Appendix A |
| Procedures: *Data* | • Updated landings history to December 31, 2007<br>• Updated nominal trap fishery catch rates to December 31, 2007<br>• Added 2007 standardized survey index point<br>• Added age proportions added for 2006 standardized survey | Appendix A |
| Procedures: *Methods* | • Dropped assessment methods based on a production model<br>• Removed precautionary risk adjustment from CA model-based methods | Section 1.5 |
| Procedures: *Rules* | • Considered only variable harvest rate decision rules<br>• Evaluated procedures that fix catch at selected values in the first projection year<br>• Evaluated procedures without 15% constraint on year-to-year TAC changes during the first 5 projection years | Section 1.5.1<br>Section 1.5.2 |
| Other indicators | • Added sablefish abundance indices derived from multi-species trawl surveys, inlets survey results | Appendix A |
| Management history | • Updated to 2007 | Appendix A |

Table 2 Distinguishing features of operating model scenarios S1-S4. Parameters are the steepness of the Beverton-Holt stock-recruitment function ($h$) and trap fishery hyperstability ($q_{2,trap}$). Equilibrium yield characteristics include the MSY, exploitation rate at MSY ($U_{MSY}$), unfished spawning biomass ($B_0$), spawning biomass ($B_{MSY}$) and depletion at MSY ($D_{MSY}$). Initial spawning biomass conditions for the operating models are given as spawning stock biomass ($B_{2007}$) and depletion ($D_{2007}$) in 2007. Biomass units are metric tonnes.

| Scenario | Parameters | Description | MSY | $U_{MSY}$ | $B_0$ | $B_{MSY}$ | $B_{2007}$ | $D_{MSY}$ | $D_{2007}$ |
|---|---|---|---|---|---|---|---|---|---|
| S1 | $h = 0.45$<br>$\hat{q}_{2,trap} = 0.422$ | Low productivity<br>Low initial depletion | 2,931 | 0.047 | 146,907 | 55,022 | 22,918 | 0.375 | 0.156 |
| S2 | $h = 0.45$<br>$q_{2,trap} = 1.0$ | Low productivity<br>Moderate initial depletion | 3,003 | 0.047 | 150,534 | 56,381 | 42,315 | 0.375 | 0.281 |
| S3 | $h = 0.65$<br>$\hat{q}_{2,trap} = 0.483$ | High productivity<br>Low initial depletion | 4,211 | 0.084 | 138,586 | 42,357 | 29,230 | 0.306 | 0.211 |
| S4 | $h = 0.65$<br>$q_{2,trap} = 1.0$ | High productivity<br>Initial depletion at MSY | 4,340 | 0.084 | 142,813 | 43,649 | 44,038 | 0.306 | 0.308 |

Table 3 Equations and definitions for data-based and catch-age harvest control rules.

| Data-based Harvest Control Rule | | Notation |
|---|---|---|
| T3.1 | $C_{T+1} = \lambda_1 C_T + (1-\lambda_1)\tilde{\lambda}_{2,T+1} I_T^*, \quad 0 \le \lambda_1 \le 1$ | $C_T$ catch in year $T$<br>$\lambda_1$ weight on $C_T$<br>$\tilde{\lambda}_2$ adjusted survey multiplier<br>$I_T^*$ 3-yr survey average |
| T3.2 | $\tilde{\lambda}_{2,T+1} = \begin{cases} 0 & I_T^* < I_{low} \\ \lambda_2 \left( \dfrac{I_T^* - I_{low}}{I_{high} - I_{low}} \right) & I_{low} \le I_T^* < I_{high} \\ \lambda_2 & I_T^* \ge I_{high} \end{cases}$ | $I_{low}$ limit reference point<br>$I_{high}$ upper stock reference<br>$\lambda_2$ reference survey multiplier |
| **Catch-age Model-based Harvest Control Rule** | | |
| T3.3 | $C_{T+1} = U_{T+1} \hat{B}_{T+1}$ | $C_{T+1}$ catch in year $T$+1<br>$U_{T+1}$ adjusted harvest rate<br>$\hat{B}_{T+1}$ projected trap biomass |
| T3.4 | $U_{T+1} = \begin{cases} 0 & \hat{D}_T < D_{low} \\ U^{ref} \left( \dfrac{D_{high}}{\hat{D}_T} \right) \left( \dfrac{\hat{D}_T - D_{low}}{D_{high} - D_{low}} \right) & D_{low} \le \hat{D}_T < D_{high} \\ U^{ref} & \hat{D}_T \ge D_{high} \end{cases}$ | $D_{low}$ limit reference point<br>$D_{high}$ upper stock reference<br>$U^{ref}$ reference harvest rate |
| T3.5 | $\hat{D}_T = \hat{S}_T / \hat{S}_{1992}$ | $\hat{D}_T$ spawning biomass depletion<br>$\hat{S}_T$ spawning biomass |

Table 4 Summary of candidate *interim* management procedures for B.C. sablefish. Each procedure consists of data, an assessment method, and a harvest control rule defined by a set of parameters.

| MP class | Data | Assessment Method | Rule Type | Rule Parameters |
|---|---|---|---|---|
| DB $\lambda_2$ | Catch<br>Survey index | 3-year running mean of survey | Variable harvest rate | $\lambda_1 = \{0.2, 0.5\}, \lambda_2 = \{120, 150, 180\}$<br>$I_{low} = \{4, 6\}$, $I_{high} = \{15, 18\}$ |
| DB $\lambda_{2,catch}$ | Catch<br>Survey index | 3-year running mean of survey index | Variable harvest rate, 2008 catch set to *catch* | $\lambda_1 = \{0.5\}$, $\lambda_2 = \{120, 150, 180\}$<br>$I_{low} = \{4\}$, $I_{high} = \{15\}$<br>$catch = \{1500, 1900, 2300, 2700\}$ |
| DB $\lambda_{2,15\%}$ | Catch<br>Survey index | 3-year running mean of survey index | Variable harvest rate, 15% per year limit on TAC change over first 5 years | $\lambda_1 = \{0.5\}$, $\lambda_2 = \{120,150,180\}$<br>$I_{low} = \{4\}$, $I_{high} = \{15\}$ |
| CA$_{U^{ref}}$ | Catch<br>Survey index<br>Trap fishery | Catch-at-age model | Variable harvest rate | $U^{ref} = \{0.04, 0.06, 0.08\}$<br>$D_{low} = \{0.25\}$, $D_{high} = \{1.0\}$ |
| CA$_{U^{ref}, catch}$ | Catch<br>Survey index<br>Trap fishery ages<br>Survey ages | Catch-at-age model | Variable harvest rate, 2008 catch set to *catch* | $U^{ref} = \{0.04, 0.06, 0.08\}$<br>$D_{low} = \{0.25\}$, $D_{high} = \{1.0\}$<br>$catch = \{1500, 1900, 2300, 2700\}$ |
| CA$_{U^{ref},15\%}$ | Catch<br>Survey index<br>Trap fishery ages<br>Survey ages | Catch-at-age model | Variable harvest rate, 15% per year limit on TAC change over first 5 years | $U^{ref} = \{0.04, 0.06, 0.08\}$<br>$D_{low} = \{0.25\}$, $D_{high} = \{1.0\}$ |

Table 5 Definitions of performance statistics used for sablefish management strategy evaluation. The interval $t = t_1, \ldots, t_2$ defines the time period over which statistics are calculated. The "-" symbol indicates that the explanation of the Performance statistic is a sufficient Definition.

| Objective Type | Performance statistic | Symbol | Definition |
|---|---|---|---|
| Conservation | Arithmetic mean of annual spawning biomass depletion. | $\overline{D}$ | $\overline{D} = \frac{1}{t_2 - t_1 + 1} \sum_{t=t_1}^{t_2} \left( \frac{S_t}{B_0} \right)$ |
| Conservation | Number of years until the 10th percentile of annual spawning biomass depletion exceeds initial depletion, $D_{init}$. | $T_{init}$ | - |
| Conservation | Number of years until the 10th percentile of annual spawning biomass depletion exceeds 20% of $B_0$. | $T_{0.2}$ | - |
| Conservation | Probability that the spawning biomass, $S_t$, exceeds 20% of $B_0$. | $P_{cons}$ | $P\left(S_t > 0.2B_0\right)$ |
| Catch variability | Average annual absolute change in catch. | $AAV$ | $AAV = \sum_{t=t_1}^{t_2} \left\lvert C_t - C_{t-1} \right\rvert \Big/ \sum_{t=t_1}^{t_2} C_t$ |
| Catch | Arithmetic mean of annual catches. | $\overline{C}$ | $\overline{C} = \frac{1}{t_2 - t_1 + 1} \sum_{t=t_1}^{t_2} C_t$ |
| Catch | Minimum catch over the time interval. | $C_{\min}$ | Minimum catch from $t = t_1, \ldots, t_2$. |
| Catch | Maximum average catch over the time interval. | $\overline{C}_{0.95}$ | 95th percentile of distribution of $\overline{C}$ |

Table 6 Performance statistics for data-based procedures applied to scenario S1. Results are sorted in priority order by (1) $T_{0.2}$ (descending), (2) $T_{init}$ (descending) and (3) Average catch over 1-10 years (ascending). The "-" symbol indicates that the time extended beyond the total 40-year simulation period. Procedures shown in bold font meet the two conservation objectives and the top ranked procedure overall is marked with "**".

| Procedure | $T_{0.2}$ | $T_{init}$ | Depletion (t = 10) | 2008 Catch | Avg. catch (1-10 yrs) | Catch (t= 10) | Min. catch (1-10 yrs) | Max. catch (1-10 yrs) |
|---|---|---|---|---|---|---|---|---|
| **$DB_{120,1500t}$ $\lambda_1$=0.5 {4,15}** | **21** | **3** | **0.193** | **1500** | **956** | **1038** | **588** | **1356** |
| **$DB_{150,1900t}$ $\lambda_1$=0.5 {6,18}** | **22** | **3** | **0.195** | **1900** | **905** | **891** | **433** | **1336** |
| **$DB_{120,1900t}$ $\lambda_1$=0.5 {4,15}** | **22** | **4** | **0.190** | **1900** | **1012** | **991** | **570** | **1408** |
| **$DB_{150,2300t}$ $\lambda_1$=0.5 {6,18}** | **22** | **5** | **0.192** | **2300** | **960** | **841** | **416** | **1380** |
| **$DB_{120,2300t}$ $\lambda_1$=0.5 {4,15}** | **22** | **6** | **0.186** | **2300** | **1068** | **945** | **552** | **1460** |
| **$DB_{150}$ $\lambda_1$=0.5 {6,18}** | **22** | **6** | **0.189** | **2660** | **1011** | **798** | **397** | **1417** |
| **$DB_{120,2700t}$ $\lambda_1$=0.5 {4,15}**** | **22** | **7** | **0.183** | **2700** | **1126** | **898** | **532** | **1512** |
| **$DB_{120}$ $\lambda_1$=0.5 {4,15}** | **22** | **7** | **0.183** | **2649** | **1118** | **905** | **533** | **1505** |
| $DB_{180,1900t}$ $\lambda_1$=0.5 {6,18} | 25 | 4 | 0.191 | 1900 | 997 | 1015 | 500 | 1497 |
| $DB_{180,2300t}$ $\lambda_1$=0.5 {6,18} | 25 | 6 | 0.187 | 2300 | 1049 | 958 | 473 | 1537 |
| $DB_{180}$ $\lambda_1$=0.5 {6,18} | 25 | 7 | 0.183 | 2850 | 1122 | 884 | 440 | 1589 |
| $DB_{120,15\%}$ $\lambda_1$=0.5 {4,15} | 25 | 13 | 0.158 | 2901 | 1569 | 772 | 772 | 1741 |
| $DB_{150,1500t}$ $\lambda_1$=0.5 {4,15} | 32 | 3 | 0.186 | 1500 | 1100 | 1222 | 701 | 1591 |
| $DB_{150,1900t}$ $\lambda_1$=0.2 {4,15} | 32 | 4 | 0.185 | 1900 | 1121 | 1293 | 562 | 1604 |
| $DB_{150}$ $\lambda_1$=0.2 {4,15} | 32 | 6 | 0.182 | 2568 | 1167 | 1234 | 530 | 1645 |
| $DB_{150,1900t}$ $\lambda_1$=0.5 {4,15} | 32 | 6 | 0.183 | 1900 | 1150 | 1164 | 679 | 1634 |
| $DB_{150,2300t}$ $\lambda_1$=0.5 {4,15} | 33 | 7 | 0.180 | 2300 | 1201 | 1113 | 655 | 1678 |
| $DB_{150,2700t}$ $\lambda_1$=0.5 {4,15} | 33 | 9 | 0.177 | 2700 | 1253 | 1057 | 627 | 1722 |
| $DB_{150}$ $\lambda_1$=0.5 {4,15} | 33 | 10 | 0.175 | 2885 | 1278 | 1029 | 622 | 1742 |
| $DB_{150,15\%}$ $\lambda_1$=0.5 {4,15} | 33 | 13 | 0.157 | 2901 | 1594 | 909 | 871 | 1859 |
| $DB_{180,1900t}$ $\lambda_1$=0.2 {4,15} | - | 6 | 0.178 | 1900 | 1266 | 1444 | 655 | 1832 |
| $DB_{180,1500t}$ $\lambda_1$=0.5 {4,15} | - | 6 | 0.181 | 1500 | 1236 | 1384 | 805 | 1808 |
| $DB_{180}$ $\lambda_1$=0.2 {4,15} | - | 7 | 0.173 | 2945 | 1329 | 1346 | 595 | 1881 |
| $DB_{180,1900t}$ $\lambda_1$=0.5 {4,15} | - | 7 | 0.177 | 1900 | 1280 | 1314 | 778 | 1845 |
| $DB_{180,2300t}$ $\lambda_1$=0.5 {4,15} | - | 10 | 0.174 | 2300 | 1327 | 1256 | 752 | 1882 |
| $DB_{180}$ $\lambda_1$=0.5 {4,15} | - | 11 | 0.168 | 3120 | 1425 | 1121 | 698 | 1959 |
| $DB_{180,2700t}$ $\lambda_1$=0.5 {4,15} | - | 11 | 0.171 | 2700 | 1374 | 1194 | 722 | 1920 |
| $DB_{180,15\%}$ $\lambda_1$=0.5 {4,15} | - | 14 | 0.149 | 3120 | 1723 | 995 | 953 | 2040 |
| Constant Catch | - | - | 0.074 | 3300 | 3300 | 3300 | 3300 | 3300 |

Table 7 Performance statistics for data-based procedures applied to scenario S2. Results are sorted in priority order by (1) $T_{0.2}$ (descending), (2) $T_{init}$ (descending) and (3) Average catch over 1-10 years (ascending). The "-" symbol indicates that the time extended beyond the total 40-year simulation period. Procedures shown in bold font meet the two conservation objectives. Procedures shown in bold font meet the two conservation objectives and the top ranked procedure overall is marked with "**".

| Procedure | $T_{0.2}$ | $T_{init}$ | Depletion (t = 10) | 2008 Catch | Avg. catch (1-10 yrs) | Catch (t= 10) | Min. catch (1-10 yrs) | Max. catch (1-10 yrs) |
|---|---|---|---|---|---|---|---|---|
| **$DB_{120,1500t}$ $\lambda_1$=0.5 {4,15}** | **1** | **3** | **0.323** | **1500** | **1364** | **1631** | **981** | **1804** |
| **$DB_{150,1900t}$ $\lambda_1$=0.5 {6,18}** | **1** | **7** | **0.325** | **1900** | **1346** | **1572** | **857** | **1975** |
| **$DB_{120,1900t}$ $\lambda_1$=0.5 {4,15}** | **1** | **10** | **0.320** | **1900** | **1427** | **1603** | **991** | **1868** |
| **$DB_{150,2300t}$ $\lambda_1$=0.5 {6,18}** | **1** | **10** | **0.322** | **2300** | **1403** | **1531** | **859** | **2027** |
| $DB_{150,1900t}$ $\lambda_1$=0.2 {4,15} | 1 | 11 | 0.311 | 1900 | 1680 | 1979 | 1047 | 2241 |
| $DB_{150,1900t}$ $\lambda_1$=0.5 {4,15} | 1 | 11 | 0.312 | 1900 | 1671 | 1934 | 1185 | 2222 |
| $DB_{180}$ $\lambda_1$=0.5 {6,18} | 1 | 11 | 0.308 | 2850 | 1644 | 1692 | 982 | 2371 |
| $DB_{150,1500t}$ $\lambda_1$=0.5 {4,15} | 1 | 11 | 0.315 | 1500 | 1612 | 1970 | 1188 | 2162 |
| $DB_{180,2300t}$ $\lambda_1$=0.5 {6,18} | 1 | 11 | 0.311 | 2300 | 1571 | 1759 | 992 | 2305 |
| $DB_{120,2700t}$ $\lambda_1$=0.5 {4,15}** | 1 | 11 | 0.313 | 2700 | 1553 | 1547 | 991 | 1997 |
| $DB_{120}$ $\lambda_1$=0.5 {4,15} | 1 | 11 | 0.314 | 2649 | 1545 | 1550 | 993 | 1989 |
| $DB_{180,1900t}$ $\lambda_1$=0.5 {6,18} | 1 | 11 | 0.314 | 1900 | 1519 | 1808 | 994 | 2258 |
| $DB_{120,2300t}$ $\lambda_1$=0.5 {4,15} | 1 | 11 | 0.317 | 2300 | 1490 | 1575 | 995 | 1933 |
| $DB_{150}$ $\lambda_1$=0.5 {6,18} | 1 | 11 | 0.319 | 2660 | 1454 | 1493 | 856 | 2074 |
| $DB_{150}$ $\lambda_1$=0.5 {4,15} | 1 | 12 | 0.304 | 2885 | 1809 | 1832 | 1168 | 2371 |
| $DB_{150,2700t}$ $\lambda_1$=0.5 {4,15} | 1 | 12 | 0.306 | 2700 | 1784 | 1851 | 1176 | 2343 |
| $DB_{150}$ $\lambda_1$=0.2 {4,15} | 1 | 12 | 0.308 | 2568 | 1732 | 1936 | 1026 | 2292 |
| $DB_{150,2300t}$ $\lambda_1$=0.5 {4,15} | 1 | 12 | 0.309 | 2300 | 1729 | 1892 | 1192 | 2283 |
| $DB_{120,15\%}$ $\lambda_1$=0.5 {4,15} | 1 | 13 | 0.301 | 2901 | 1765 | 1465 | 1186 | 2094 |
| $DB_{150,15\%}$ $\lambda_1$=0.5 {4,15} | 1 | 14 | 0.293 | 2901 | 1901 | 1736 | 1352 | 2402 |
| $DB_{180,2700t}$ $\lambda_1$=0.5 {4,15} | 1 | 15 | 0.295 | 2700 | 2004 | 2127 | 1369 | 2679 |
| $DB_{180}$ $\lambda_1$=0.2 {4,15} | 1 | 15 | 0.295 | 2945 | 1997 | 2165 | 1188 | 2654 |
| $DB_{180,2300t}$ $\lambda_1$=0.5 {4,15} | 1 | 15 | 0.298 | 2300 | 1954 | 2173 | 1375 | 2625 |
| $DB_{180,1900t}$ $\lambda_1$=0.2 {4,15} | 1 | 15 | 0.299 | 1900 | 1926 | 2239 | 1221 | 2581 |
| $DB_{180,1900t}$ $\lambda_1$=0.5 {4,15} | 1 | 15 | 0.301 | 1900 | 1903 | 2221 | 1385 | 2569 |
| $DB_{180,1500t}$ $\lambda_1$=0.5 {4,15} | 1 | 15 | 0.304 | 1500 | 1851 | 2264 | 1377 | 2512 |
| $DB_{180,15\%}$ $\lambda_1$=0.5 {4,15} | 1 | 16 | 0.286 | 3120 | 2112 | 1967 | 1545 | 2733 |
| $DB_{180}$ $\lambda_1$=0.5 {4,15} | 1 | 16 | 0.292 | 3120 | 2056 | 2073 | 1339 | 2736 |
| Constant Catch | 1 | - | 0.230 | 3300 | 3300 | 3300 | 3300 | 3300 |

Table 8 Performance statistics for CA based procedures applied to scenarios S1 and S2. Results are sorted in priority order by (1) $T_{0.2}$ (descending), (2) $T_{init}$ (descending) and (3) Average catch over 1-10 years (ascending). The "-" symbol indicates that the time extended beyond the total 40-year simulation period. Procedures shown in bold font meet the two conservation objectives and the top ranked procedure overall is marked with "**".

| Procedure | $T_{0.2}$ | $T_{init}$ | Depletion (t = 10) | 2008 Catch | Avg. catch (1-10 yrs) | Catch (t= 10) | Min. catch (1-10 yrs) | Max. catch (1-10 yrs) |
|---|---|---|---|---|---|---|---|---|
| **Scenario S1** | | | | | | | | |
| **$CA_{0.04,1900t}$ {0.25,1.0}** | **22** | **3** | **0.186** | **1900** | **1142** | **1100** | **865** | **1437** |
| **$CA_{0.04,1500t}$ {0.25,1.0}** | **22** | **3** | **0.187** | **1500** | **1121** | **1118** | **888** | **1418** |
| **$CA_{0.04,2300t}$ {0.25,1.0}**** | **22** | **4** | **0.184** | **2300** | **1163** | **1083** | **845** | **1455** |
| $CA_{0.04,2700t}$ {0.25,1.0} | 23 | 5 | 0.182 | 2700 | 1184 | 1066 | 823 | 1476 |
| $CA_{0.04,15\%}$ {0.25,1.0} | 28 | 12 | 0.164 | 2901 | 1485 | 892 | 680 | 1713 |
| $CA_{0.06,1500t}$ {0.25,1.0} | 36 | 11 | 0.170 | 1500 | 1480 | 1410 | 1139 | 1885 |
| $CA_{0.06,2300t}$ {0.25,1.0} | 36 | 12 | 0.168 | 2300 | 1506 | 1371 | 1087 | 1908 |
| $CA_{0.06,1900t}$ {0.25,1.0} | 36 | 12 | 0.169 | 1900 | 1494 | 1391 | 1112 | 1898 |
| $CA_{0.06,2700t}$ {0.25,1.0} | 36 | 13 | 0.166 | 2700 | 1518 | 1354 | 1063 | 1919 |
| $CA_{0.06,15\%}$ {0.25,1.0} | 36 | 15 | 0.156 | 2901 | 1659 | 1217 | 988 | 1991 |
| $CA_{0.08,1500t}$ {0.25,1.0} | - | 22 | 0.155 | 1500 | 1763 | 1605 | 1296 | 2258 |
| $CA_{0.08,15\%}$ {0.25,1.0} | - | 24 | 0.148 | 2901 | 1852 | 1459 | 1182 | 2295 |
| $CA_{0.08,2700t}$ {0.25,1.0} | - | 24 | 0.152 | 2700 | 1779 | 1539 | 1199 | 2280 |
| $CA_{0.08,2300t}$ {0.25,1.0} | - | 24 | 0.153 | 2300 | 1774 | 1562 | 1225 | 2275 |
| $CA_{0.08,1900t}$ {0.25,1.0} | - | 24 | 0.154 | 1900 | 1769 | 1584 | 1256 | 2268 |
| **Scenario S2** | | | | | | | | |
| $CA_{0.04,2700t}$ {0.25,1.0} | 1 | 14 | 0.306 | 2700 | 1755 | 1806 | 1320 | 2177 |
| $CA_{0.04,2300t}$ {0.25,1.0}** | 1 | 14 | 0.307 | 2300 | 1727 | 1818 | 1340 | 2154 |
| $CA_{0.04,1900t}$ {0.25,1.0} | 1 | 14 | 0.309 | 1900 | 1699 | 1829 | 1357 | 2130 |
| $CA_{0.04,1500t}$ {0.25,1.0} | 1 | 14 | 0.310 | 1500 | 1670 | 1841 | 1377 | 2107 |
| $CA_{0.04,15\%}$ {0.25,1.0} | 1 | 15 | 0.296 | 2901 | 1918 | 1759 | 1459 | 2285 |
| $CA_{0.08,15\%}$ {0.25,1.0} | 1 | - | 0.254 | 2901 | 2848 | 2787 | 2285 | 3523 |
| $CA_{0.08,2700t}$ {0.25,1.0} | 1 | - | 0.255 | 2700 | 2827 | 2816 | 2246 | 3547 |
| $CA_{0.08,2300t}$ {0.25,1.0} | 1 | - | 0.256 | 2300 | 2813 | 2832 | 2278 | 3527 |
| $CA_{0.08,1900t}$ {0.25,1.0} | 1 | - | 0.257 | 1900 | 2796 | 2847 | 1900 | 3507 |
| $CA_{0.08,1500t}$ {0.25,1.0} | 1 | - | 0.258 | 1500 | 2776 | 2862 | 1500 | 3486 |
| $CA_{0.06,15\%}$ {0.25,1.0} | 1 | - | 0.277 | 2901 | 2368 | 2382 | 1915 | 2949 |
| $CA_{0.06,2700t}$ {0.25,1.0} | 1 | - | 0.280 | 2700 | 2338 | 2393 | 1871 | 2940 |
| $CA_{0.06,2300t}$ {0.25,1.0} | 1 | - | 0.281 | 2300 | 2318 | 2408 | 1889 | 2916 |
| $CA_{0.06,1900t}$ {0.25,1.0} | 1 | - | 0.282 | 1900 | 2295 | 2422 | 1899 | 2892 |
| $CA_{0.06,1500t}$ {0.25,1.0} | 1 | - | 0.283 | 1500 | 2270 | 2436 | 1500 | 2868 |

Table 9 Performance evaluation for choosing a management procedure. The final column indicate the number of candidate management procedures that meet the objectives.

| Type | Objective | Performance statistic | Target value | Time period | Scenario | MPs remaining |
|---|---|---|---|---|---|---|
| Conservation | Rebuild spawning stock above $B_{20\%}$ within 1.5 generations with 90% certainty | $T_{0.2}$ | ≤ 22.5 years | - | S1 | DB: 8/28<br>CA: 3/15 |
| Conservation | Rebuild spawning stock above $D_{init}$ within 10 years or less with 90% certainty | $T_{\text{init}}$ | ≤ 10 years | - | S1 | DB: 8/28<br>CA: 3/15 |
| Catch variability | Maintain less than 20% interannual variability | *AAV* | ≤ 15% | 11-20 | S1-S2 | DB: 8/28<br>CA: 3/15 |
| Catch | Maximise average annual catch | $\bar{C}$ | Max | 1-10 | S1-S2 | $DB_{120,2700}$<br>$CA_{0.04,2300}$ |

Table 10 Summary of uncertainties, operating model assumptions and qualitative effects on management procedures.

| **Uncertainty (priority order)** | **Assumptions in operating model** | **Confidence in Assumption** | **Effect on management procedure** | |
|---|---|---|---|---|
| | | | **Data-based** | **Catch-at-age** |
| Historical discards | None | Very low | High (proportional to discard rate) | Age composition may indicate higher *F* or reduced recruitment |
| Age proportion sampling and ageing errors | Unbiased | Low | None | Medium |
| Std. survey catchability | Constant | Medium/low<br>(survey in core areas) | High/persistent | Medium/persistent |
| Std. survey selectivity | Constant | Medium<br>(surveys along juvenile migration path) | High/transient | Medium transient |
| Spatial structure | Closed B.C. | Low | Medium | Medium/low |
| Life history parameters | No male/female differences<br>Known *M*<br>Known growth parameters | Low | Low | Medium/low |

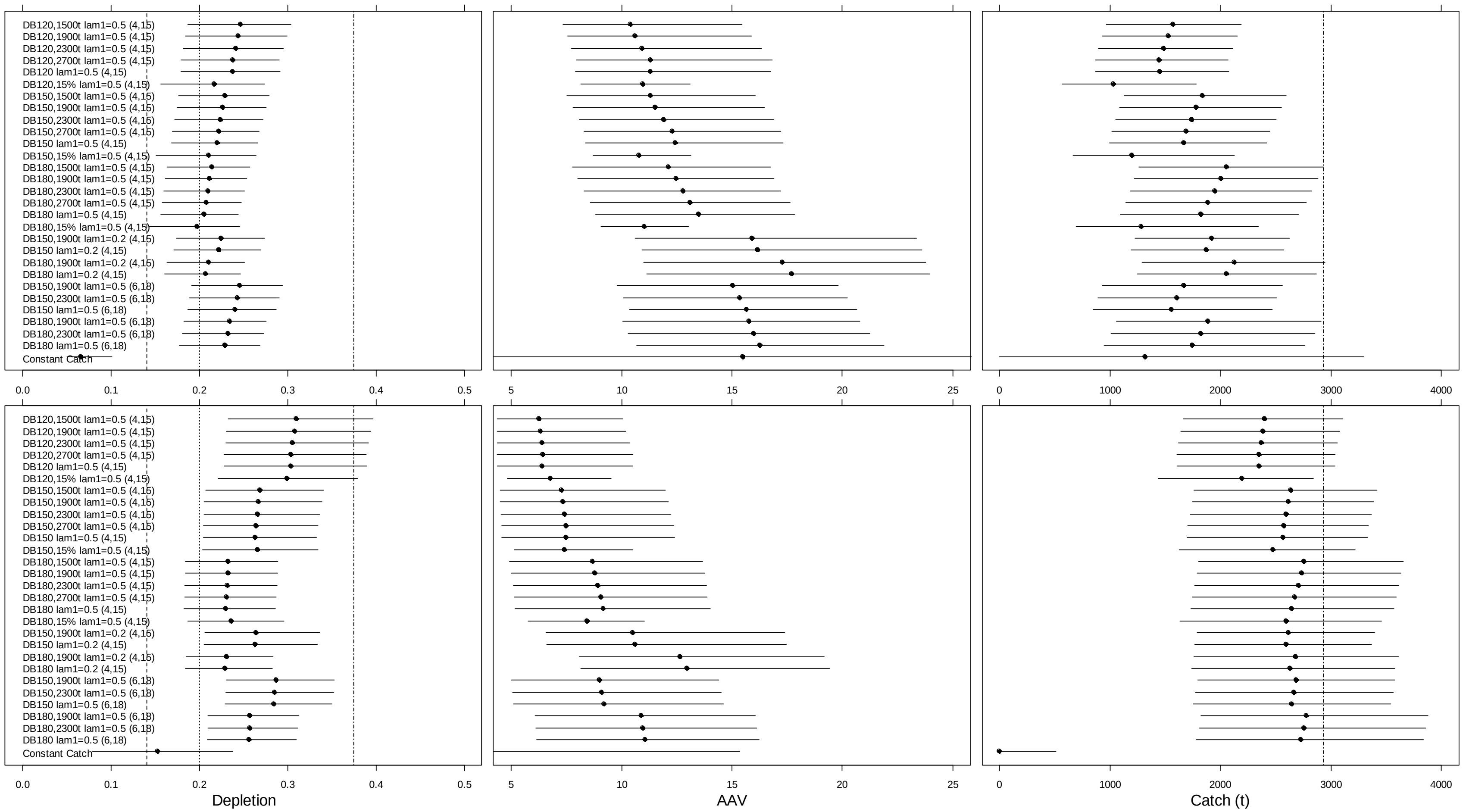


**Figure 1** Summary under scenario S1 of spawning biomass depletion (left), catch variability (middle), and catch (right) performance for data-based procedures over 11-20 years (top) and 21-40 years (bottom). Horizontal bars cover 10$^{th}$ to 90$^{th}$ percentiles and circles indicate medians ($N$=100). Depletion panels include $D_{\mathrm{MSY}}$ (dot-dash lines), 0.2$B_0$ (dotted line) and $D_{init}$ (dashed line) and catch panels show the MSY (dot-dash line).

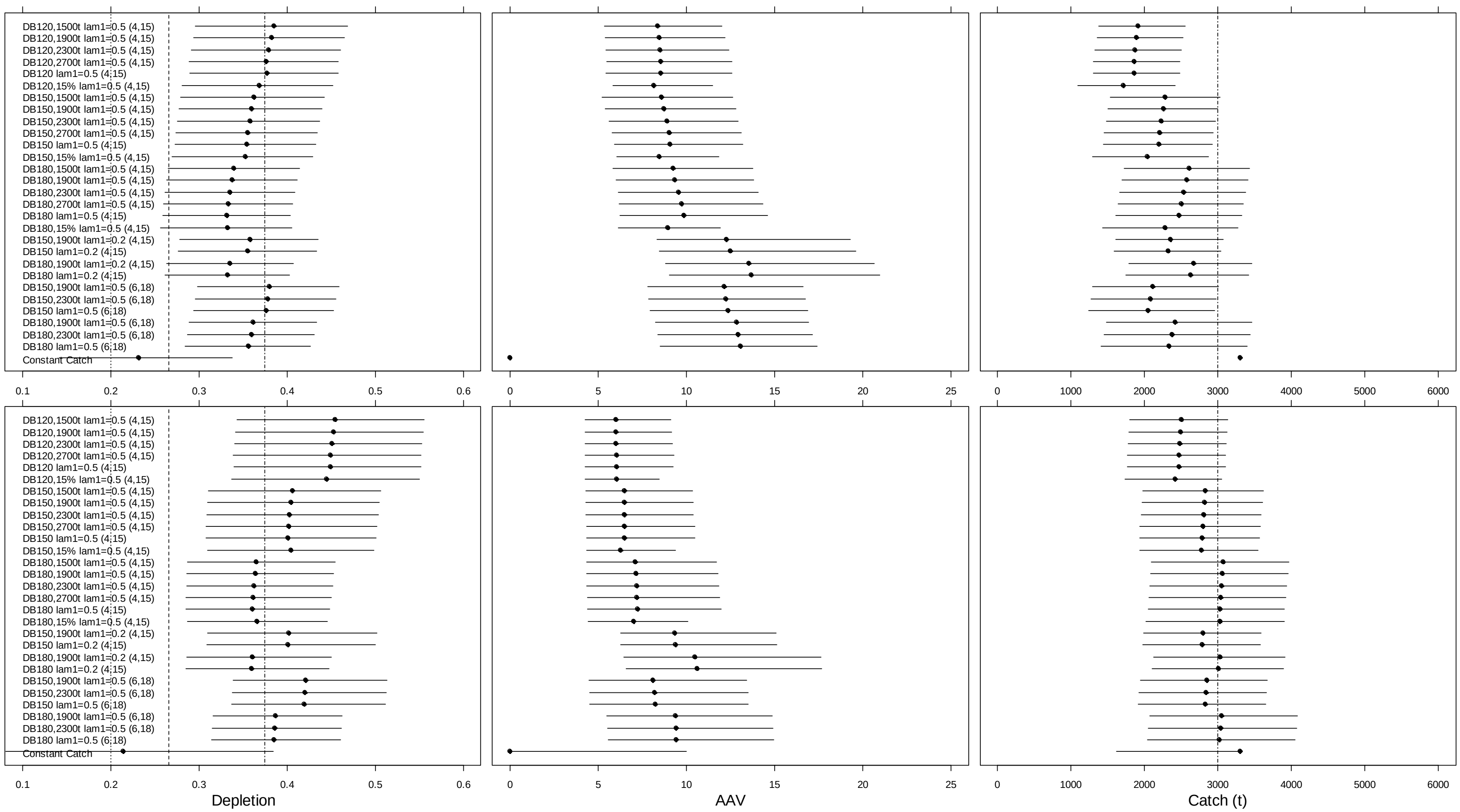


Figure 2 Summary under scenario S2 of spawning biomass depletion (left), catch variability (middle), and catch (right) performance for data-based procedures over 11-20 years (top) and 21-40 years (bottom). Horizontal bars cover 10th to 90th percentiles and circles indicate medians ($N$=100). Depletion panels include $D_{\mathrm{MSY}}$ (dot-dash lines), $0.2B_0$ (dotted line) and $D_{init}$ (dashed line) and catch panels show the MSY (dot-dash line).

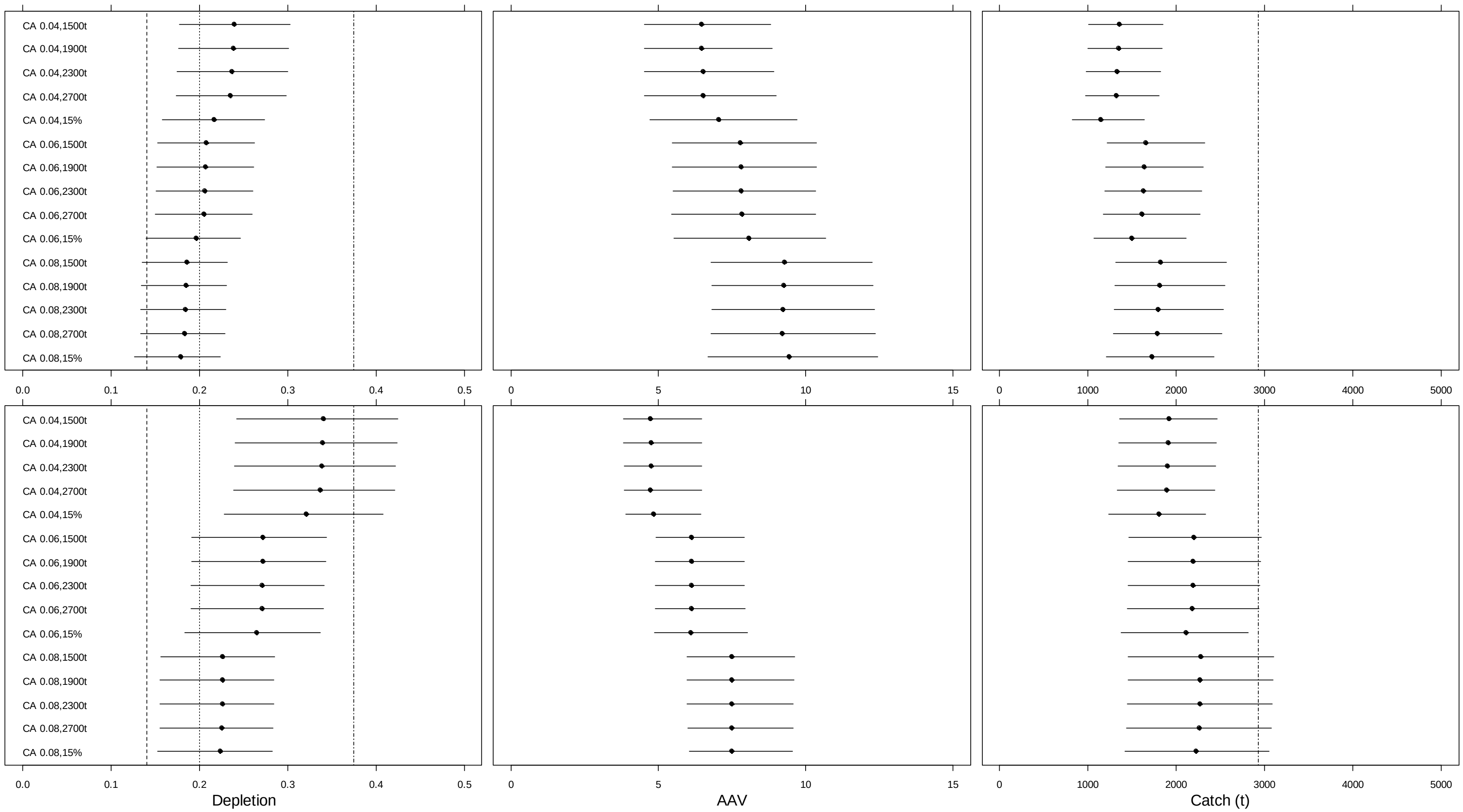


**Figure 3** Summary under scenario S1 of spawning biomass depletion (left), catch variability (middle), and catch (right) performance for catch-age procedures over 11-20 years (top) and 21-40 years (bottom). Horizontal bars cover 10th to 90th percentiles and circles indicate medians (*N*=100). Depletion panels include $D_{\mathrm{MSY}}$ (dot-dash lines), $0.2B_0$ (dotted line) and $D_{init}$ (dashed line) and catch panels show the MSY (dot-dash line)..

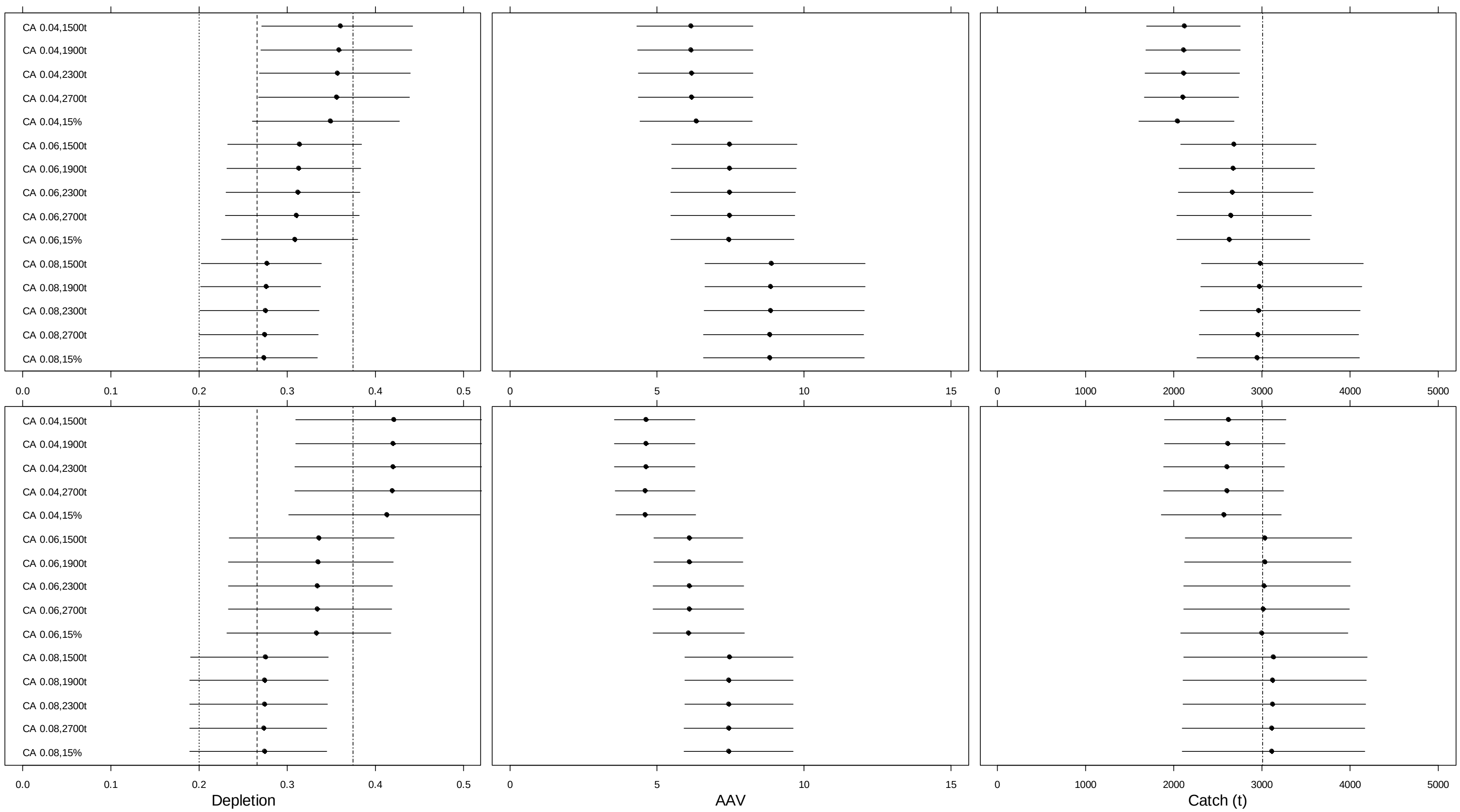


**Figure 4** Summary under scenario S1 of spawning biomass depletion (left), catch variability (middle), and catch (right) performance for catch-age procedures over 11-20 years (top) and 21-40 years (bottom). Horizontal bars cover 10th to 90th percentiles and circles indicate medians ($N$=100). Depletion panels include $D_{\mathrm{MSY}}$ (dot-dash lines), 0.2$B_0$ (dotted line) and $D_{init}$ (dashed line) and catch panels show the MSY (dot-dash line).

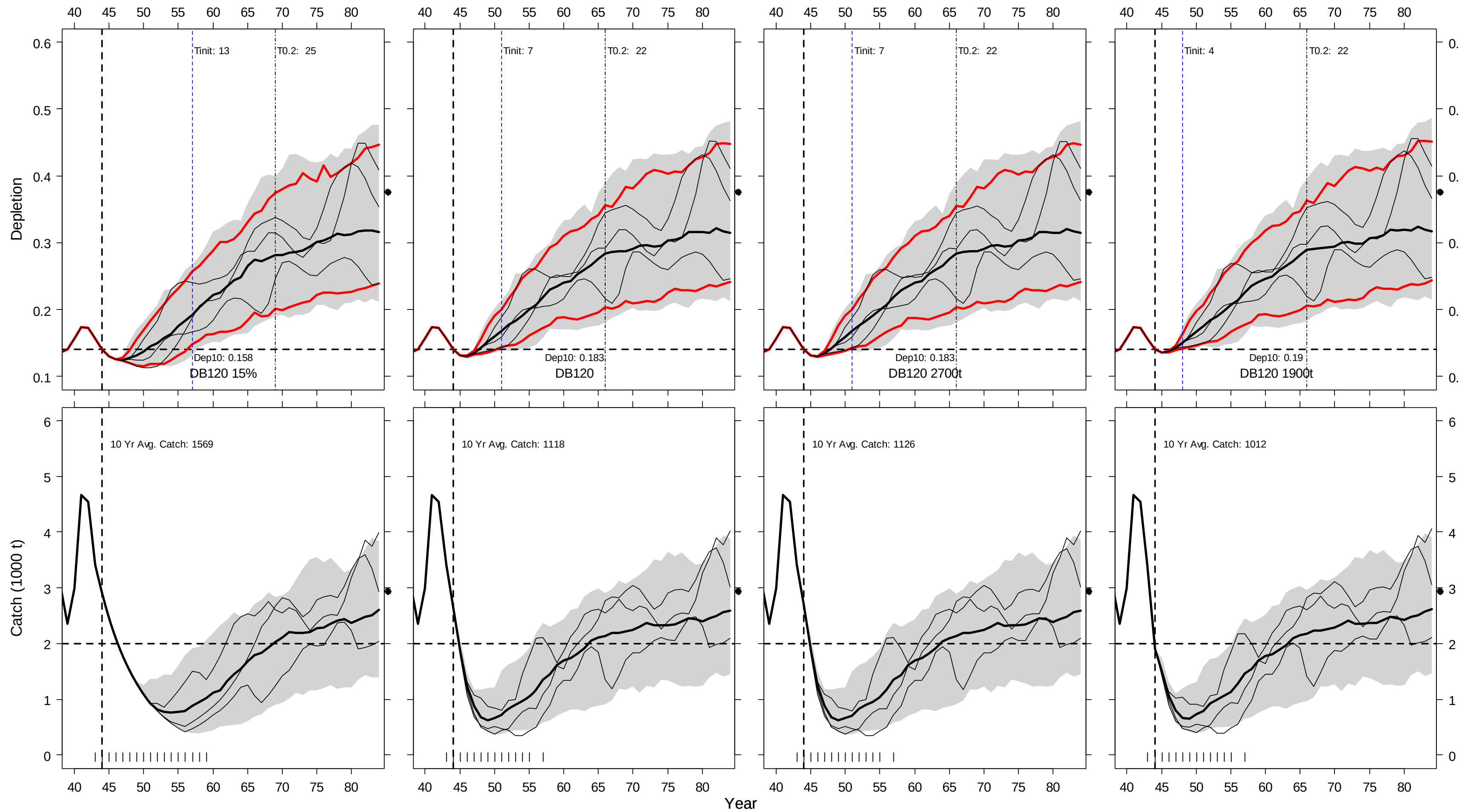


**Figure 5** Simulation envelopes of spawning biomass depletion (top) and catch (bottom) for four $DB_{120}$ procedures under scenario S1. Envelopes include the 5$^{th}$ to 95$^{th}$ percentiles (shaded area), 10$^{th}$ and 90$^{th}$ percentiles (red lines; not shown for Catch), medians (thick black lines), and three individual trajectories (thin black lines). Depletion panels indicate $D_{init}$ (horizontal dash), $T_{0.2}$ (vertical dot-dash), and $T_{init}$ (vertical blue dash). Hash marks at bottom of Catch panels indicate *Cautious Zone* of harvest rule based on median. Dots on right of panels indicate $D_{\mathrm{MSY}}$ and MSY levels.

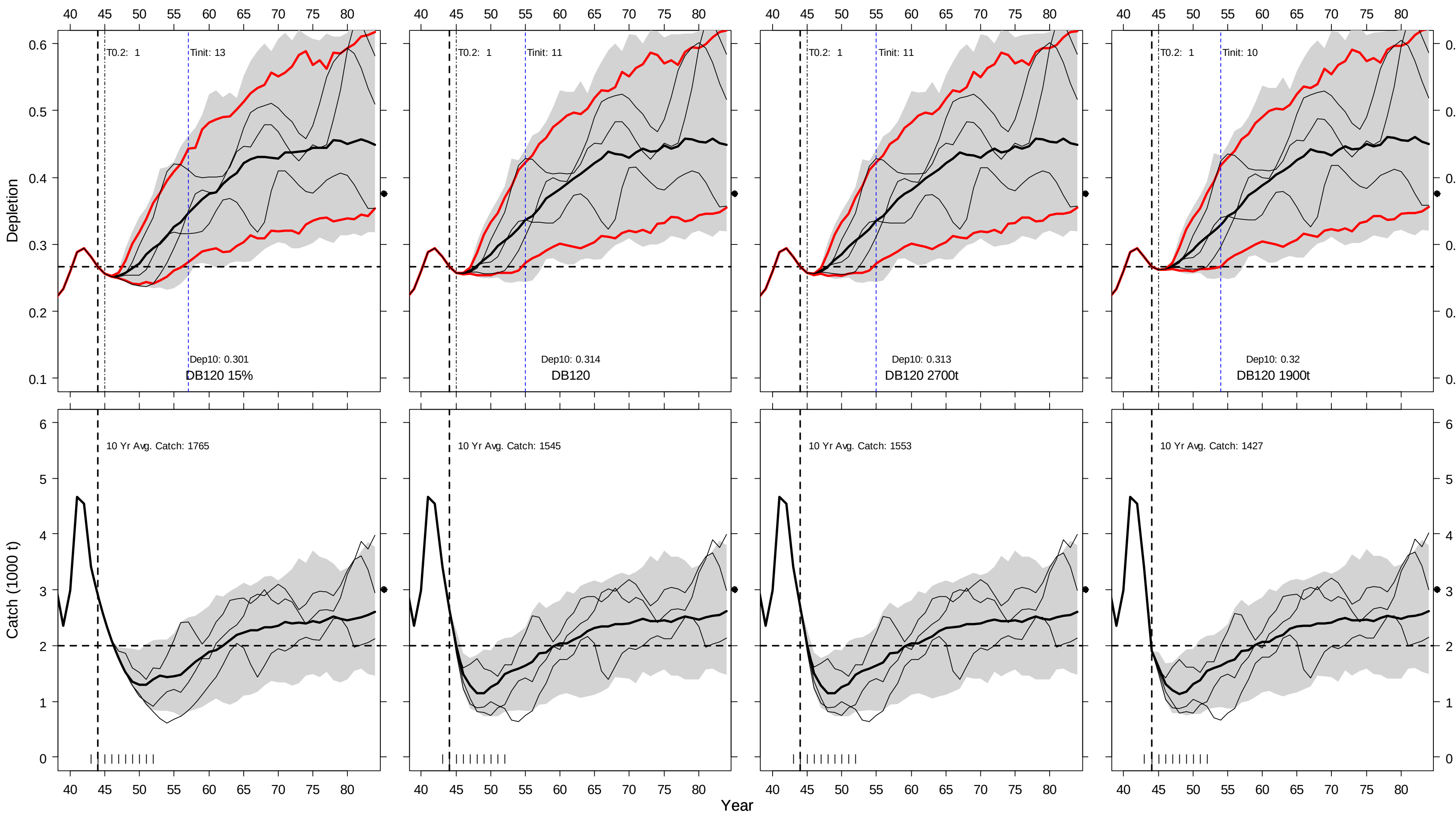


**Figure 6** Simulation envelopes of spawning biomass depletion (top) and catch (bottom) for four $DB_{120}$ procedures under scenario S2. Envelopes include the $5^{th}$ to $95^{th}$ percentiles (shaded area), $10^{th}$ and $90^{th}$ percentiles (red lines; not shown for Catch), medians (thick black lines), and three individual trajectories (thin black lines). Depletion panels indicate $D_{init}$ (horizontal dash), $T_{0.2}$ (vertical dot-dash), and $T_{init}$ (vertical blue dash). Hash marks at bottom of Catch panels indicate *Cautious Zone* of harvest rule based on median. Dots on right of panels indicate $D_{MSY}$ and MSY levels.

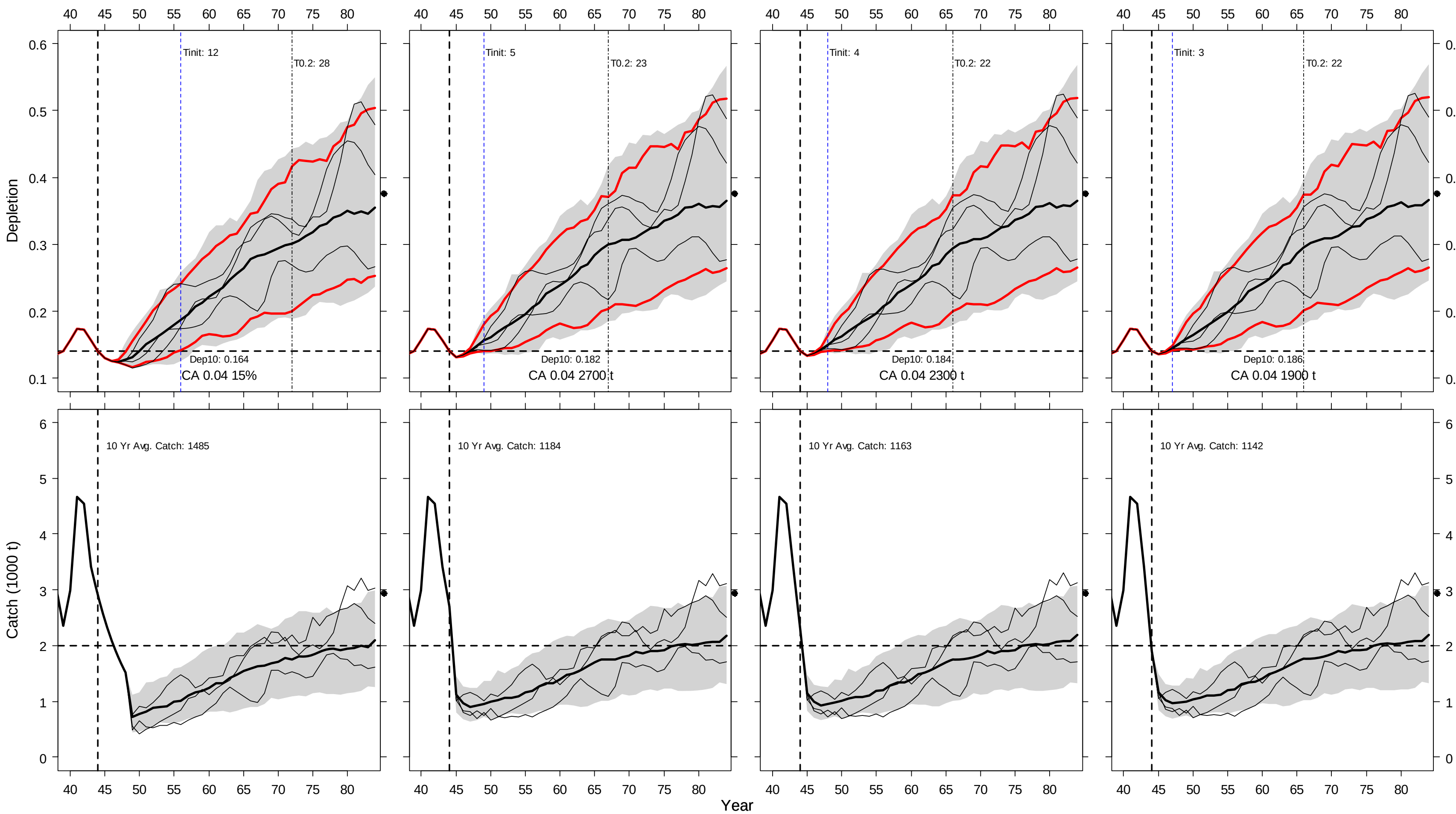


**Figure 7** Simulation envelopes of spawning biomass depletion (top) and catch (bottom) for four $CA_{0.04}$ procedures under scenario S1. Envelopes include the 5th to 95th percentiles (shaded area), 10th and 90th percentiles (red lines; not shown for Catch), medians (thick black lines), and three individual trajectories (thin black lines). Depletion panels indicate $D_{init}$ (horizontal dash), $T_{0.2}$ (vertical dot-dash), and $T_{init}$ (vertical blue dash). Dots on right of panels indicate $D_{MSY}$ and MSY levels.

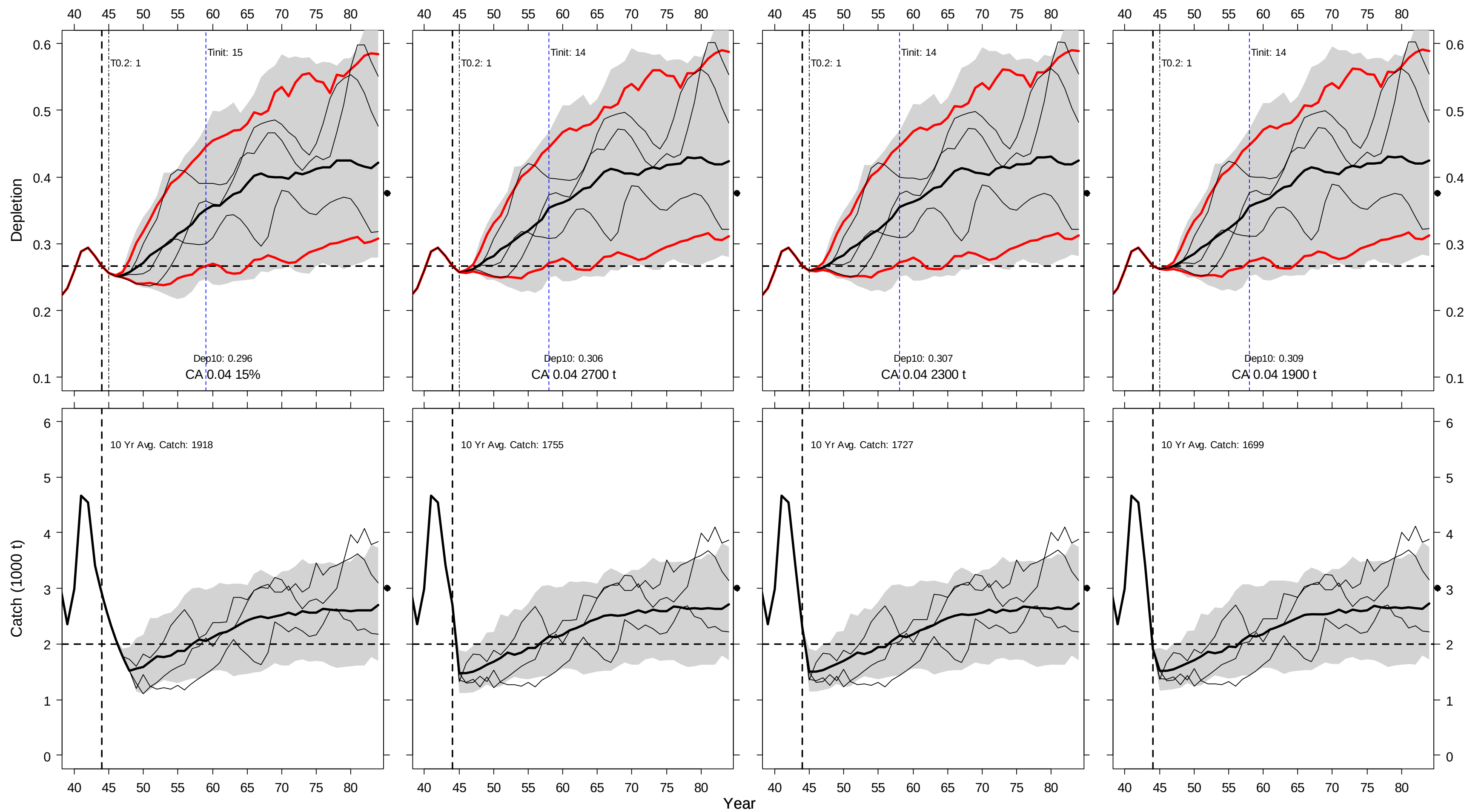


**Figure 8** Simulation envelopes of spawning biomass depletion (top) and catch (bottom) for four $CA_{0.04}$ procedures under scenario S1. Envelopes include the $5^{th}$ to $95^{th}$ percentiles (shaded area), $10^{th}$ and $90^{th}$ percentiles (red lines; not shown for Catch), medians (thick black lines), and three individual trajectories (thin black lines). Depletion panels indicate $D_{init}$ (horizontal dash), $T_{0.2}$ (vertical dot-dash), and $T_{init}$ (vertical blue dash). Dots on right of panels indicate $D_{MSY}$ and MSY levels.

**Appendices**

Appendix A Data

Appendix B Performance Statistics