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Management procedures for the multi-gear sablefish (*Anoplopoma fimbria*) fishery in British Columbia, Canada

Procédures de gestion de la pêche à la morue charbonnière (*Anoplopoma fimbria*) à l'aide de divers engins de pêche en Colombie-Britannique (Canada)

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ABSTRACT

This paper describes a management strategy evaluation process for the multi-gear sablefish (*Anoplopoma fimbria*) fishery in British Columbia, Canada. Fishery objectives and reference points are based on Canada's Sustainable Fisheries Framework (SFF; DFO 2009b) and consultation with fishery stakeholders. Management procedures are developed to address topics of concern to both industry stakeholders and managers, including: (*i*) potential risks associated with discontinuing the sablefish standardized survey; (*ii*) evaluating management options to reduce the conservation and economic impacts of at-sea release and release mortality of sub-legal sablefish; and (*iii*) identifying a new management procedure for providing the best catch and catch stability performance. Part of this new management procedure involves "tuning" priors on stock assessment model parameters to improve catch performance. The operating model used to test management procedure robustness was developed to represent alternative hypotheses about sablefish natural mortality, at-sea release mortality rates, individual growth rate, and recruitment autocorrelation. The model is structured by age and also by growth-group, where the latter dimension is added as part of our evaluation of size-based at-sea release processes and potential regulatory changes aimed at reducing these activities. Our results suggest that full retention or avoidance of sub-legal sablefish would provide the best overall catch, catch stability, and conservation performance although the gains are small relative to current management. Because these options would require a regulation change they are not feasible in the short-term. The next best procedure uses only the stratified random sablefish survey, a stock assessment model with very informative priors, and a harvest control rule that is less conservative than the DFO's SFF default rule. Consistent application of these procedures results in sablefish biomass growth to levels near or above B^{MSY} and an extremely low probability of decline (<5%) to levels below $0.4B^{\text{MSY}}$ as required under the SFF. Projected catch levels in the short-term were very sensitive to stock assessment model tuning and the harvest control rule. Under the apparent "best" rule, median catch levels increase steadily to levels near, or just below MSY, and inter-annual variation remains below approximately 8%.

RÉSUMÉ

Le présent document décrit un processus d'évaluation de stratégie de gestion de la pêche à la morue charbonnière (*Anoplopoma fimbria*) à l'aide de divers engins de pêche en Colombie-Britannique (Canada). Les objectifs de pêche et les points de référence sont fondés sur le Cadre pour la pêche durable du Canada (MPO 2009b) et des consultations auprès des intervenants du secteur des pêches. Des procédures de gestion sont élaborées pour aborder les sujets qui préoccupent tant les intervenants du secteur des pêches que les gestionnaires, notamment : *i*) les risques éventuels liés à l'abandon du relevé normalisé sur la morue charbonnière; *ii*) l'évaluation des options de gestion pour réduire les incidences de la conservation et les incidences économiques de la remise à l'eau et de la mortalité attribuable à la remise à l'eau des morues charbonnières de taille non réglementaire; *iii*) la détermination d'une nouvelle procédure de gestion afin d'offrir le meilleur rendement des prises et rendement de la stabilité des prises. Une partie de cette nouvelle procédure de gestion consiste à « rajuster » les données a priori sur les paramètres des modèles d'évaluation des stocks afin d'améliorer le rendement des prises. Le modèle opérationnel utilisé pour vérifier la robustesse des procédures de gestion a été élaboré de manière à présenter des hypothèses différentes à propos de la mortalité naturelle de la morue charbonnière, des taux de mortalité attribuables à la remise à l'eau, du taux de croissance individuel et de l'autocorrélation dans le recrutement. Le modèle est structuré par âge et par groupe de croissance, ce dernier élément étant ajouté dans le cadre de notre évaluation des processus de remises à l'eau fondées sur la taille et des changements éventuels de la règlementation visant à réduire ces activités. Nos résultats laissent entendre que l'entière conservation ou l'évitement des morues charbonnières de taille non réglementaire offrirait le meilleur rendement général en matière de prises, de stabilité des prises et de rendement en matière de conservation, bien que les gains soient peu élevés par rapport à la gestion actuelle. Ces options ne sont pas réalisables à court terme, car elles nécessiteraient un changement de règlementation. La meilleure procédure utilise seulement le relevé aléatoire stratifié de morues charbonnières, un modèle d'évaluation des stocks avec information a priori et une règle de contrôle de l'exploitation moins conservative que la règle implicite du Cadre pour la pêche durable du MPO. L'application uniforme de ces procédures entraîne une croissance de la biomasse à des niveaux approchant ou dépassant la valeur de B_{RMS} et une probabilité extrêmement faible d'un déclin (<5 %) à des niveaux inférieurs à 0,4 B_{RMS} conformément au Cadre pour la pêche durable. Les niveaux prévus de prises à court terme étaient très sensibles au rajustement du modèle d'évaluation des stocks et à la règle de contrôle de l'exploitation. Dans le cadre de la « meilleure » règle apparente, les niveaux de prises moyens ont augmenté de façon continue aux niveaux approchant le rendement maximal soutenu (RMS) ou tout juste au-dessous et la variation d'une année à l'autre demeure inférieure à environ 8 %.

1 DEVELOPMENT OF A SABLEFISH FISHERY MANAGEMENT STRATEGY

There is an increasing need to develop fishery management strategies that incorporate Canada's commitments to uphold the precautionary approach for capture fisheries (e.g., DFO 2006, DFO 2009b). Management strategies addressing this need for the British Columbia sablefish fishery were developed by Cox and Kronlund (2008, 2009) and Cox et al. (2009). They adopted a management strategy evaluation (MSE) approach that combined industry stakeholder and manager consultation with closed-loop simulation (Walters 1986, de la Mare 1986, 1996, 1998, Smith 1993, Smith et al. 1999) of alternative fishery management procedures and sablefish population dynamics scenarios. Simulation scenarios represented hypotheses about sablefish stock productivity and current stock size, while the management procedures included data-based decision rules as well as model-based procedures involving formal catch-at-age stock assessment models. The data-based procedures set annual total allowable catches (TACs) by averaging the preceding year's total retained catch with a fixed multiple of the 3-year average survey index of abundance. The model-based procedures set annual catch limits by applying an exploitation rate policy to estimates of stock biomass from a catch-at-age model. Both types of management procedure incorporated variable harvest rate control rules to link the estimate of stock status to a catch as required by Canadian fisheries policy (DFO 2006).

There are four main reasons for developing a new sablefish management strategy at this time. First, DFO has developed a new suite of fishery objectives under the Sustainable Fisheries Framework (DFO 2009b). Second, industry stakeholders expressed dissatisfaction with catch performance of the data-based harvest rule developed by Cox et al. (2009). Third, part of the reason for dissatisfaction with data-based rules is the high variability of the Standardized Survey that was used directly to indicate changes in stock status. The effects of discontinuing this survey and switching to the more precise Stratified Random Survey needs to be evaluated for cost-savings and for potential over-fishing risks on the stock. Finally, both industry and DFO managers expressed interest in evaluating the impacts of at-sea release and release mortality of sub-legal sablefish on conservation performance. Industry stakeholders view full retention and/or avoidance management measures as a potential means of improving conservation performance of management strategies without resorting to more conservative harvest control rules and lower quotas.

In this paper, we address most of these concerns by extending the MSE process and modeling work of Cox et al. (2009) to (*i*) develop a more flexible operating model that could account for at-sea releases and post-release mortality; (*ii*) test a wider range of population dynamics assumptions about body growth, natural mortality, and recruitment variability; (*iii*) evaluate management procedures that simulate full retention and avoidance of sub-legal sablefish; and (*iv*) evaluate management procedures that depend only on landed catch and one or two fishery-independent surveys in the future. This work has been guided over the past two years by ongoing collaboration with DFO managers and industry stakeholders from all groundfish sectors.

A fishery management strategy is defined by four components: (*i*) operational fishery objectives that provide the basis for management choices; (*ii*) a management procedure that includes monitoring data, a stock assessment method, and a harvest control rule that together assess changes in status of the fish stock and adjust fishery regulations and catch limits; (*iii*) performance measures used to judge whether the management procedure meets the stated objectives; and (*iv*) a prospective evaluation of the procedure described in (*ii*) using the set of performance statistics in (*iii*) (de la Mare 1996). The following four sub-sections describe completed as well as proposed revisions to each of these four sablefish management strategy components.

1.1 FISHERY OBJECTIVES

Sablefish fishery objectives have been revised to reflect a new suite of Canadian fisheries policy requirements, as well as industry input. DFO (2009b) recently introduced the Sustainable Fisheries Framework (SFF) that expanded on the existing DFO Harvest Strategy (DFO 2006, Shelton and Sinclair 2008) by adding target biomass reference points, an upper default limit fishing mortality rate of F^{MSY}, and a suite of state-dependent risk tolerances for stock decline. The original DFO Harvest Strategy (DFO 2006) described a harvest control rule for scaling fishery harvest to stock status using three reference points: (*i*) a *reference removal rate*, (*ii*) an *upper stock biomass reference point* (USR), and (*iii*) a *limit biomass reference point* (LRP). The LRP and USR mark the bounds of the Critical-Cautious and Cautious-Healthy zones of stock status, respectively (Figure 1, upper panel). The SFF suggested default biomass reference points LRP = $0.4B^{MSY}$ and USR = $0.8B^{MSY}$, where B^{MSY} is the spawning biomass at maximum sustainable yield. Although a particular *target biomass reference point* is not explicitly recommended, the SFF specifies that the *reference removal rate* should not exceed the fishing mortality at maximum sustainable yield (F^{MSY}), which implies a minimum target biomass of B^{MSY}.

The main difference between the SFF and the DFO (2006) Harvest Strategy is that management actions under the SFF are adjusted in response to changes in stock status as well as additional risk factors that depend on the zone. For instance, when the stock is thought to be in the Cautious or Healthy zones, the tolerance for preventable stock decline is adjusted to reflect (*i*) the location of the stock within the zone, and (*ii*) the recent stock trajectory (see Table 1 of DFO 2009b). Tolerance is stated as the probability of preventable stock decline, which we term *P*(*decline*), and it ranges from very low (< 5%) to high (95%) over seven risk categories (Table 2).

Revised fishery objectives for sablefish management procedure choices are:

1. Maintain spawning stock biomass above LRP = $0.4B^{MSY}$ in 95% of years measured over two sablefish generations (i.e., 36 years, Appendix D);

2. When in the Cautious Zone limit the probability of decline over the next 10 years from very low (5%) at the LRP to moderate (50%) at the target reference point. At intermediate stock status levels, we defined the tolerance for decline by linearly scaling probabilities according to

   (1) $$P(decline) = 0.05 + 0.45(B - LRP)/(B^{MSY} - LRP) \ ,$$

   where B is current spawning stock biomass and B^{MSY} is the target reference point (Figure 1).

3. Maintain the spawning biomass above the target reference point of B^{MSY} in 50% of the years measured over two sablefish generations, except when rebuilding from the Critical zone.

4. Maximize the average annual catch over 10 years subject to meeting Objectives 1-3.

When assessing management procedure performance, these objectives are applied in priority order 1-4, which means that performance of a management procedure against Objectives 2-4 cannot be considered if that procedure failed to meet Objective 1. Management strategy performance relative to Objective 3 depends on the initial state of the stock and the time horizon over which the system is simulated because, under some scenarios, population growth towards B^{MSY} is slow. If a candidate management procedure is not rejected at priority levels (1) or (2), then assessment of performance relative to Objective 3 should consider the trade-off between stock growth towards B^{MSY} and economic performance of the fishery over the short-term. Further development of guidelines for long-term fishery objectives are anticipated in updates to the SFF (DFO 2009b, footnote 8).

1.2 CANDIDATE MANAGEMENT PROCEDURES

We define a management procedure (MP) as a combination of monitoring data, stock assessment method, harvest control rule, and measures governing at-sea release of sub-legal sablefish. This section provides the rationale for the various options available under each candidate MP (Table 3).

1.2.1 Management procedures – Survey options

One of the main goals of this particular MSE process is to evaluate the economic and conservation consequences of discontinuing the Standardized (Std) Survey in the future, while retaining the existing data for assessments. In comparison, the Stratified Random Survey (StRs) is designed to benefit from the advantages of survey sampling methodology by virtue of random allocation of sampling units, has a larger sample size, and achieves broader spatial coverage than the Std Survey, so it could become the only fishery-independent survey. Fishery CPUE is not considered part of future data options, although we continue to include the historical series 1979 – 2009 for annual assessments. Thus, future abundance index data options include the StRs only and both surveys, denoted StdStRs (Table 3).

Although the at-sea catch sampling and ageing program for B.C. sablefish has generated catch-age samples since 1988, there is a significant gap of missing data from 2003 to 2008 while the voluntary program was in hiatus. At the present time, the commercial fishery sampling program continues to operate on a voluntary basis. Therefore, it is possible that future management procedures for this difficult to age species (Heifetz et al. 1998, Pearson and Shaw 2004) will involve only catch-by-gear and abundance index data (e.g., survey catch rates).

The stock assessment model defined below ignores at-sea releases and potential release mortality, so the simulated total catch data are based on landings only, and are aggregated over all gear types. Note that the at-sea release process and mortality continues to exist within the operating model (described below).

1.2.2 Management procedures - Stock assessment options

Although our earlier work showed that a simple empirical harvest control rule could be used to set interim quotas for B.C. sablefish without compromising fishery objectives, industry stakeholders eventually became concerned that quotas would be reduced to very low levels even if surveys remained stable in the short-term due to smoothing achieved by using a moving average of survey index values and a lag term related to the previous TAC. From a scientific point-of-view, the empirical rule did not take full advantage of new information, whereby harvest control rule parameters get updated and (hopefully) improve over time. Therefore, we chose to develop and apply an errors-in-variables production model for annual stock assessments (Cox et al. 2009, Punt 2003).

The production model uses the historical data, as well as data that will be available for sablefish stock assessments in the future. Historical stock abundance data including catch rates from the trap fishery (1979-2009), the Std survey (1990 – 2009), and StRs survey (2003-2009) remain available for future assessments. However, as noted above only the StRs is continued into the future under all MPs, while the Std survey is only continued under two MPs (Table 3).

The production model stock assessment (Appendix E) contains several assumptions that are clearly violated given the underlying operating models that we used to test management procedure robustness. First, it assumes a single spawning-exploitable stock whereas in the operating model spawning stock and exploitable stocks are treated separately because fish recruit to the spawning population, fisheries, and surveys at different sizes and ages. Perhaps more important, the mean relationship between stock biomass and production in the Schaefer model is symmetric where $B^{MSY} = 0.5B_0$, compared to the operating model's production function, which is asymmetric such that $B^{MSY} < 0.5B_0$. The production model typically under-estimates unfished biomass relative to the operating model because during the early fishery, when the stock is near unfished, the production model has greater production per unit biomass. Thus, biomass will generally be under-estimated, while optimal harvest rate may be under- or over-estimated depending on the data.

Mis-specification of the assessment model, combined with potentially noisy relative biomass indices, has the potential to generate strong biases in estimated biomass, optimal harvest rate, and B^{MSY}. Therefore, we chose to apply informative priors to the leading production model parameters optimal exploitation rate, U^{MSY}, and maximum sustained yield, MSY, such that stock assessment model performance is consistent with the range of operating models we tested. Prior distribution parameter "tuning" therefore becomes a defining characteristic of each management procedure (Table 3). The two prior tunings we use are (note that second entries for all normal distributions presented in this paper are standard deviations unless stated otherwise):

(1) LowTune – MSY ~ N(3 400, 3 400) and $U^{MSY} \sim N(0.08, 0.08)$;

(2) HiTune – MSY ~ N(3 400, 1 700) and $U^{MSY} \sim N(0.08, 0.04)$.

The prior mean for MSY is slightly larger than the true values for the operating model, while the optimal legal harvest rate lies in the mid-range of the operating model values. We included the LowTune model to examine whether the simulated stock assessment could learn the true operating model values of MSY and U^{MSY} over time, and incorporate this learning toward improved management strategy performance. As we will show, using diffuse priors cause the LowTune option to output low average catch (and highly variable catch) during the early years of harvest strategy implementation. Therefore, we included the HiTune option to determine whether more precise priors could reduce the initial variability while also allowing for some learning in the future.

1.2.3 Management procedures - Harvest control rule options

The harvest control rule (HCR) is a state-dependent feedback function for computing a total allowable catch limit or quota (TAC) based on stock assessment information, a reference harvest rate, and possibly other management adjustments (Table 4). According to DFO (2006), the harvest control rule must reduce the harvest rate when stock status is assessed below the target biomass (e.g., B^{MSY}). However, the rule does not need to be the same mathematical form, or utilize the same biomass reference points (e.g., LRP = $0.4B^{MSY}$ and USR = $0.8B^{MSY}$), as specified in the fishery objectives or DFO (2009b) (e.g., Figure 1, lower vs. upper panel). Instead, a harvest control rule is chosen such that fishery objectives are met under the range of conditions specified by the operating model scenarios.

After a stock assessment is completed, the harvest control rule calculates a TAC by multiplying an adjusted harvest rate and an estimate of exploitable biomass $\hat{B}_t$, where the reference removal rate, (i.e., maximum target legal harvest rate) parameter is set to the estimated optimal harvest rate from the stock assessment model. The adjusted legal harvest rate formula in H4.2 implements a harvest control rule consistent with DFO (2006, 2009b) based on the policy parameters (H4.1). We define the lower bound, $B_{\text{lower}} = 0.4B^{\text{MSY}}$, and upper bound, $B_{\text{upper}} = 0.6B^{\text{MSY}}$, as multiples of the estimated target biomass B^{MSY}. Similar to the harvest rate, B^{MSY} is estimated by the stock assessment model.

We examined two alternative harvest control rules to examine the sensitivity of MP performance to (1) DFO's default suggestion for $B_{\text{upper}} = 0.8B^{\text{MSY}}$ and (2) stock assessment model errors. Presumably, DFO's default upper limit was created so that stocks would spend more time in the Healthy Zone. However, our early simulation trials demonstrated that adjusting the harvest rate when the stock is within 80% of B^{MSY} generates unnecessary reductions in catch without adding any significant conservation benefits. Thus, we show one example of this behaviour to demonstrate our motivation for the choice of upper limit at 60% of B^{MSY}.

We created a benchmark "perfect information" procedure specific to each scenario to examine catch and conservation performance in the absence of stock assessment model errors. Catch limits for perfect information procedures were computed using the same harvest control rules (H4.2), but with the true optimal legal harvest rate, the true legal biomass in year T-1 (because the rule is applied before legal biomass is updated), and the true operating model B^{MSY}.

The legal-sized catch limit is allocated among trap, hook, and trawl fisheries, as well as the fishery-independent surveys, using proportions by gear calculated from the 2008-2010 landings (Appendix B). Such a constant allocation scheme may not be realistic in the future because new regulations designed to reduce bycatch and to promote greater accountability may affect how the final catch is distributed over gear-types (Koolman et al. 2007, DFO 2010). However, the choice is probably reasonable until patterns of catch distribution among gear sectors stabilize under the new integrated fisheries regime.

1.2.4 Management procedures – Sub-legal release regulation options

At-sea release of sub-legal sablefish has been flagged a potential conservation concern by the directed sablefish fleet for several years, and was also identified as a key uncertainty in previous stock assessments (Cox and Kronlund 2008, 2009; Cox et al. 2009). Initially, the main target of concern was the bottom trawl fishery, because their interception rates of small sablefish can be high while prosecuting the shallow water component of their fishery (e.g., fresh fillet rockfishes, flatfishes, Pacific cod). However, with the inception of the electronic monitoring programs in all groundfish fleets, it became apparent that at-sea releases in trawl fisheries were matched, and sometimes exceeded, by trap and hook fisheries (Appendix B). At-sea release monitoring data indicate that total releases over all fleets has ranged from approximately 300 t to 630 t between 2006 and 2010. Clearly, the fate of these releases is important because this range represents approximately 10% to 20% of the estimated total annual sablefish production at B^{MSY} regardless of the operating model scenario (Appendix D). According to operating model fits to historical data, the B.C. sablefish stock is probably smaller than B^{MSY} at the present time (Appendix D), which means that the proportion of production released at sea is probably greater than 10% - 20%.

At the outset of the MSE process, sablefish industry stakeholders proposed that we examine the potential impacts of removing the 55 cm legal size limit. The consequence of such a change is that all fisheries would operate under full retention of all sablefish. We developed a full retention management procedure (labeled "Retain") that invokes this change in Year 2012, since it is unlikely that such a change would be implemented for 2011.

Avoidance of sub-legal sablefish is one alternative to establishing full retention. Avoidance has the potential benefit of increasing the average size in the catch, which, for sablefish, means higher average prices per pound for the landed catch. Each fishery harvesting sablefish has demonstrated an ability to avoid sub-legal sablefish if necessary. For instance, gear modifications and improved communication have possibly helped the trawl fleet reduce interception and release of sub-legal sablefish over the past several years (Brian Mose and Bruce Turris, personal communication). Longer soak times in trap fisheries may lead to greater bait depletion and movement of sub-legal fish out of traps via escape rings (Erling Olson, personal communication, 7 December 2010, WCS Science Committee Meeting, Vancouver, B.C.). Finally, longline fisheries may choose to fish more in the fall when sablefish are larger and interceptions of sub-legal fish are lower (Chris Acheson, personal communication, 7 December 2010, WCS Science Committee Meeting, Vancouver, B.C.). Any of these modifications to avoid sub-legal fish will tend to increase the amount of effort required to catch legal fish, so it is important to examine whether the gains in catch and conservation performance would be worthwhile. Therefore, we included an avoidance procedure (labelled "Avoid") on selected management procedures.

We recognize that implementing full retention may eventually lead to avoidance via a variety of mechanisms, but we take no account of such adaption at this time. Because these changes are currently only verbal proposals, we use our Retain and Avoid procedures to mimic the impacts of a variety of management changes that could be developed in coordination with fishery managers and industry. Our simulations attempt to indicate whether these options, combined with rule-based TAC adjustments, lead to improved economic and conservation performance.

1.3 PERFORMANCE MEASURES

Evaluating management procedures by simulation requires a quantitative performance indicator for each fishery objective. Stock status indicators are all measured using the true operating model spawning stock biomass. We use two sablefish generations (36 years) as the "reasonable" time frame required by the SFF, and 10 years as the short-term. Performance statistics corresponding to each of Objectives 1-4, as well as other quantities of interest are listed in Table 5. Each statistic is calculated for a simulation replicate, and the expected performance for a management procedure is summarized by the mean (or median) of 100 replicates of each simulation.

1.4 EVALUATING MANAGEMENT PROCEDURES BY CLOSED-LOOP SIMULATION

We use the following closed-loop simulation algorithm to evaluate each candidate management procedure (e.g., Walters 1986, de la Mare 1998, Cooke 1999, Punt and Smith 1999, Sainsbury et al. 2002, Butterworth 2007):

1. Define a management procedure based on (*i*) data types, (*ii*) assessment method, (*iii*) harvest control rule, and (*iv*) sub-legal regulation;

2. Initialize a pre-conditioned operating model scenario for the period (1965 – 2010) based on historical data;

3. Project the operating model population and fishery one time step into the future. At each step apply the following:

    a. Generate the data (1.*i*) available for stock assessment;
    b. Apply the stock assessment method (1.*ii*) to the data to estimate quantities required by the control rule;
    c. Apply the harvest control rule (1.*iii*) to generate a catch limit;
    d. Update the operating model population given the fishing mortality rate generated by the catch limit and sub-legal regulation (1.*iv*), and new recruitment;
    e. Repeat Steps 3a-3d until the projection period ends.

4. Calculate quantitative performance statistics for the replicate;

5. Repeat Steps 2-4 for 100 replicates.

2 OPERATING MODEL AND SCENARIOS

The sablefish fishery operating model was developed to represent alternative hypotheses about sablefish population dynamics, at-sea release mortality rates, individual growth rate, and recruitment autocorrelation. The model is structured by age and also by growth group, where the latter dimension is added as part of our evaluation of size-based discarding, high-grading at sea, and potential regulatory changes aimed at reducing these activities. Details of the model and conditioning on historical data are given in Appendix D.

During MSE consultations[1], both industry and DFO managers expressed the desire to avoid specifying multiple operating model scenarios, however the adoption of a single scenario devolves the quota-setting procedure back to the requirement to pick one model. One of the requirements that led to the original development of the MSE approach is to explicitly acknowledge uncertainty in model determination and to test the robustness of management procedures to those uncertainties. Nevertheless, their concern was that decision-makers placed too much weight on the most pessimistic scenario in Cox and Kronlund (2009; Scenario S1 in that paper), even though that particular model was not the most likely. Such behaviour is known as max-min decision-making in which a decision maker ignores uncertainty and only

[1] Sablefish Advisory Committee Minutes, 26 May 2010, SFU Segal School of Business, Vancouver, B.C.

seeks the best performance under the worst possible scenario (Morgan and Henrion 1990). In fisheries, the max-min approach seems inevitable given the abundance of alternative models, and the high risk of management procedure failure in the most pessimistic cases.

We dealt explicitly with uncertainty about sablefish natural mortality by estimating this parameter as part of the operating model conditioning step. We used an informative $N\left(0.08, 0.005\right)$ prior on the natural mortality rate (*M*) to overcome the well-established difficulties in estimating *M* along with other production parameters, and to guard against implausible values. We refer to the resulting operating model based on estimated *M* as "S1:Baseline" because this model fits the observed data the best (Appendix D).

We developed seven secondary scenarios as tests of sensitivity and potential robustness of sablefish management procedures to a fixed natural mortality rate, slower body growth rate, and moderate recruitment autocorrelation (Table 6). The first of these models (S2:Fixed *M*) is identical to S1, except that the natural mortality is fixed at the prior mean *M* = 0.08/yr. This scenario is expected to generate an operating model similar to that used in our previous work (Cox et al. 2009, Cox and Kronlund 2009). Scenarios "S3:S1+Growth" and "S4:S2+Growth" are identical to S1 and S2, respectively, except that each uses a lower growth rate parameter *k* = 0.25/yr, which is closer to the growth rate used in U.S. sablefish assessments (Appendix C). Scenarios "S5:S1+AR" and "S6:S2+AR" are also identical to S1 and S2, respectively, except that recruitment autocorrelation is fixed at γ = 0.4 for projection years 2011 – 2046. We chose this moderate autocorrelation value because recruitment estimates from Alaskan sablefish assessments (that assume annual recruitment deviations are independent) did not appear to be highly correlated (Hanselman et al. 2009). Finally, scenarios "S7:S1-Mean" and "S8: S1-10th" address parameter uncertainty by using model parameters corresponding to the posterior mean and 10th percentile of the posterior distributions for MSY.

The suite of operating model scenarios differ substantially in their production relationships to biomass, despite all having nearly identical values for MSY with the exception of S8 (Table 7). The greatest productivity differences are between scenarios S1 and S2, whereas differences due to slower body growth (S3 and S4) tend to be small (Figure 2). Scenarios derived from S1 tend to have more sharply peaked production curves, lower B^{MSY}, and an optimal legal harvest rate of 11%, while scenarios based on S2 have broader yield curves, high B^{MSY}, and optimal harvest rates near 6%. These differences can be attributed to higher estimated biomass and lower estimated exploitation rates when *M* is fixed at relatively high values (Clark 1999).

3 SIMULATION RESULTS

3.1 MP PERFORMANCE IN SCENARIOS BASED ON S1: BASELINE

All procedures meet conservation Objectives 1-3 under all scenarios derived from S1 (Table 8). The procedure that appeared to generate the best overall performance under this scenario was MP4:RetainStRsHiTuneH46 because it ranked second in average short-term catch (Objective 4), first in inter-annual variation in catch and minimum catch, second in maximum short-term catch, and first in the proportion of years in the Healthy zone. The procedure based on avoidance of sub-legal sablefish MP3:AvoidStRsHiTuneH46 ranked just behind MP4 in all of these categories.

Of the procedures that could be implemented for 2011, MP2:StRsHiTuneH46 ranked first in inter-annual variation in catch, minimum short-term catch, and proportion of years in the Healthy zone, and second in the average and maximum short-term catch. Where StRsHiTuneH46 ranked first, StRsLowTuneH46 ranked second and vice versa. However, the inter-annual variability in catch was approximately 14% for the low tuning procedure compared to only 7% for high tuning.

3.2 MP PERFORMANCE IN SCENARIOS BASED ON S2:FIXEDM

All procedures meet conservation Objectives 1-2 under all scenarios derived from S2, except under autocorrelated recruitment (S6:S2+AR) where several procedures failed to meet Objective 2 (10-year stock trend). The tolerance for decline under these scenarios is $P(decline) = 0.24$ whereas the failing procedures showed decline rates ranging from $P(\beta < 0) = 0.27$ to $P(\beta < 0) = 0.36$ (Table 8). The procedure coming closest to Objective 2 was RetainStRsHiTuneH46, which had $P(\beta < 0) = 0.28$ (Figure 3).

3.3 MP PERFORMANCE IN BAYES POSTERIOR SCENARIOS

Under scenario S1:Baseline, in which operating model parameters were set to their maximum likelihood estimates, all procedures met conservation Objectives 1-3. However, this was not the case for scenario S7:S1-Mean, in which operating model parameters were set to their posterior means. Only one procedure was able to maintain spawning stock biomass above B^{MSY} for at least 50% of years between 2011 and 2046 (Table 8). This result reflects the slower population growth implied by the posterior mean parameterization so that, even with perfect information about stock biomass and the optimal harvest rate, the stock would not grow fast enough to meet this objective. The procedure StdStRsLowTuneH48 meets Objective 3 at the expense of very poor catch and catch stability performance (reasons for this are described below). Inability to meet Objective 3 for other procedures does not mean that conservation performance is poor. On the contrary, all procedures rebuild median spawning biomass to B^{MSY} or higher within 12-31 years (Figure 4) and maintain the stock within the Healthy zone in 63% to 86% of all years (Table 8).

The operating model scenario based on the 10th percentile of the posterior distribution for MSY represents the most pessimistic scenario we examined. In this case, only the perfect information and MP7:StdStRsLowTuneH48 (e.g., both surveys combined with DFO default harvest rule) satisfied Objectives 1-2, while maintaining the stock in the Healthy zone in more than 50% of years. However, as noted above, the cost of better conservation performance by MP7 is very poor catch performance, especially in the first few years. Median spawning stock biomass does not rebuild to B^{MSY} or greater within two sablefish generations, for any MP, although all long-term median trends are positive and several MPs eventually rebuild the median biomass to the Healthy zone. Although the B^{MSY} rebuilding objective is not met, none of the MPs examined causes long-term stock decline. For instance, under the apparent "best" procedure (MP2:StRsHiTuneH46), less than 1% (i.e., zero) of simulated spawning biomass levels declined below $0.5B^{MSY}$ (Figure 5). Combining this low probability of decline with the low probability that this particular scenario is true (i.e., it represents the 10th percentile of MSY), means that this management procedure presents an extremely low risk of future stock collapse.

3.4 MANAGEMENT PROCEDURE - SURVEY OPTIONS

Management procedures based on both Std and StRs surveys generally performed worse under S1:Baseline than procedures based on the StRs survey alone, when both MPs used low tuning stock assessments and (0.4,0.6) harvest rule multipliers. Over the first 10 projection years, procedures using the StRs survey provided approximately 300 t more in average catch, 1,100 t more in minimum catch, 150 t less in maximum catch, and 14% average annual variability compared to 35% for procedures using both surveys (Table 8). The high variability of the Std survey causes a wider range of stock assessment model errors (Figure 6) which, in turn lead to frequent reductions in target harvest rates (Figure 8) and high variability in catch limits (Figure 8). Note we discuss reasons for stock assessment errors and variation in target harvest rates in the next two sections.

3.5 MANAGEMENT PROCEDURE - STOCK ASSESSMENT OPTIONS

Stock assessment estimates of biomass have both systematic and random biases. When these biases combine to result in an estimated decline in biomass, catch limits will be reduced incorrectly. Similarly, when biomass errors result in estimated stock increases, catch limits are increased incorrectly. For constant harvest rate management strategies, these errors will tend to be small and will generally offset one another. However, when precautionary harvest control rules are used, as in our case, stock assessment errors result in magnification of catch limit errors. The degree of magnification depends on the steepness of the harvest rule as well as its position relative to average biomass levels. If the descending limb of the harvest rule is encountered often, such as for imprecise stock assessment models based on imprecise data, catch levels will tend to be reduced unnecessarily.

Stock assessment model tuning had substantial effects on management procedure performance because it affected estimates of both exploitable biomass and harvest control rule breakpoints via estimation of B^{MSY}. Under StRsHiTuneH46, the bias in biomass and harvest rule breakpoints are negligible in the first assessment year mainly because the priors have a strong influence on how the production model interprets the historical data. Over the projection period, the estimate of B^{MSY} generally increases (increasing positive bias), probably because of the symmetry constraint on the Schaefer production function. These increases in estimates of B^{MSY} are accompanied by decreases in estimated U^{MSY} (Figure 9). Offsetting biases combine to limit the range of harvest rates such that there is less than 10% chance of exceeding U^{MSY} throughout most the projection period. In the short-term, the chance of exceeding U^{MSY} is greater, but the over-fishing levels are quite small (Figure 10).

Under the low tuning StRsLowTuneH46 procedure, B^{MSY} is drastically under-estimated and U^{MSY} is over-estimated by a factor of two (Figure 9). The realized harvest rate on the stock, however, comes quite close to that achieved by the high tuning procedure, although the range of outcomes is broader as expected given less precise priors on U^{MSY} and MSY. Over time, the low tuning procedure reduces the estimated target harvest rate from approximately 20% down to less than 10% (i.e., less than U^{MSY} for this scenario) within seven years of implementation. This procedure also makes additional downward adjustments to the target harvest rate in six out of the first seven years, which adds additional inter-annual variation to the catch. In contrast, the high tuning procedure only adjusts the target harvest rate downward in the seventh year, which avoids unnecessary changes in catch. The range of realized harvest rates under low tuning is therefore wider during the first few years of procedure implementation (Figure 10).

3.6 HARVEST CONTROL RULE OPTIONS

The choice of upper bound on the harvest control rule impacts conservation and economic performance in several ways. For the two upper bounds we evaluated, the DFO default upper bound of $0.8B^{MSY}$ tended to result in frequent and seemingly unnecessary large reductions in catch limits, compared to an upper bound of $0.6B^{MSY}$ that provided some buffering against stock assessment errors. Neither of these choices presented risks to the stock as indicated by rapid biomass growth to B^{MSY} levels (Figure 11). Faster biomass growth under the DFO upper bound is accompanied by substantially lower average catch and minimum catch, as well as greater average annual variation in catch compared to the $0.6B^{MSY}$ upper bound option (AAV, Table 8). The most pronounced difference happens immediately upon procedure implementation as the procedure based on DFO's upper bound reduces 2011 catch to less than 1000 t in more than 50% of simulation replicates. Further comparison of these two MPs with StRsHiTuneH46 shows that even better stability of catch, average annual catch, minimum catch, and AAV can be obtained while still providing good conservation performance. In this case, the improved survey and tighter tuning reduce stock assessment errors.

4 DISCUSSION

4.1 THE NEED FOR A SABLEFISH MANAGEMENT STRATEGY

Although there is uncertainty about the status of B.C. sablefish, all of the operating models we considered indicate that the B.C. sablefish stock is below B^{MSY}. Rebuilding the stock to more productive levels requires consideration of the trade-offs between stock growth and short-term economic performance. Exposing these trade-offs is critical to ensure that the health of both the fishing industry and the stock improve in the future.

We used a collaborative management strategy evaluation process to more clearly define the operational objectives for this fishery, define candidate management procedures, and evaluate those procedures in closed-loop computer simulations. Our results indicate that several management procedures could have positive benefits for stock growth, while also providing both short-term stability of catch and long-term catch growth. Overall, the average projected harvest levels are lower than catches have been in the past, and in most cases, lower than current estimates of maximum sustainable yield for the B.C. sablefish stock (i.e., around 3,200 t). Projections of stock biomass under these management procedures further suggest extremely low chances of creating conservation concerns, even under the most pessimistic scenarios for the true sablefish stock. Expectations for stock growth over two sablefish generations range from levels at or above B^{MSY}, to levels near, but not above B^{MSY} under the more pessimistic scenarios.

We found that a management procedure based on the new stratified random survey alone would not compromise fishery conservation objectives. In fact, when used in combination with a highly tuned stock assessment model and slightly less restrictive harvest control than the SFF default, using only the StRs survey gives better catch and stability of catch performance for the fishery than when the standardized survey is also used. In the sections below, we elaborate on some of the insights we've gained from simulating these management procedures. Then, we describe the options available to industry and managers for further improving performance of selected management procedures. Finally, we identify some limitations of this work, as well as possible directions for future research.

4.2 WHY AREN'T TWO SABLEFISH SURVEYS ALWAYS BETTER THAN STRS ALONE?

Using both StRs and Std surveys for quantitative stock assessments resulted in worse overall performance compared to using the StRs survey alone. Estimates of the survey CVs are 16% and 29% for StRs and Std surveys, respectively (Appendix D, Table D-5). By most statistical standards, these would both be considered reasonably good fishery-independent surveys. However, the stock assessment model transfers some of the random survey errors into biomass and reference point parameter estimates (e.g., U^{MSY}, B_{upper}, and B_{lower}). When these reference points are conservative, such as the SFF default upper value of $0.8B^{MSY}$, stock assessment errors are magnified into highly variable catches because both biomass and the target harvest rate are changing often. Because the DFO harvest control rule is asymmetric (i.e., harvest rate is adjusted downward when $B < 0.8B^{MSY}$), this variability leads to lower average catch as well. Walters (1998) used closed-loop simulations to examine relationships between a management loss function (deviations of annual quotas from a target trajectory during fishery development) and assessment errors arising from survey variability. He showed that the relative loss incurred by quota fishing policies increases rapidly with survey CV up to a maximum loss at CVs ≥ 50%. For a CV~30%, like our Std survey, losses were 80-90% of the maximum. Therefore, combining the Std and StRs surveys shifts the effective combined survey variance closer to the Std level where losses increase rapidly.

4.3 USE OF HIGHLY TUNED STOCK ASSESSMENT MODELS IN FISHERY MANAGEMENT

Tuning a procedure incorporates what is known about the process (e.g., range of sablefish scenarios) into the control of that process. The high tuning stock assessment procedure incorporates knowledge about the range of MSY and U^{MSY} values used in the operating model. Although this may seem to give these assessments an unfair advantage, system engineers tune procedure parameters all the time for controlling much more complex systems (Dorf and Bishop 2008). In harvest management, the International Whaling Commission has used highly tuned stock assessments in developing their harvest algorithms (Cooke 1999). In our case, we knew that MSY is nearly identical among the 8 operating model scenarios for sablefish population dynamics, so we chose a prior mean for MSY of 3,400 t. The optimal harvest rate differed considerably among scenarios, so we chose a prior mean near the middle of the range at U^{MSY}=0.08.

We adopted the intuitive term "tuning" to describe the selection of stock assessment model priors so as to improve management procedure performance over the range of scenarios considered (Cooke 1999). In all cases, prior tuning is informative because prior CVs < 100% imply reasonably good knowledge about the parameter values. Yet, even with informative priors, estimates of biomass occasionally varied several-fold over a 36-year simulation and these changes were negatively correlated with optimal harvest rate estimates. Such high, correlated variability among parameters causes every component of the harvest control rule to change, and this adds variability to fishery performance. As noted above, asymmetry in the harvest control rule usually translates this variability into punitive losses in fishery catch and high inter-annual variability in catch without much conservation benefit. In our high tuning scenario, with prior CVs = 50%, biomass estimates and harvest rule parameters tended to be more consistent from year-to-year, even though they were often biased (i.e., because we chose a prior that was the midrange of U^{MSY}).

A more flexible stock assessment model might allow us to relax the prior precision on estimated parameters, thereby improving the rates at which models learn about the true parameters. But it seems clear from fitting the operating model as well as simulating the production model assessments, that the existing datasets are just not that informative about sablefish production relationships. For example, we examined Pella-Tomlinson formulations of the production model (not shown), but they were typically unstable, even when the power parameter was fixed. We also developed a reduced version of the age-/growth-structured operating model in an attempt to utilize more of the assessment data in management procedures (e.g., age-composition, at-sea releases); however, that model was not yet stable enough to provide the consistent performance needed in closed-loop simulations.

Management procedures based on high tuning production model stock assessments provided conservation performance across scenarios that was similar to perfect information procedures with the exception of S8. This difficult stock scenario is solely intended to insure that the objective of maintaining the stock above the limit reference point in 95% of the years over two generations is likely to be achieved even under low productivity conditions. This result suggests the largest benefits to improving stock assessments is not in conservation performance but instead in greater catch performance. For example, the potential loss in average annual catch due to assessment errors under S1:Baseline and MP2:StRsHiTuneH46 ranged from 5% to 11% per year, or 125 to 275 t of average annual yield. Given sablefish landed values of approximately $1 million/100 t, investment in improved stock assessment models might pay economic benefits.

4.4 THE BEST STRATEGIES FOR MANAGING SABLEFISH HARVEST

The SFF harvest strategy (DFO 2009b) was developed based on "precautionary" considerations to maintain stock sizes near or above B^{MSY} as much as possible, while also avoiding very low stock sizes that may impair future recruitment (DFO 2006). However, although our simulation results show that such rules do increase stock biomass rapidly, the default choices of $0.4B^{MSY}$ and $0.8B^{MSY}$ resulted in poor economic performance compared to the other options we considered. Walters (1998) showed similar losses associated with "precautionary" harvest rules, and speculated that unnecessary variations in catch associated with such rules may risk stakeholder distrust. Even under the most pessimistic scenarios, we examined, the less conservative harvest control rules using $0.4B^{MSY}$ and $0.6B^{MSY}$ provided negligible risks to the stock and did not inflict unnecessary penalties on the fishing industry.

The management procedure RetainStRsHiTuneH46, which is based on full retention of all sablefish combined with a less conservative ($0.4B^{MSY}$ and $0.6B^{MSY}$) harvest control rule, provided the best overall performance across all scenarios. A similar procedure using avoidance rather than retention provided the next best performance. Mandatory retention would have consequences for all fisheries, especially in the short-term while the fishery developed better measures to avoid small sablefish. For instance, under a full retention procedure and selectivity patterns similar to the ones we simulated, the trawl fishery, for which landings and at-sea releases are approximately equal, would reach their 8.75% quota in about half the time. Trap and hook fisheries would be affected much less because their at-sea releases only represent about 10-15% of the total landed catch. On the other hand, sablefish catch in trawl fisheries is usually not directed, which means that the change in fishing time is probably not a linear function of the quota as we assume in the operating model, so the exact impact is unknown.

Differences between avoidance and full retention options were not very large, which means that neither presents an obvious choice based on conservation benefits. However, these options have different implementation costs and potential impacts on each fishery. Therefore, a cost-benefit analysis in coordination with fishery managers and industry would be required before we could determine which option would likely provide the greatest benefits in the future.

In developing an approach to evaluating avoidance and full retention strategies, we should focus on extending the operating model so that a broader appraisal of the potential impacts of these strategies can be made. For instance, in this paper, we only consider the total landed catch biomass and therefore, we take no account of the price premium for landing larger sablefish. Under full retention, the average size of the landed catch would decline, possibly causing lower average prices per pound across all sectors. Furthermore, as shown in Appendix D, our current operating model structure could not match the full length time-series of at-sea releases in trawl fisheries because, as we speculated, trawl selectivity may already be practicing improved sablefish avoidance. Finally, in the future it is also possible that release mortality will be greater regardless of gear type because of depredation by marine mammals (Sigler et al. 2008).

4.5 MANAGEMENT STRATEGY IMPLICATIONS FOR THE 2011/12 FISHERY

Although management procedures based on full retention or avoidance of sablefish proved to be the best in our simulation analyses, we do not believe these options have been explored in enough detail and, in any case, neither is feasible to implement for the 2011/2012 fishing year. Among the remaining management procedure options, StRsHiTuneH46 appears to provide performance that is consistent with the fishery objectives, and is also feasible to implement immediately. We note that further modifications to this procedure could provide even better short-term catch performance without compromising conservation objectives, but we did not have time to fully explore such changes. In particular, we could evaluate the industry's short-term economic interests for maintaining the current catch limit (i.e., not reducing quota below the FY 2010/11 amount of 2,350 t) by determining whether any trade-off with conservation performance compromised the achievement of Objectives 1-3.

In the meantime, we provide a forecast of what the quota would be for a range of possible 2010 StRs survey outcomes under the StRsHiTuneH46 management procedure. Specifically, we computed the range of possible FY 2011/12 quotas as a function of the survey catch rate relative to the value observed in 2009 (Figure 12). Results indicate that maintaining the FY 2010/11 quota would require a 40-50% increase in the StRs survey relative to 2009, which is unlikely given the variability exhibited by the survey over the 2003-2009 period. If the survey remains the same as 2009, a quota of 2,106 t, or a 10% reduction, would result because there would be no strong indication in the data of stock stabilization or increase. Note, however, that the simulated catch projection for FY 2011/12 (i.e., C_{2011} in Table 8) is 2,170 t owing to a projected slight increase in the stock and StRs index, on average.

4.6 LIMITATIONS AND FUTURE WORK

Testing management procedures via closed-loop simulation presents several technical challenges for which improvements are probably needed. First, in most cases the stock assessment model used in the management procedure rarely agrees completely with the operating model about stock status and productivity, especially when the stock assessment uses a reduced dataset and has a fundamentally different structure. In our case, operating models were fitted to three abundance indices, three age-composition datasets, gear-specific landings and at-sea releases, and gear-specific tag returns. The production model used in the management procedure used only landed catch and three abundance indices, which it further assumes all come from the same spawning/exploitable biomass. These two models only agree on the historical biomasses and production when we put relatively informative priors on the stock assessment model parameters. Otherwise (e.g., low tuning), they really don't agree at all. Perhaps one way to deal with this discrepancy is to somehow include the stock assessment model in the initial operating model conditioning step. For example, the stock assessment model estimates of current biomass and B_0 could be used as priors on the operating model values.

Even where the assessment model can be made to agree with the operating model assessment of the historical states, the transition between fixed historical data and future simulated data needs to be carefully considered. In our previous work (Cox et al. 2009), we noted several potential problems with the Std survey that make it difficult to accurately represent the true variability. For instance, the Std survey appears to have runs of low variance years interspersed with occasionally high variance years. Such processes are difficult to parameterize based on short time-series. Fortunately, in this paper, the (under) estimated Std survey variance alone made a fairly obvious impact on the results, so that we probably need not consider the survey (or simulating data from it) in the future. Simulating age-composition data, on the other hand, is far more treacherous because the fishery sampling is rarely random and ageing errors are unknown. In our previous work (Cox et al. 2009), for example, we noticed an almost immediate improvement in catch-age model performance as the simulated data accumulated. Such improvements are probably unrealistic and that is one reason why we chose only an aggregated stock assessment model for this analysis.

Future research should seek to develop stock assessment models that improve over time (i.e., less biased, more precise). Under most of the procedures we examined, sablefish biomass growth in the short term generates information about fundamental population growth rates. Improved stock assessment models might be able to take advantage of this information to achieve better catch performance relative to MSY since our current models generally fish at levels below the true MSY. On the other hand, following a management procedure that is designed to limit variability in catch and biomass works against providing the informative variation needed to help learn about sablefish productivity. In fact, many of the procedures we examined showed improved estimation performance in the short term, as expected, but eventually got worse as biomass approached B^{MSY}. Future trade-offs among control, information, and fishery value are complex and may be worth exploring in further detail (Walters 1986, Walters and Collie 1989), especially if processes such as climate change cause systematic variation in future sablefish production rates. Also, it is unlikely that a single management procedure would be followed indefinitely, which raises questions about how often and by how much procedures and operating models should be modified in an attempt to improve overall fishery performance.

Admittedly, we could extend our Bayesian approach to include more, or even all, operating model parameters. However, freeing up some parameters could create pathological problems. For instance, we know that ageing errors may be significant, especially for the earlier age-composition samples from both fisheries and surveys. Attempts to estimate autocorrelation in historical recruitment will therefore favor higher, most likely biased, values. Like any state-space approach, we would need to provide informative priors on variance parameters in order to separate observation and process noise.

Finally, future simulation work evaluating management procedures should take fishery value into account rather than limiting the definition of "value" to total landed catch alone. Using only landed catch probably under-estimates the value of increasing sablefish biomass because it does not take catch-per-unit-effort, catch size-structure, and size-based price premiums into account. Our current operating model already provides population and fishery size-structure, so it would be a simple matter to compute landed value using size-specific dockside prices.

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Table 1. Summary of uncertainties and operating model assumptions that were identified in Cox and Kronlund (2009) and the actions taken for this assessment.

Uncertainty	**Operating model Assumption**	**Confidence in Assumption**	**Actions**
Historical discards	None	Very low	Revised operating model to account for at-sea releases (due to sub-legal size and high-grading) as well as the fate of releases depending on gear-specific release mortality Management procedures based on annual production model assessments do not take discarding into account.
Age proportion sampling and ageing errors	Unbiased	Low	Management procedures based on catch-age modeling are not considered in this assessment. Work needs to be done to evaluate the effects of ageing error as well as non-random biological sampling of fishery catch.
Standardized survey catchability	Constant	Medium/low (survey in core areas)	As in Cox et al. (2009) we do not assume that survey variance is known *a priori* based on within-year variance alone. Models fits indicate that considerable year-to-year variation is remains unaccounted for.
Standardized survey selectivity	Constant	Medium (surveys along juvenile migration path)	In this assessment, we evaluate discontinuing this survey in future management procedures.
Spatial structure	Closed B.C.	Low	No action.
Life history parameters	No male/female differences	Low	In the process of accounting for size-based discarding, we extended the operating model to

Uncertainty	Operating model Assumption	Confidence in Assumption	Actions
	Known M Known growth parameters		account for variation in size-at-age. This does not account for male-female differences. Natural mortality is now estimated within the operating model; however, we include an informative normally distributed prior with a mean of 0.08 and standard deviation of 0.005 to limit confounding with other production parameters. We developed a comprehensive analysis of growth parameter estimates based on all possible (B.C.) sources of size-at-age data for sablefish (as well as other biological parameters for maturity, length-weight, etc.). We tested MP performance against alternative values for L_1, k, L_∞, and σ_L.

Table 2. Risk tolerances and management actions specified by DFO's Sustainable Fisheries Framework (DFO 2009b).

Stock Status	Stock trajectory	Risk tolerance
Healthy		
	Increasing	High (75-95%)
	Decreasing	Moderate (25-50%) if near USR Neutral (50%) otherwise
Cautious		
	Increasing	Low (5-25%) or moderate (25-50%) if near the USR Management actions must encourage stock growth into the Healthy zone within a reasonable time frame§
	Stable	Low (5-25%) or moderate (25-50%) if status is near the USR Management actions must encourage stock growth into the Healthy zone the short-term
	Decreasing	Low (5-25%) or very low (<5%) if the stock is near the LRP Management actions must arrest the decline in the short-term.
Critical		
	n.a.	Management actions must promote the building of biomass out of the Critical zone with high probability within a reasonable time frame
	n.a.	Removals must be kept to the lowest possible level

§ A reasonable time frame is defined as 1.5 to 2 generations, or longer for long-lived species (DFO (2009), Annex 2B, footnote 12)

*Table 3. Component specifications for seven candidate management procedures for the B.C. sablefish fishery. Index data available for stock assessments include the stratified random (StRs) and standardized (Std) surveys. Prior distributions P(*MSY*) and P(U^{MSY}) used in production model stock assessments include high and low precision "tunings" based on the prior standard deviations. Values shown under B_{lower}, B_{upper} are the multipliers of estimated B^{MSY} used to define the harvest control rule. Sub-legal regulations are either the status quo "Release" protocol, "Avoidance" for which all selectivity-at-length functions are set to zero for lengths L < 55 cm, or "Full Retention" where the size limits are set to 20 cm for all gears/sectors. The final column shows the labels used to identify MPs in graphics and tables.*

Management procedure	Index Data	*P*(MSY)*	*P*(U^{MSY})	U^{MSY}	B_{lower}, B_{upper} multipliers	Sub-legal Regulation	Label
MP1	--	--	--	True	(0.4, 0.6)	Release	PerfectH46
MP2	StRs	*N*(3.4, 1.7)	*N*(0.08, 0.04)	Est.	(0.4, 0.6)	Release	StRsHiTuneH46
MP3	StRs	*N*(3.4, 1.7)	*N*(0.08, 0.04)	Est.	(0.4, 0.6)	Avoidance	AvoidStRsHiTuneH46
MP4	StRs	*N*(3.4, 1.7)	*N*(0.08, 0.04)	Est.	(0.4,0.6)	Full Retention	RetainStRsHiTuneH46
MP5	StRs	*N*(3.4, 3.4)	*N*(0.08, 0.08)	Est.	(0.4, 0.6)	Release	StRsLowTuneH46
MP6	Std, StRs	*N*(3.4, 3.4)	*N*(0.08, 0.08)	Est.	(0.4, 0.6)	Release	StdStRsLowTuneH46
MP7	Std, StRs	*N*(3.4, 3.4)	*N*(0.08, 0.08)	Est.	(0.4, 0.8)	Release	StdStRsLowTuneH48

* Units for MSY are thousands of metric tonnes to coincide with the units of the production model.

Table 4. Harvest control rule component of management procedures. Parameters of the rule (H4.1) are derived from the production model stock assessment (Appendix E) estimates of the optimal harvest rate U^{MSY}, biomass producing maximum potential yield B^{MSY}, multipliers (0.4,0.6) of B^{MSY} that define the bounds B_{lower} and B_{upper}, respectively, and a 1-step-ahead projection of the estimated exploitable biomass that determine the total quota Q_{T+1} of legal fish.

H4.1	$\Psi = \left(\hat{U}^{\text{MSY}}, \hat{B}_{\text{lower}}, \hat{B}_{\text{upper}}, \hat{B}_{T+1}\right)$
H4.2	$U_{T+1} = \begin{cases} 0 & \hat{B}_{T+1} < \hat{B}_{\text{lower}} \\ \hat{U}^{\text{MSY}}\left(\dfrac{\hat{B}_{T+1} - \hat{B}_{\text{lower}}}{\hat{B}_{\text{upper}} - \hat{B}_{\text{lower}}}\right) & \hat{B}_{\text{lower}} \le \hat{B}_{T+1} < \hat{B}_{\text{upper}} \\ \hat{U}^{\text{MSY}} & \hat{B}_{T+1} \ge \hat{B}_{\text{upper}} \end{cases}$
H4.3	$Q_{T+1} = U_{T+1}\hat{B}_{T+1}$

Table 5. Performance statistics calculated for each simulation replicate of a management procedure/scenario combination. The interval $t = t_1, \ldots, t_2$ defines the time period over which each statistic is calculated. The probability P(decline) differs among scenarios depending on operating model stock status as defined in Equation (1). The indicator function I(x is TRUE) = 1 or I(x is FALSE) = 0.

No.	Objective	Description	Probability or Statistic	Definition
P.1	Objective 1	Proportion of projection years where spawning biomass exceeds $0.4B^{\mathrm{MSY}}$. (Period: t_1 = 2011, t_2 = 2046)	$P\left(B > 0.4B^{\mathrm{MSY}}\right)$	$P\left(B > 0.4B^{\mathrm{MSY}}\right) = \frac{\sum_{t_1}^{t_2} \mathrm{I}\left(B_t > 0.4B^{MSY}\right)}{t_2 - t_1 + 1}$
P.2	Objective 2	Proportion of 10-year trends that are declining (Period: t_1 = 2011, t_2 = 2020)	$P(\beta < 0) < P(decline)$	$P(\beta < 0) = \frac{1}{100}\sum_{1}^{100} \mathrm{I}(\beta < 0)$
P.3	Objective 3	Proportion of projection years where spawning biomass exceeds B^{MSY} (Period: t_1 = 2011, t_2 = 2046)	$P\left(B > B^{\mathrm{MSY}}\right)$	$P\left(B > B^{\mathrm{MSY}}\right) = \frac{\sum_{t_1}^{t_2} \mathrm{I}\left(B_t > B^{MSY}\right)}{t_2 - t_1 + 1}$
P.4	Objective 4	Mean of annual landed catch (Period: t_1 = 2011, t_2 = 2020)	$\overline{C^L}$	$\overline{C^L} = \frac{1}{t_2 - t_1 + 1}\sum_{t_1}^{t_2} C_t^L$
P.5	Surrogate for Objective 3	Proportion of projection years where spawning biomass is in the Healthy. (Period: t_1 = 2011, t_2 = 2046)	$P\left(B > 0.8B^{\mathrm{MSY}}\right)$	$P\left(B > 0.8B^{\mathrm{MSY}}\right) = \frac{\sum_{t_1}^{t_2} \mathrm{I}\left(B_t > 0.8B^{MSY}\right)}{t_2 - t_1 + 1}$
P.6	Min and Max	Minimum and Maximum landed catch (Period: t_1 = 2011, t_2 = 2020)	Min *C* Max *C*	$\min\left(C_{2011}^L, C_{2012}^L, \ldots C_{2021}^L\right)$ $\max\left(C_{2011}^L, C_{2012}^L, \ldots C_{2021}^L\right)$
P.6	Industry preference	Average annual absolute change in the landed catch (Period: t_1 = 2011, t_2 = 2020)	*AAV*	$AAV = \sum_{t=t_1}^{t_2} \left\lvert C^L{}_t - C^L{}_{t-1} \right\rvert \Big/ \sum_{t=t_1}^{t_2} C^L{}_t$

Table 6. Operating model scenarios for B.C. sablefish. Release mortality rates are given in order for trap, longline hook and trawl gears. Scenarios S7 and S8 are based on parameters obtained from the mean of the Bayes posterior distribution of scenario S1 (S7) or on a draw from the posterior corresponding to the 10th percentile of the distribution of MSY *(S8). The S-R column indicates the value of stock-recruitment auto-correlation* $\left(\gamma_R\right)$ *simulated in the projection period.*

Scenario	**Release mortality**	**Natural mortality (*M*)**	**MSY quantile**	**Growth rate (*k*)**	**S-R** $\left(\gamma_R\right)$	**Label**
S1	(0.15,0.30,0.80)	Estimated	--	0.30	0	S1:Baseline
S2	(0.15,0.30,0.80)	Fixed 0.08	--	0.30	0	S2:FixedM
S3	(0.15,0.30,0.80)	Estimated	--	0.25	0	S3:S1+Growth
S4	(0.15,0.30,0.80)	Fixed 0.08	--	0.25	0	S4:S2+Growth
S5	(0.15,0.30,0.80)	Estimated	--	0.30	0.40	S5:S1+AR
S6	(0.15,0.30,0.80)	Fixed 0.08	--	0.30	0.40	S6:S2+AR
S7	(0.15,0.30,0.80)	Estimated	--	0.30	0	S7:S1-Mean
S8	(0.15,0.30,0.80)	Estimated	10th	0.30	0	S8:S1-10th

Table 7. Distinguishing features of operating model scenarios S1-S8. Leading model parameters for each scenario are stock-recruitment steepness (h), the natural mortality rate (M), and the unfished spawning biomass (B_0). Equilibrium characteristics include the maximum sustainable yield (MSY), optimal legal harvest rate (U^{MSY}), spawning biomass (B^{MSY}), spawning biomass depletion (D^{MSY}), and depletion at the limit reference point $0.4B^{MSY}$ (D^{LRP}). The remaining two columns give projections for Year 2011 of spawning biomass (B_{2011}) and depletion (D_{2011}). Biomass units are thousands of metric tonnes.

Scenario	h	M	B_0	MSY	U^{MSY}	B^{MSY}	D^{MSY}	D^{LRP}	B_{2011}	D_{2011}
S1: Baseline	0.88	0.06	114.77	3.23	0.11	27.68	0.24	0.10	21.09	0.18
S2: FixedM	0.50	0.08	147.73	3.21	0.06	53.13	0.36	0.14	34.85	0.24
S3: S1+Growth	0.85	0.06	122.10	3.31	0.10	32.21	0.26	0.10	27.25	0.22
S4: S2+Growth	0.51	0.08	152.65	3.22	0.06	55.68	0.36	0.15	39.07	0.26
S5: S1+AR	0.88	0.06	114.77	3.22	0.11	27.68	0.24	0.10	21.18	0.18
S6: S2+AR	0.50	0.08	147.73	3.21	0.06	53.13	0.36	0.14	34.96	0.24
S7: S1-Mean	0.75	0.06	120.05	3.06	0.09	33.70	0.28	0.11	22.74	0.20
S8: S1-10th	0.59	0.06	121.08	2.53	0.06	40.02	0.33	0.13	24.59	0.19

Table 8. Performance summary for seven management procedures tested against eight operating model scenarios. Objectives that are satisfied by a procedure are indicated by (●). A procedure meets Objective 1 if the stock remains above the LRP in 95% of years, on average, over two generations. Objective 2 is met if the proportion of growing stock trajectories is greater than P(decline) over the first 10 projection years. Objective 3 is met if spawning biomass is greater than B^{MSY} in 50% of years over 2 generations. Values under Objective 4 are median average catches (000s t) in the first 10 years of the projections. Values of performance measures are provided where a procedure fails under Objectives 2 or 3. Values under "Healthy" are the average proportion of years that the true $B > 0.8B^{MSY}$ over two generations, "Min C" and "Max C" are the medians of minimum and maximum catch, respectively, over the first 10 projection years, AAV is the average absolute annual variation in catch, and D_{2011} and C_{2011} are the average spawning biomass depletion and average projected legal catch for 2011. Note that alternative regulations are not implemented until 2012, so the average quota C_{2011} is identical for all HiTune MPs.

Scenario Management procedure	**Objective** 1	2	3	4	Healthy	Min *C*	Max *C*	*AAV*	D_{2011}	C_{2011}
S1: Baseline										
PerfectH46	●	●	0.40	2.50	0.83	2.21	2.82	4.25	0.18	2.22
StRsHiTuneH46	●	●	●	2.37	0.88	1.97	2.69	7.18	0.18	2.06
AvoidStRsHiTuneH46	●	●	●	2.39	0.90	1.98	2.74	7.13	0.18	2.06
RetainStRsHiTuneH46	●	●	●	2.42	0.90	2.02	2.76	6.89	0.18	2.06
StRsLowTuneH46	●	●	●	2.43	0.88	1.62	2.85	13.71	0.18	1.77
StdStRsLowTuneH46	●	●	●	2.10	0.93	0.52	3.03	34.58	0.18	1.33
StdStRsLowTuneH48	●	●	●	1.83	0.96	0.38	3.25	43.69	0.18	0.69
S2: FixedM										
PerfectH46	●	●	0.16	2.14	0.50	1.96	2.34	4.74	0.24	1.97
StRsHiTuneH46	●	●	0.12	2.37	0.42	2.10	2.63	6.36	0.24	2.17
AvoidStRsHiTuneH46	●	●	0.16	2.38	0.48	2.10	2.65	6.28	0.24	2.17
RetainStRsHiTuneH46	●	●	0.14	2.40	0.46	2.12	2.67	6.22	0.24	2.17
StRsLowTuneH46	●	●	0.12	2.43	0.40	1.79	2.85	12.04	0.24	1.98
StdStRsLowTuneH46	●	●	0.21	2.10	0.56	0.67	2.96	33.66	0.24	1.62
StdStRsLowTuneH48	●	●	0.28	1.77	0.69	0.46	3.05	44.55	0.24	0.88
S3: S1+Growth										
PerfectH46	●	●	0.40	2.73	0.92	2.53	3.00	3.42	0.22	2.56
StRsHiTuneH46	●	●	●	2.42	0.98	2.10	2.75	6.71	0.22	2.12
AvoidStRsHiTuneH46	●	●	●	2.45	0.99	2.11	2.79	6.66	0.22	2.12
RetainStRsHiTuneH46	●	●	●	2.47	0.99	2.12	2.82	6.52	0.22	2.12
StRsLowTuneH46	●	●	●	2.51	0.98	1.75	2.91	12.13	0.22	1.89
StdStRsLowTuneH46	●	●	●	2.19	0.99	0.71	3.04	31.52	0.22	1.53
StdStRsLowTuneH48	●	●	●	1.92	1.00	0.52	3.27	41.43	0.22	0.82

Scenario Management procedure	Objective 1	2	3	4	Healthy	Min C	Max C	AAV	D_{2011}	C_{2011}
S4: S2+Growth										
PerfectH46	●	●	0.18	2.25	0.56	2.10	2.44	3.43	0.26	2.11
StRsHiTuneH46	●	●	0.16	2.41	0.51	2.14	2.66	6.34	0.26	2.18
AvoidStRsHiTuneH46	●	●	0.22	2.42	0.58	2.15	2.68	6.29	0.26	2.18
RetainStRsHiTuneH46	●	●	0.20	2.45	0.55	2.16	2.71	6.18	0.26	2.18
StRsLowTuneH46	●	●	0.15	2.48	0.49	1.83	2.89	11.46	0.26	2.03
StdStRsLowTuneH46	●	●	0.25	2.17	0.64	0.77	3.02	31.93	0.26	1.70
StdStRsLowTuneH48	●	●	0.33	1.83	0.77	0.54	3.17	43.66	0.26	0.93
S5: S1+AR										
PerfectH46	●	●	0.38	2.48	0.73	2.19	2.85	4.91	0.18	2.22
StRsHiTuneH46	●	●	●	2.36	0.81	1.91	2.66	8.13	0.18	2.06
AvoidStRsHiTuneH46	●	●	●	2.38	0.84	1.91	2.71	7.93	0.18	2.06
RetainStRsHiTuneH46	●	●	●	2.40	0.84	1.95	2.74	7.65	0.18	2.06
StRsLowTuneH46	●	●	●	2.43	0.81	1.56	2.88	14.13	0.18	1.77
StdStRsLowTuneH46	●	●	●	2.11	0.90	0.54	3.03	35.93	0.18	1.33
StdStRsLowTuneH48	●	●	●	1.84	0.94	0.37	3.25	44.46	0.18	0.70
S6: S2+AR										
PerfectH46	●	●	0.19	2.11	0.43	1.94	2.32	5.26	0.24	1.97
StRsHiTuneH46	●	0.31>0.24	0.17	2.36	0.40	2.07	2.65	6.74	0.24	2.17
AvoidStRsHiTuneH46	●	0.27>0.24	0.20	2.38	0.43	2.08	2.66	6.63	0.24	2.17
RetainStRsHiTuneH46	●	0.28>0.24	0.19	2.39	0.42	2.10	2.69	6.49	0.24	2.17
StRsLowTuneH46	●	0.36>0.24	0.16	2.43	0.38	1.70	2.87	12.36	0.24	1.98
StdStRsLowTuneH46	●	●	0.24	2.11	0.48	0.60	2.99	35.39	0.24	1.63
StdStRsLowTuneH48	●	●	0.29	1.77	0.62	0.45	3.13	45.00	0.24	0.89
S7: S1-Mean										
PerfectH46	●	●	0.28	2.15	0.70	1.88	2.41	5.41	0.19	1.91
StRsHiTuneH46	●	●	0.28	2.27	0.65	1.90	2.55	7.70	0.19	2.06
AvoidStRsHiTuneH46	●	●	0.35	2.30	0.71	1.92	2.58	7.44	0.19	2.06
RetainStRsHiTuneH46	●	●	0.33	2.31	0.69	1.96	2.60	7.17	0.19	2.06
StRsLowTuneH46	●	●	0.28	2.32	0.63	1.55	2.77	14.50	0.19	1.77
StdStRsLowTuneH46	●	●	0.46	1.96	0.80	0.46	2.90	37.63	0.19	1.32
StdStRsLowTuneH48	●	●	●	1.67	0.86	0.36	3.00	47.02	0.19	0.69

Scenario Management procedure	Objective 1	2	3	4	Healthy	Min C	Max C	AAV	D_{2011}	C_{2011}
S8: S1-10th										
PerfectH46	●	●	0.17	1.65	0.52	1.48	1.82	8.17	0.20	1.48
StRsHiTuneH46	●	0.45>0.21	0.02	2.23	0.15	1.92	2.49	7.03	0.20	2.13
AvoidStRsHiTuneH46	●	0.32>0.21	0.04	2.26	0.21	1.96	2.51	6.81	0.20	2.13
RetainStRsHiTuneH46	●	0.35>0.21	0.03	2.27	0.19	1.98	2.52	6.48	0.20	2.13
StRsLowTuneH46	●	0.49>0.21	0.02	2.26	0.15	1.55	2.75	14.10	0.20	1.89
StdStRsLowTuneH46	●	●	0.09	1.90	0.34	0.53	2.86	39.15	0.20	1.46
StdStRsLowTuneH48	●	●	0.16	1.60	0.53	0.37	2.91	47.43	0.20	0.78

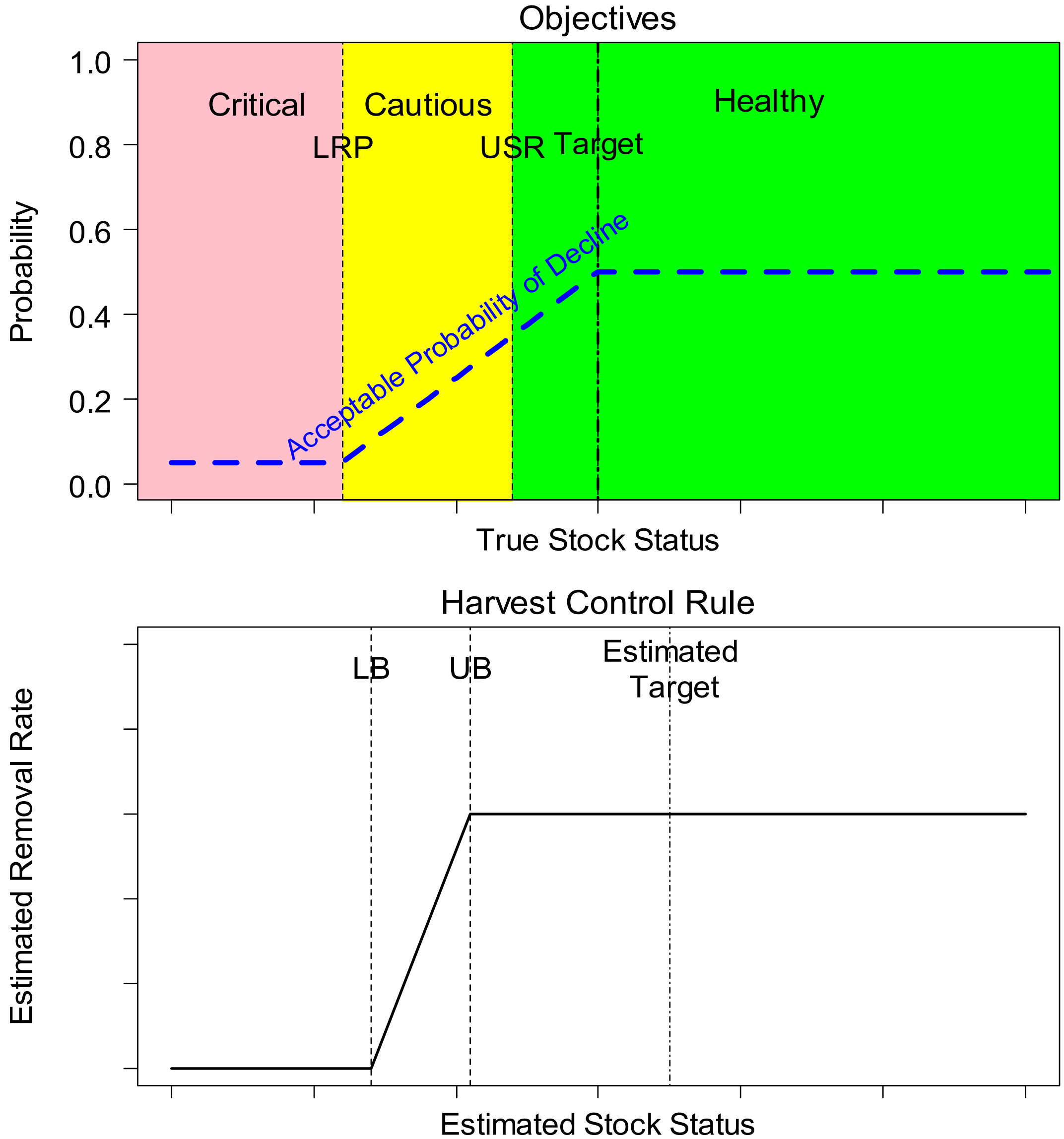

*Figure 1. Comparison of fishery objectives with an example harvest control rule as required under the Sustainable Fisheries Framework. Objectives (upper panel) use a limit reference point (*LRP*) and upper stock reference (*USR*) to define the Critical, Cautious and Healthy zones of true stock status. "Target" stock status lies within the Healthy zone. The dashed line indicates how the acceptable probability of decline scales linearly between the* LRP *and* Target*. A harvest control rule (lower panel) translates an estimate of stock status into a catch limit by adjusting the target harvest rate (solid line). The lower bound (*LB*), upper bound (*UB*) and target of the rule are all estimated (annually) as part of the management procedure.*

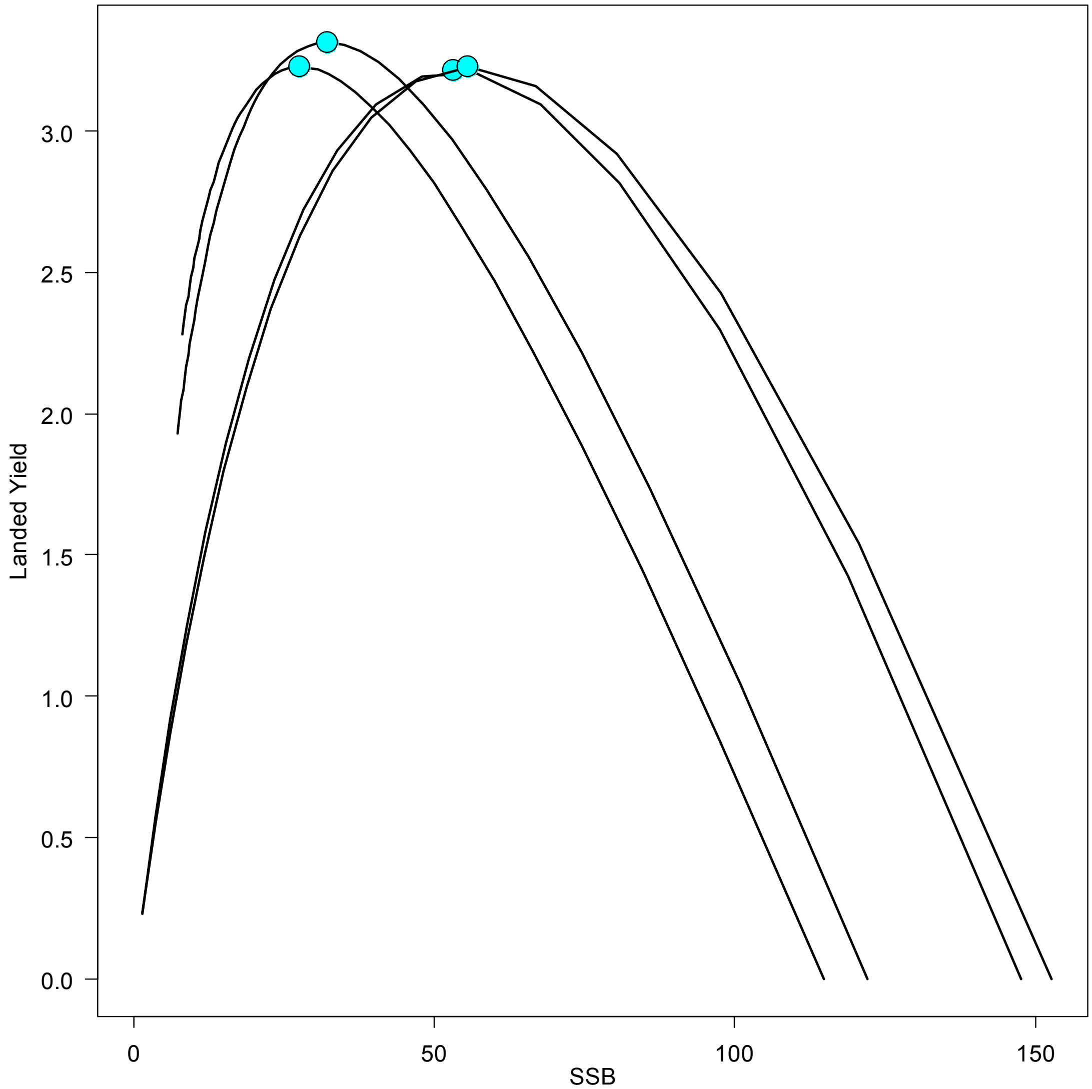

Figure 2. Relationships between spawning stock biomass and total equilibrium yield (000s t) from B.C. sablefish fisheries. From left to right, lines represent scenarios S1:Baseline, S3:S1+Growth, S2:FixedM, and S4:S2+Growth.

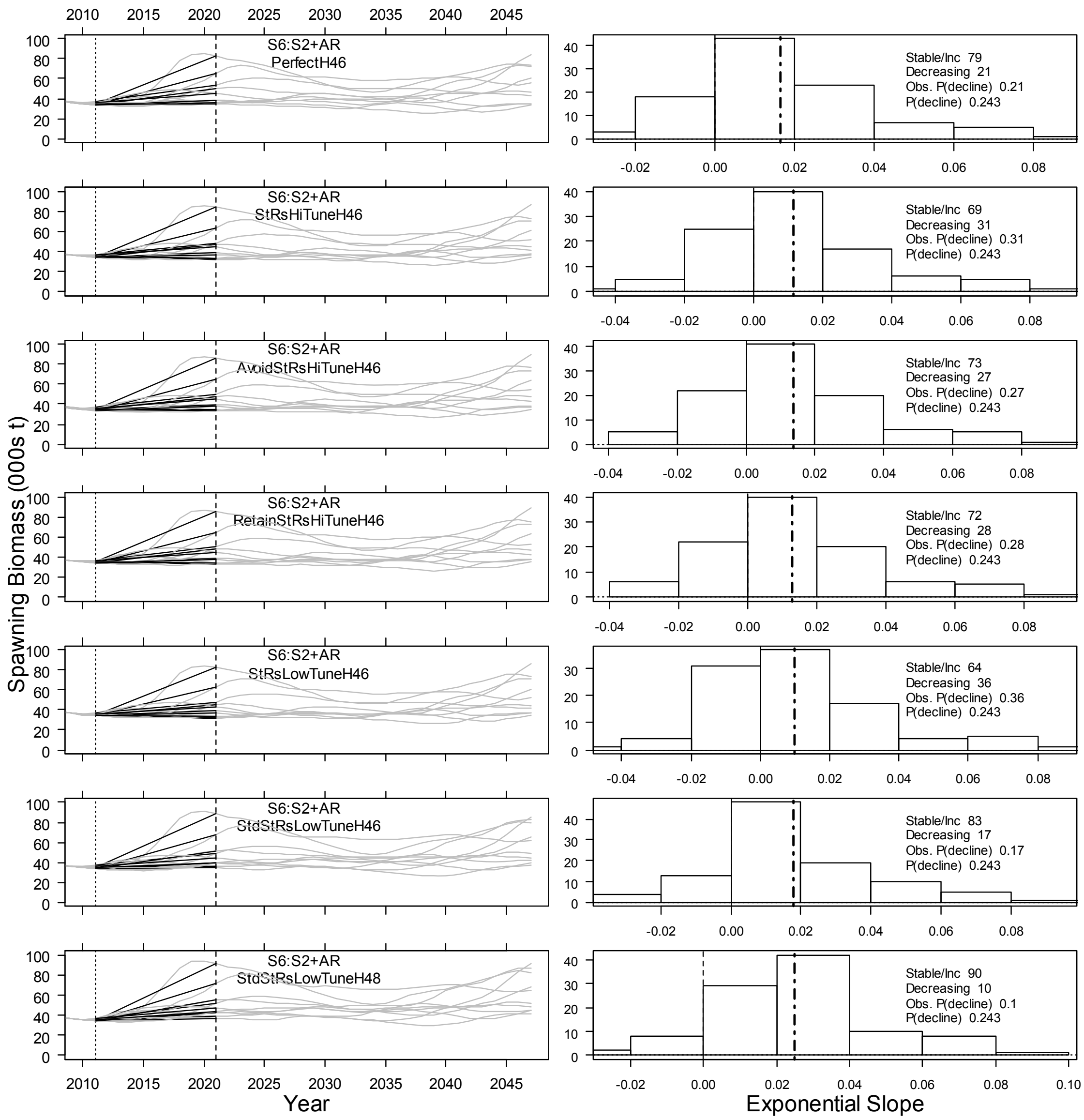

Figure 3. Performance of seven management procedures in meeting Objective 3 (10-year stock trend) under Scenario S6:S2+AR. Left panel shows 10 randomly chosen stock biomass trajectories (gray lines) and their corresponding 10-year trend estimates (black lines). Right panel shows histograms of all 100 stock trend statistics for each MP, the threshold tolerance for decline "P(decline)", and the proportion of declining trends "Obs. P(decline)". The vertical dashed line shows the mean trend.

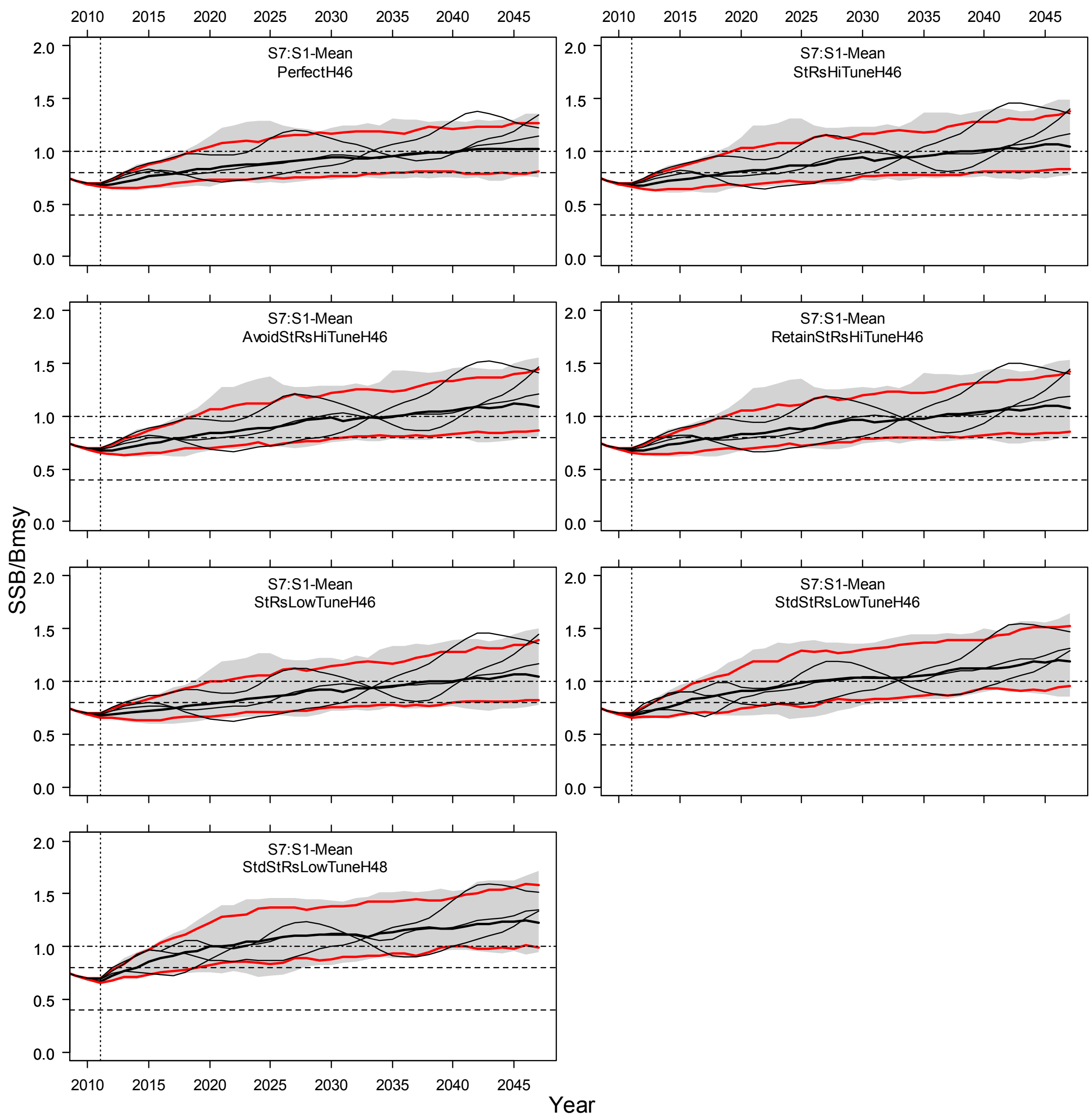

Figure 4. Trajectory envelopes of spawning biomass relative to B^{MSY} for all MPs applied to scenario S7: S1-Posterior means. Each plot shows the median relative biomass (thick black line), upper 90th and lower 10th percentiles (red lines), central 90% region (shaded area), and three individual traces. From top-to-bottom, the horizontal dashed lines indicate B^{MSY}, 0.8B^{MSY}, and 0.4B^{MSY}. The outcome in the bottom left plot is the only one satisfying Objective 3.

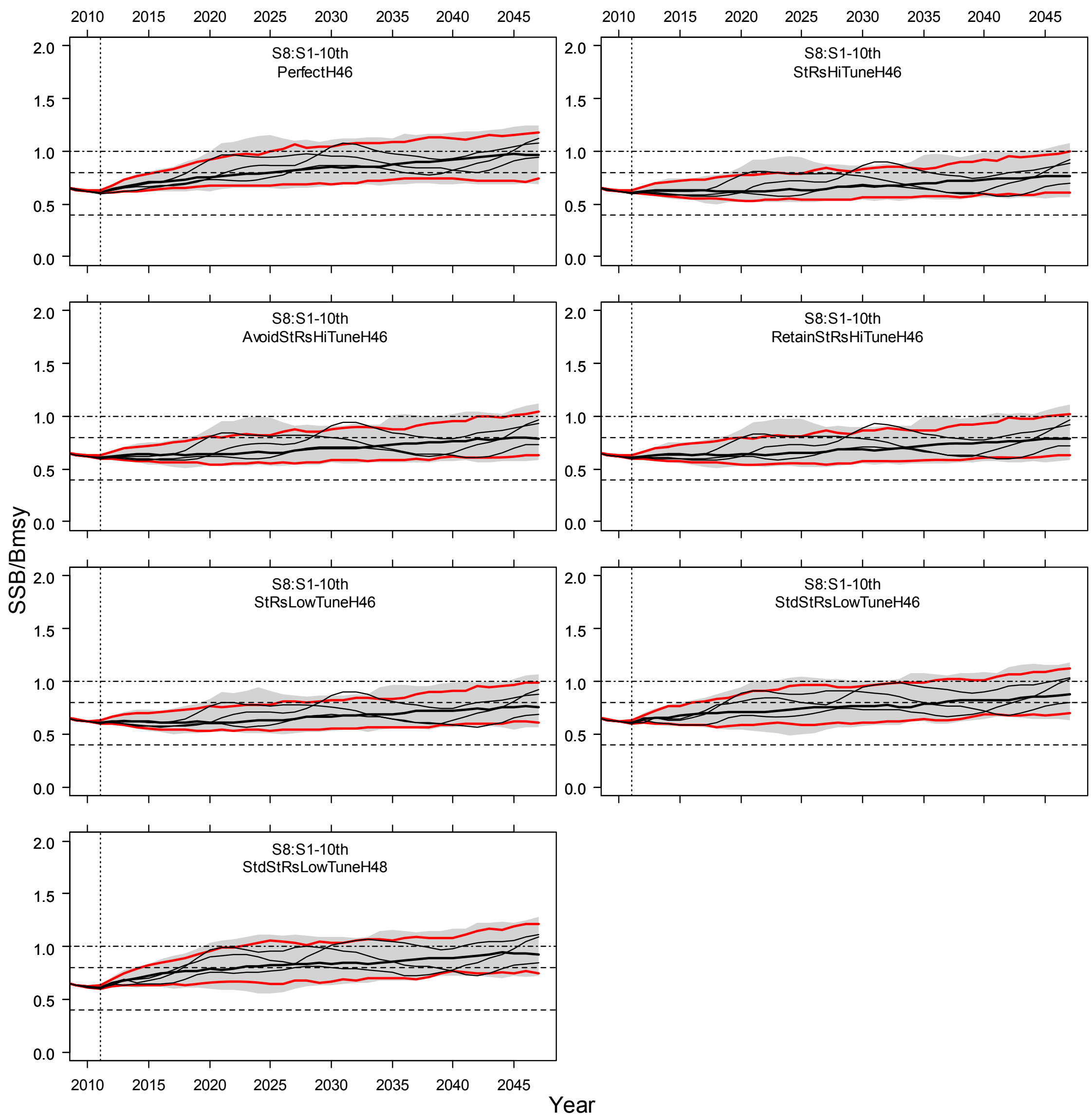

Figure 5. Trajectory envelopes of spawning biomass relative to B^{MSY} for all MPs applied to scenario S8:S1-10th. Each plot shows the median relative biomass (thick black line), upper 90^{th} and lower 10^{th} percentiles (red lines), central 90% region (shaded area), and three individual traces. From top-to-bottom, the horizontal dashed lines indicate B^{MSY}, $0.8B^{MSY}$, and $0.4B^{MSY}$.

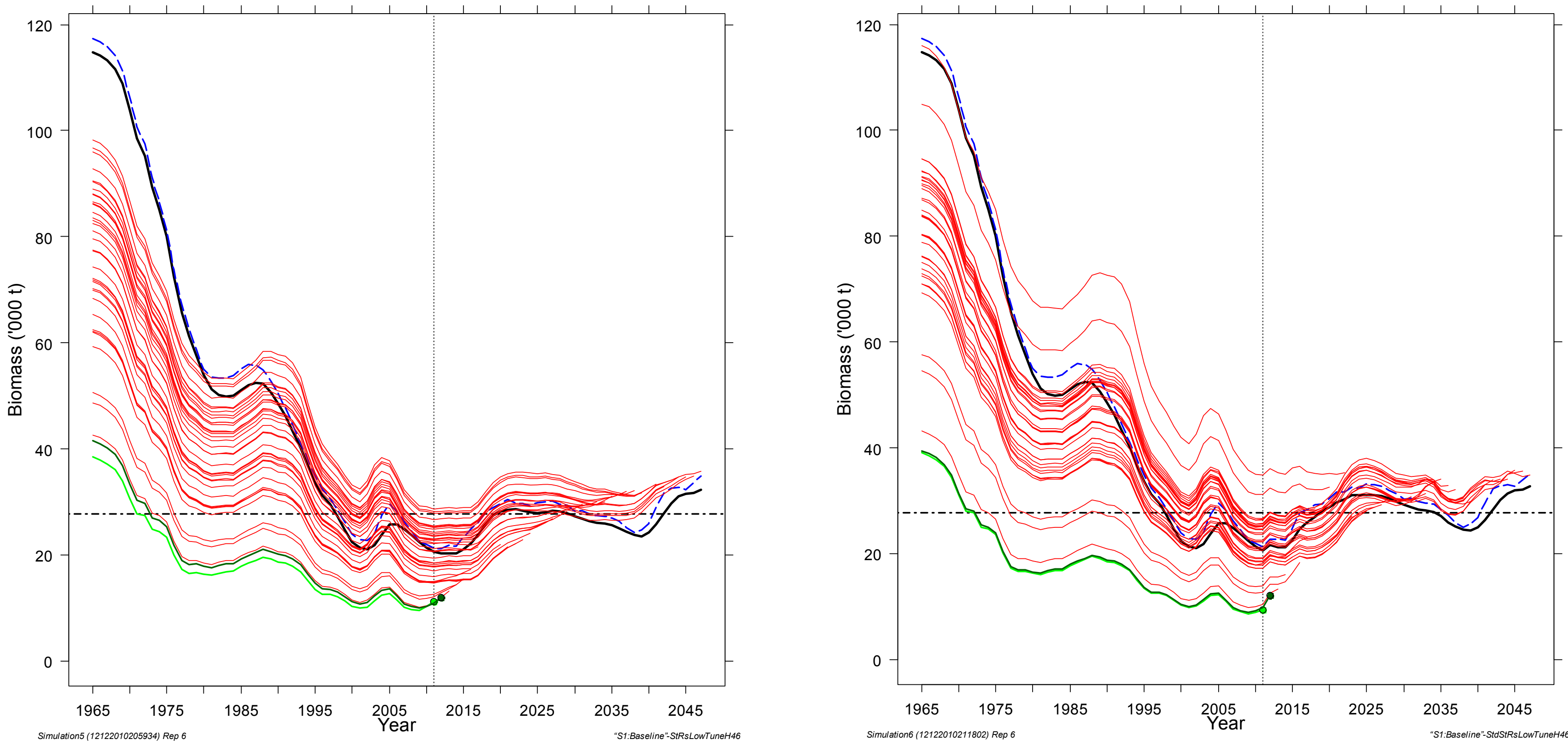

Figure 6. Examples of simulated retrospective stock assessment estimates of legal biomass (red lines) for one replicate of a management procedure based on only the StRs survey (left) and on both Std and StRs surveys (right). The light and dark green lines ending in dots are the simulated assessments for years 2010 and 2012, respectively. Random numbers are identical for the two simulations and the scenario is S1:Baseline.

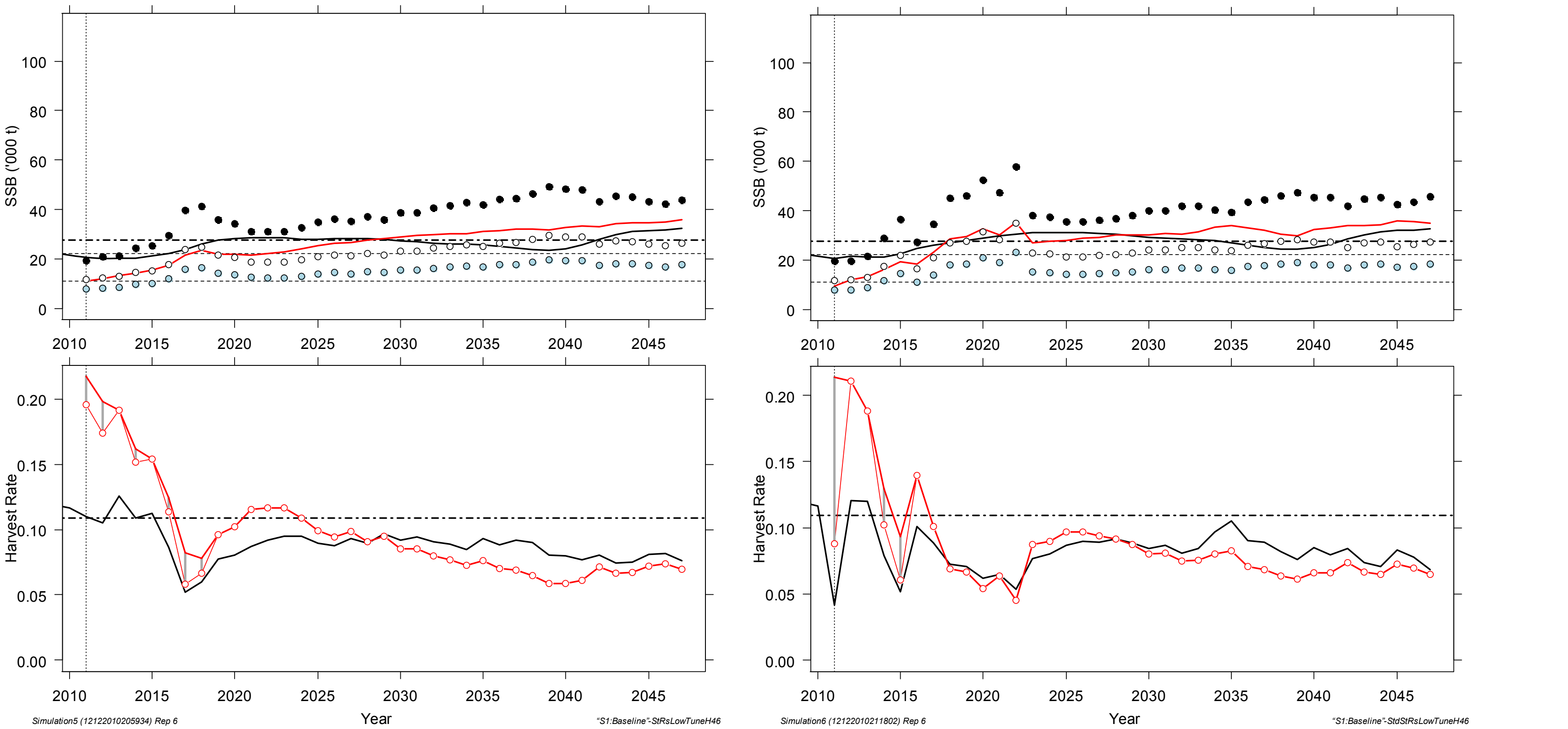

Figure 7. Example of management procedure component updating in each projection year when using StRs survey alone (left panels) and both Std and StRs (right panels). Top panels show estimated harvest rule components including biomass (red line), B^{MSY} (black circles), B_{upper} (open circles), and B_{lower} (gray circles) and true operating model spawning biomass (black line), true B^{MSY} (dot-dashed line), and LRP and USR reference points (gray dashed lines). Lower panels show the true operating model U^{MSY} (dot-dashed line), true legal-sized harvest rate on operating legal biomass (black line), estimated U^{MSY} (solid red line) and the adjusted target harvest rate U_{T+1} generated by the harvest rule (open circles). Gray vertical lines indicate when/how target harvest rates are adjusted by the harvest control rule when biomass is assessed below B_{upper} (i.e., when the red lines fall between white and gray circles in the top panel.

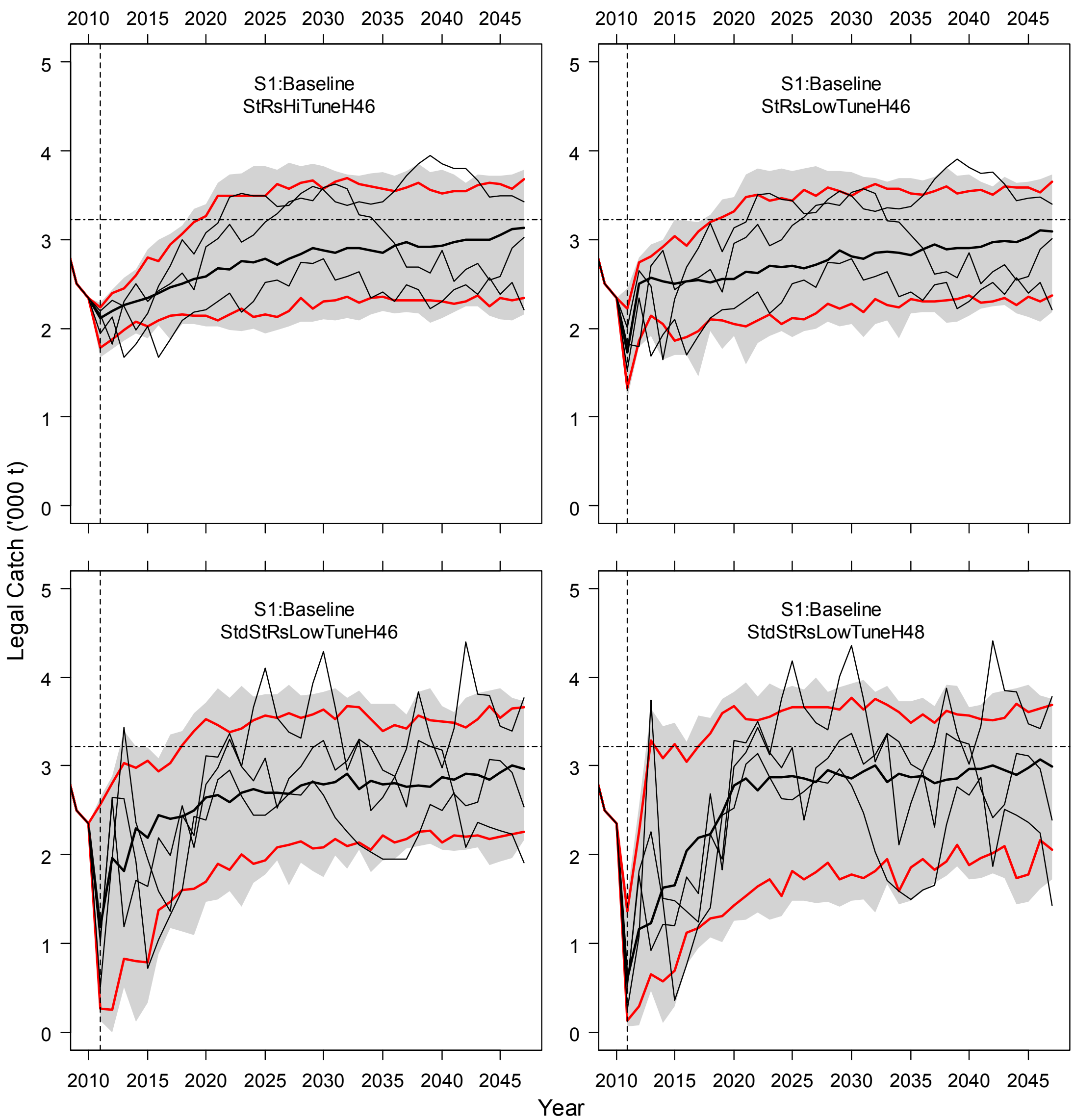

Figure 8. Simulation envelopes (S1:Baseline) of landed legal catch ('000 tonnes) for StRsHiTuneH46 (top left), StRsLowTuneH46 (top right), StdStRsLowTuneH46 (lower left), and StdStRsLowTuneH48 (lower right). Horizontal line shows MSY. *See Figure 4 for envelope quantile specification.*

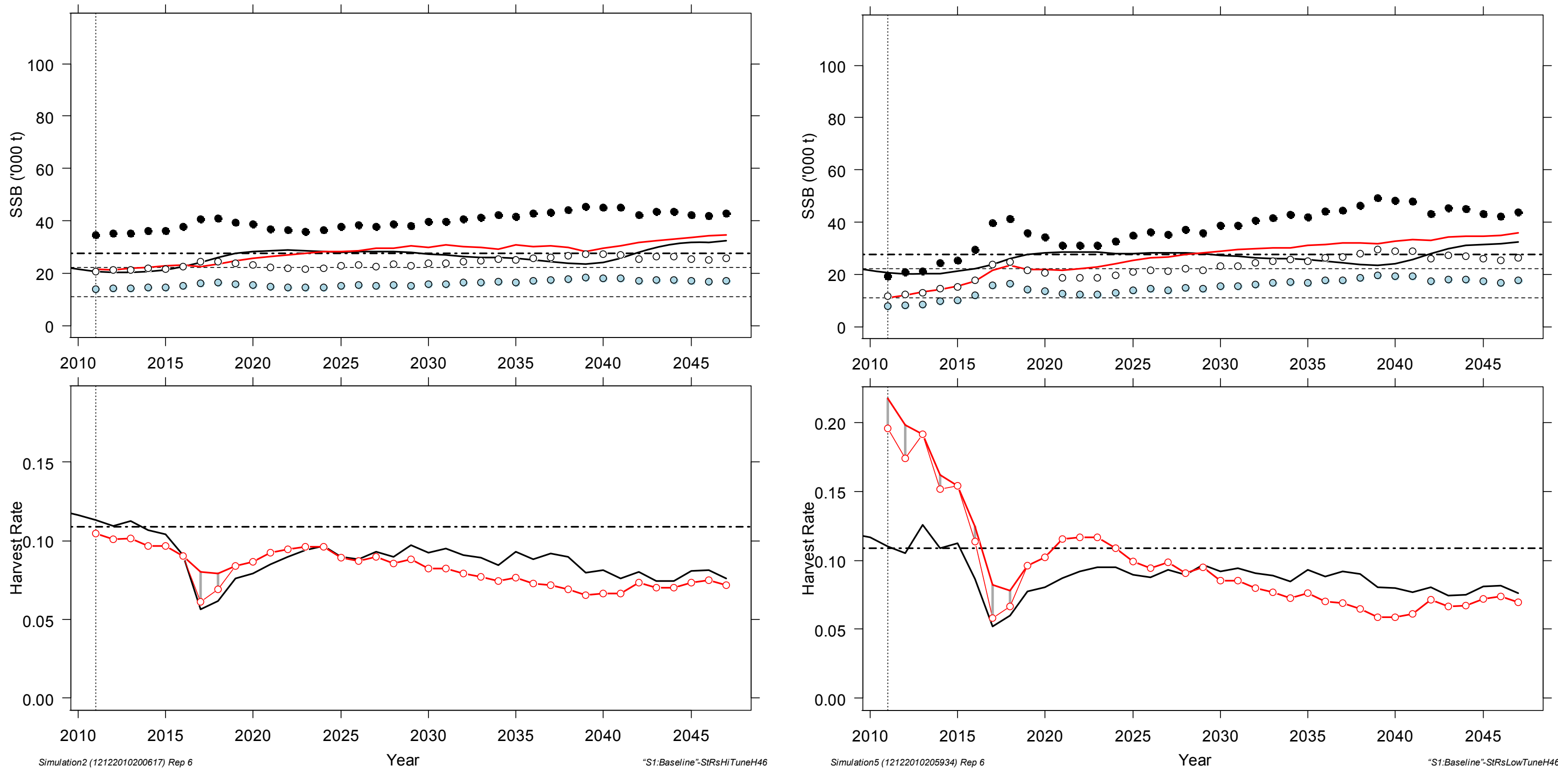

Figure 9. Example of management procedure component updating in each projection year when using StRsHiTuneH46 (left panels) and StRsLowTuneH46 (right panels). Top panels show estimated harvest rule components including biomass (red line), B^{MSY} (black circles), B_{upper} (open circles), and B_{lower} (gray circles) and true operating model spawning biomass (black line), true B^{MSY} (dot-dashed line), and LRP and USR reference points (gray dashed lines). Lower panels show the true operating model U^{MSY} (dot-dashed line), true legal-sized harvest rate on operating legal biomass (black line), estimated U^{MSY} (solid red line) and the adjusted target harvest rate U_{T+1} generated by the harvest rule (open circles). Gray vertical lines show when/how target harvest rates are adjusted by the harvest control rule when biomass is assessed below B_{upper} (i.e., when the red lines fall between white and gray circles in the top panels).

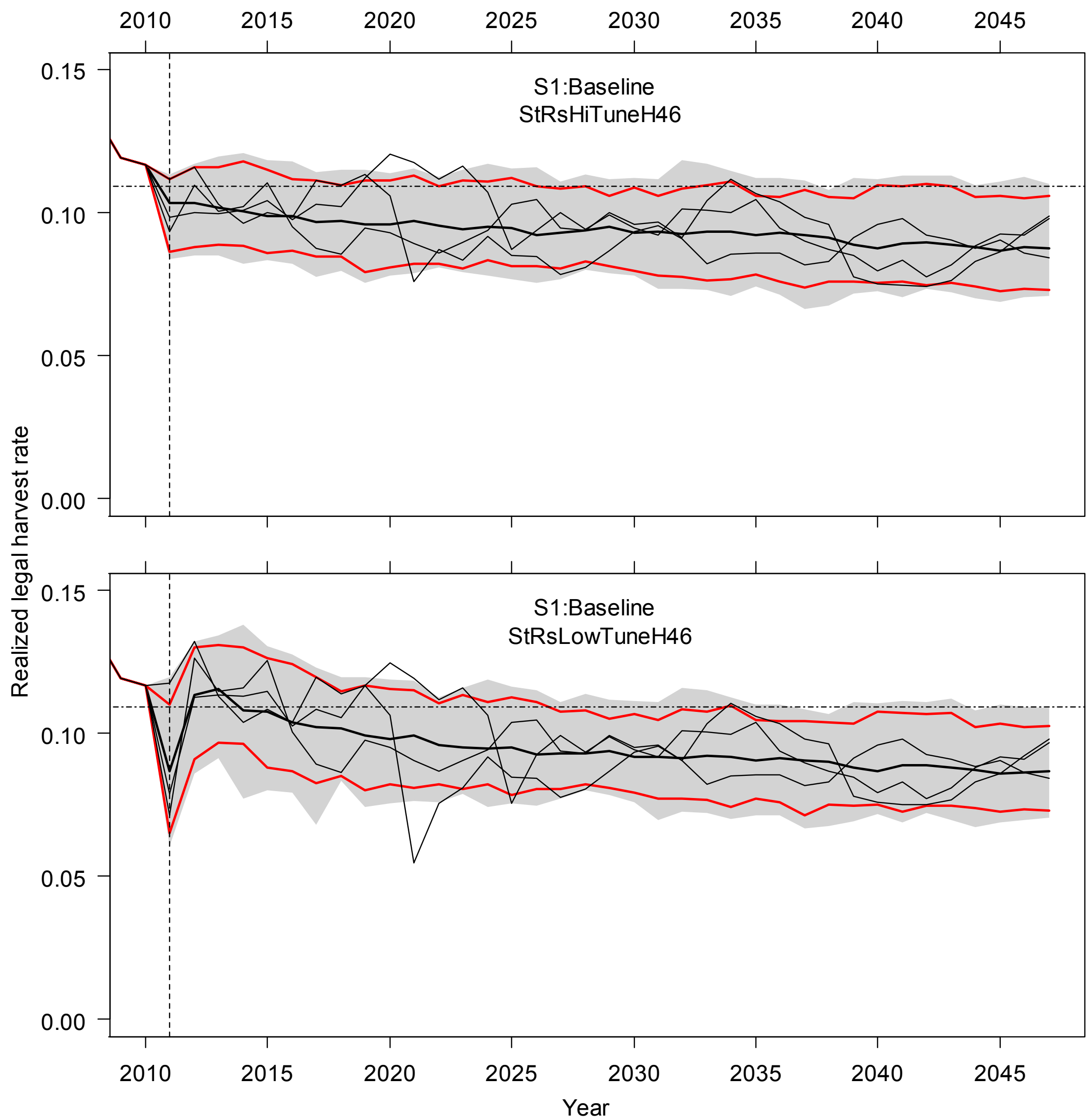

Figure 10. Simulation envelopes (S1:Baseline) of harvest rates realized by the sablefish operating model compared to the true operating model legal harvest rate (horizontal dot-dashed line) for high (top) and low (bottom) stock assessment tunings. Note the difference between harvest rate reductions in Year 32 for one of the traces. See Figure 4 for envelope quantile specifications.

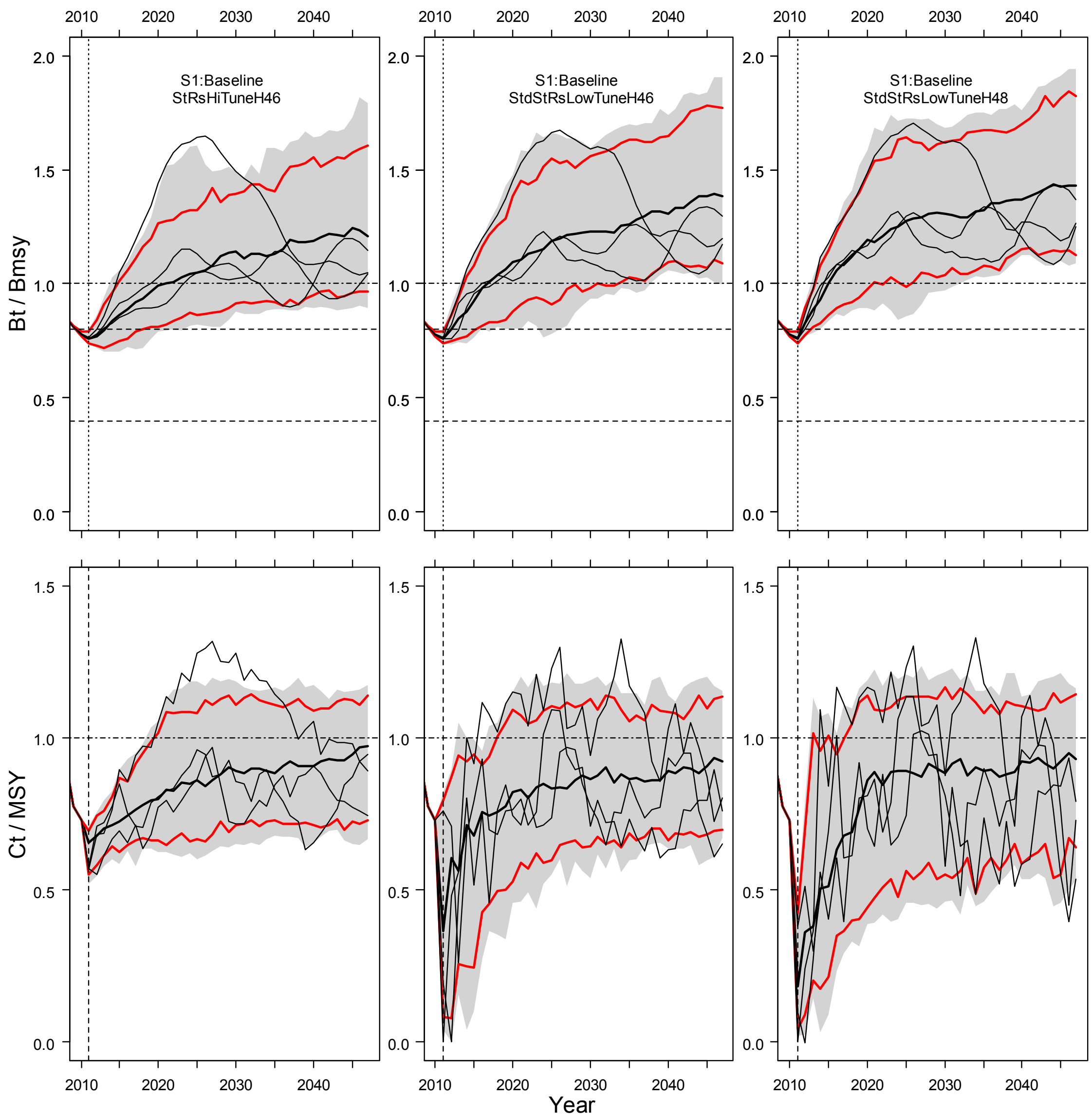

Figure 11. Simulation envelopes (S1:Baseline) of true operating model biomass relative to B^{MSY} *and catch relative to true* MSY *for StRsHiTuneH46 and two variants of StdStRsLowTune in which the upper bound on the harvest control rule is set to 0.6 (left column) and the DFO default value of 0.8 (right column). See Figure 4 for envelope quantile specifications.*

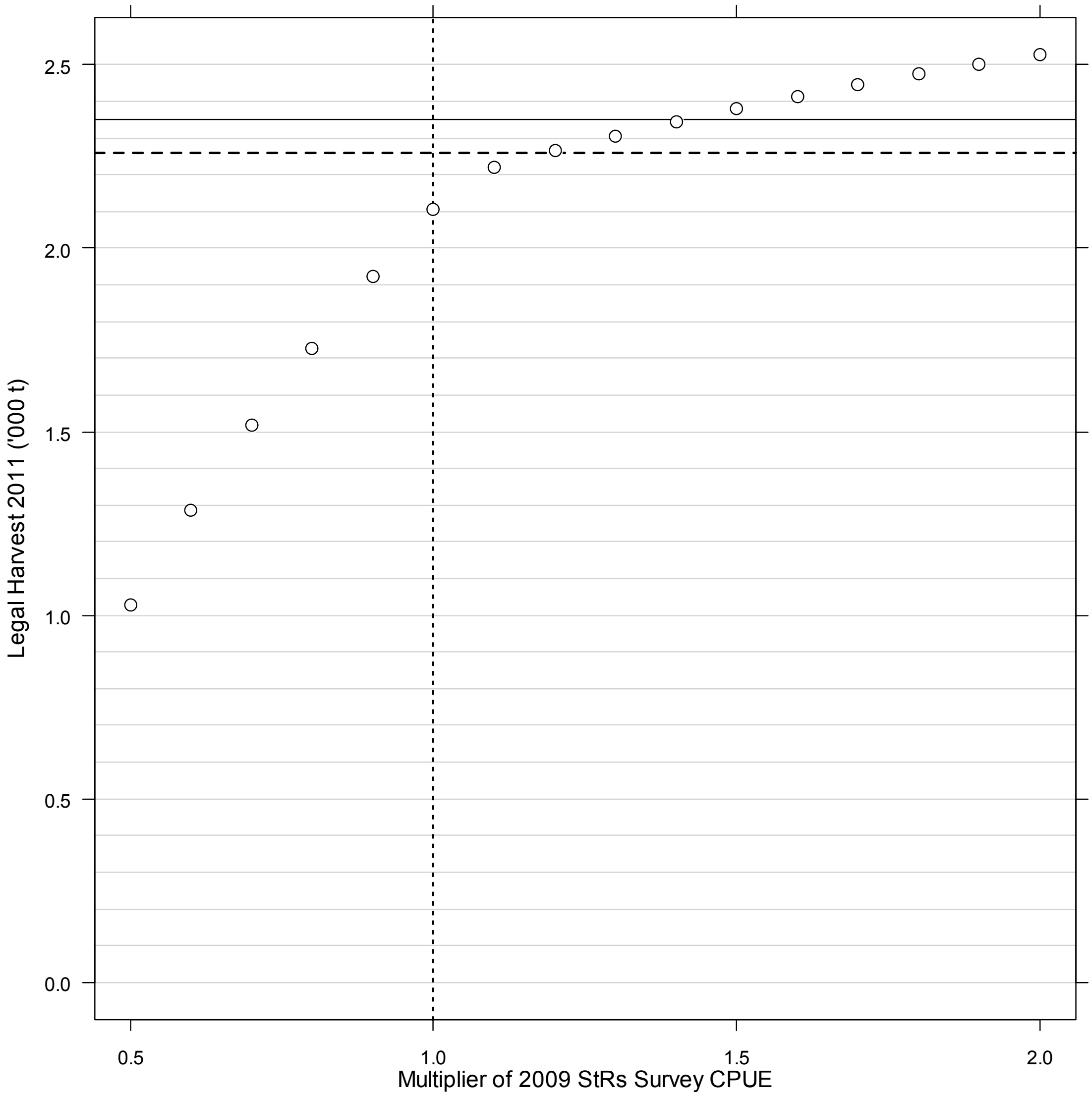

Figure 12. Legal harvest levels that would be recommended by the StRsHiTuneH46 management procedure for different levels of 2010 StRs catch rates. The vertical line indicates a survey outcome identical to 2009. The solid horizontal line shows the current 2010 TAC level and the dashed line show the current recommendation in the absence of the survey.

APPENDIX A REQUEST FOR SCIENCE INFORMATION AND/OR ADVICE

PART 1: DESCRIPTION OF THE REQUEST (to be filled by the Branch requesting Information/Advice)

Date (Initial submission to Science): January 15, 2010

Directorate, Branch or group initiating the request and category of request	
Directorate/Branch	Category of Request
☒ Fisheries and Aquaculture Management	
☐ Oceans and Habitat Management	☐ Stock Assessment
☐ Policy	☐ Species at Risk
☒ Science	☐ Habitat
☐ Other (please specify): Industry Supported	☐ Aquaculture
	☐ Ocean Action Plan
	☒ Other (please specify): Fishing activity risk assessment.

Initiating Branch Contact:	
Name: Adam Keizer, GMU/Tamee Mawani, GMU	Telephone Number: (604)-666-0912
Email: Adam.Keizer@dfo-mpo.gc.ca	Fax Number: (604)-666-8525

Issue Requiring Science Advice (i.e., "the question"):
(Issue posed as a question for Science response)

A directed longline trap and longline hook commercial fishery exists for sablefish (*Anoplopoma fimbria*) off Canada's Pacific coast. However, sablefish are also intercepted by non-directed groundfish fisheries including other longline hook and trawl fisheries. Sablefish enter the commercial fisheries at a few years of age, but are released by regulation when measuring less than 55 cm fork length. There is a need to evaluate the potential impacts of post-release mortality on the achievement of fishery objectives when developing an action plan for the 2011/12 season.

Rationale for Advice Request:
(What is the issue, what will it address, importance, scope and breadth of interest, etc.)

In 2008, a Management Strategy Evaluation (MSE) approach was developed for sablefish assessment and management in British Columbia and was reviewed through a Canadian Science Advisory process. MSE outputs can be used to (*i*) inform decisions about a long-term harvest strategy, (*ii*) evaluate the likely trade-offs among conservation, yield and inter-annual variability in yield, and (*iii*) provide a consistent procedure for determining annual harvest advice. Fisheries and Aquaculture Management has requested advice from Science to inform planning for the 2011/12 fishing year that incorporates the consequences of release mortality on the sablefish stock. The advice should update the MSE approach to reflect new fishery policy objectives that were not considered in the previous analysis. This evaluation should consider the effects of a full retention option for sablefish, i.e., removal of the current size limit. It is expected that advice will be compliant with both the "DFO Sustainable Fisheries Framework" (SFF) policy and "A fishery decision making framework incorporating the Precautionary Approach" (PA) policy.

Intended Uses and Potential Impacts of Advice within DFO:
(Who will be the end user of the advice, e.g., DFO, another government agency or Industry? What impact could the advice have on other sectors?)

This advice will be used by the Groundfish Management Unit (DFO) in determining potential management changes for the directed Sablefish fishery, as well as other commercial groundfish fisheries that incidentally intercept Sablefish. As a result, the groundfish fishery may be impacted by the advice, particularly the K and T licensed fleet. Advice is expected to include (*i*) advice for sablefish that uses MSY-based fishery reference points and a harvest control rule in compliance with the SFF, (*ii*) consideration of all sources of removals including releases, (*iii*) evaluation of whether mortality attributable to at-sea releases across all fishery sectors compromises the achievement of fishery objectives, (*iv*) evaluation of the impacts of future management measures such as full retention or avoidance, and (*v*) recommendations on the requirement to continue two fishery-independent trap gear surveys for the purposes of providing harvest advice.

Date Advice Required:

Latest possible date to receive Science advice: January 2011.

Rationale: 2011/12 fishing year begins February 21, 2011.

Funding:

Source of funding: DFO Biologist/Analyst, DFO Biologist funded via A-base.
Sablefish industry analyst funding provided by Wild Canadian Sablefish, Ltd.

Rationale: N/A.

Initiating Branch Approval:

Approved by initiating Director: Date:

Name of initiating Director:

Send form via e-mail attachment following instructions below:

Regional request: Depending on the region, the coordinator of the Regional Centre for Science Advice or the Regional Director of Science will be the first contact person. Please contact the coordinator in your region to confirm the approach.

National request: At *HQ, the Director of the Canadian Science Advisory Secretariat* Jean Francois La Rue (Jean-Francois.LaRue@dfo-mpo.gc.ca) *AND the Director General of the Ecosystem Science Directorate* Sylvain Paradis (Sylvain.Paradis@dfo-mpo.gc.ca) will be the first contact persons.

APPENDIX B DATA

MANAGEMENT HISTORY

The history of sablefish fishery management from 1981 to 2010 is summarized in Table B-1. The table lists total allowable catches (TACs), landings and quota allocations to the directed sablefish sector (K license), the non-directed trawl sector (T license), First Nations, and research by sablefish fishing year. A number of substantive management measures have been applied to the sablefish fishery over time including:

1. Application of weight-based size limits introduced in 1945, that when converted to fork length effectively created a 63 cm fork length limit, a 54 cm fork length in 1965 and by 1977 the current regulated size limit of 55 cm fork length (see detailed discussion in McFarlane and Beamish 1983, p. 20);
2. The establishment of the Canadian 200 mile Economic Exclusion Zone that resulted in departure of foreign fleets fishing sablefish in Canadian waters by 1981;
3. The establishment of total allowable catch management in 1977;
4. The introduction of license limitation in 1981 which created 49 license holders under the "K" designation fishing either longline trap or longline hook gear (McFarlane and Beamish 1983);
5. The trawl allocation of a fixed 8.75% of the total allowable catch in 1981 which was based on historic average trawl landings;
6. The introduction of Individual Vessel Quota (IVQ) management to the sablefish license sector in 1990;
7. Several changes to the definition of a fishing year, including adjustments to start and end dates and to the length of the fishing "year". These changes often resulted in sablefish fishing years which did not coincide with either the calendar year or the fishing year definitions for other groundfish sectors;
8. Various changes to "carry-over" rules that allow a percentage of uncaught IVQ ("an underage") to be taken in the following fishing year, or an overrun of IVQ ("an overage") to be applied against the following year's IVQ;
9. The introduction of electronic at-sea catch monitoring to the groundfish fleets, including the sablefish sector, beginning in 2006;
10. Changes in quota transferability due to the Integrated Groundfish Pilot Project (2006+) that allowed non-K license sectors to access a portion of K quota on a temporary basis.

McFarlane and Beamish (1983) indicated that total allowable catch management was introduced with the advent of the Canadian 200 mile limit under Extended Jurisdiction in 1977. A 5,000 t quota set in 1977 was reduced to 3,500 t for 1978 to 1984 and quotas were set between 4,000 t and 4670 t until 1990 (Table B-1). Subsequently quotas were set following stock assessments that attempted to provide low and high risk options or decision tables based on fixed catch options. Although Table B-1 lists both directed sablefish "K" and trawl "T" quotas, note that beginning with the 1999/2000 sablefish fishing year the two quota values cannot be added to obtain the overall yearly quota by the sablefish fishing year because of the difference in fishing year definitions between the two sectors. For example, the 282 t trawl allocation for 2007/08 begins on April 1, 2008 which is 8 months after the start of the 2007/08 sablefish fishing year on August 1, 2007. This fishing year difference resulted when the 1999 sablefish fishing year was extended to a duration of 19 months to establish an August 1, 1999 to July 31, 2000 "fishing year". The August 1 to July 31 sablefish fishing year was maintained until 2008 when the sablefish 2008/09 fishing year was shortened to 204 days to achieve alignment with other groundfish sectors starting February 21, 2009. Note also that the 2009/2010 sablefish fishing year was effectively "extended" by one month although the fishing year termination date was not changed. This exception allowed K license holders to fish until the end of March 2010 but attribute their landings to the IVQ allocated in the previous 2009/2010 fishing year rather than the current 2010/2011 fishing year.

Details of sablefish and trawl fishing years from 2001/2002 to 2010/2011 fishing year quotas and allocations are provided in Table B-2 to illustrate the lag between sablefish and trawl allocations and the results of carry-over provisions. The "carry-over" provision is a management tactic intended to allow individual quota holders the opportunity to delay catching current fishing year IVQ until the following year, and to accommodate over-runs of IVQ in the current fishing year. For sablefish, the overage/underage rules (i.e. "carry-over") have changed in two ways since their inception. First, the allowable percentages of overage and underage have been varied over time (e.g., various management plans such as DFO 2002, 2007, 2010). For example, the practice was introduced in 1994 when a 5% carry-over was permitted. The percentage allowable was increased to 10% in 1995. Second, the percentage overage was applied to the quota *remaining* to the vessel in the current fishing year when the overage was introduced, but in 1999 the percentage was applied to the vessel's *total individual* quota. Beginning with the 2006/2007 sablefish fishing year, sablefish vessels were permitted to carry-over up to 15% of uncaught IVQ. A one-time 100% carry-over was permitted for the sablefish sector into the 2009/2010 common groundfish fishing year. Trawl vessels fishing their T-quota sablefish are permitted a carryover/underage of 30% of the vessel's IVQ holdings (DFO 2010, Section 13.6.1).

Sablefish are caught incidentally in the directed halibut (*Hippoglossus stenolepis*), directed "ZN" rockfish (*Sebastes* sp.), and the lingcod (*Ophiodon elongatus*) and dogfish (*Squalus acanthius*) longline hook fisheries prosecuted under a Schedule II license. Prior to the development of the commercial Groundfish Integration Pilot Proposal in 2006, sablefish could not be landed by these sectors when fishing under their respective licenses. With the implementation of the commercial groundfish integration program, license holders that do not hold K or T quota are responsible for leasing quota to account for their interceptions of legal-sized sablefish which can then be landed and sold. By regulation, sub-legal sablefish must be released at-sea by all sectors.

The various groundfish sectors joined the electronic monitoring (EM) program at different dates starting with the halibut sector on March 2, 2006, lingcod and spiny dogfish sectors April 1, 2006, the sablefish sector on August 1, 2006, and the rockfish inside and outside sectors on March 31, 2007. At-sea observer logbooks provide estimates of groundfish catch for the trawl sector beginning in 1996. In contrast, logbooks completed by fishermen are accepted as the basis for estimating at-sea catch beginning in 2006 for non-trawl sectors because of the introduction of the at-sea electronic video monitoring (EM). The EM program provides fishery-independent auditing of fishery logbook accuracy by mandatory review of 10% of the video coverage from each trip (DFO 2010, Section12). Although the video audit does not provide a complete census of the catch there are increasingly punitive costs to individual fishermen whose logbooks fail to meet agreed-upon tolerances of reporting accuracy. Mandatory fishery-independent dockside validation of retained catch applies to all groundfish sectors.

At-sea releases of sablefish were reported in logbooks on a voluntary basis for all groundfish fishery sectors before 1996 when at-sea observers were required for trawl vessels (Option A only). Other groundfish sectors relied on fishery-dependent logbooks until 2006. The accuracy of sablefish releases reported in fishery-dependent logbooks is unknown but is likely to underestimate actual releases (Fargo 2005, Appendix B). The pre-1996 (all sectors) and pre-2006 (non-trawl sectors) logbook data were not used to estimate the absolute amount of released sablefish as their accuracy cannot be independently verified. Reported releases reflect a combination of the diligence of individuals in completing logbooks, anticipatory responses to management measures (e.g., establishment of fishing history prior to the introduction and allocation of IVQ), as well as the amount of sablefish actually released at sea. We use at-sea observer (trawl sector 1996-2010) and EM audited (non-trawl sectors 2006-2010) logbook data in this analysis.

In the case of the trawl sector, the amount of legal and sub-legal sablefish catch is estimated by at-sea observers and the legal sablefish catch is verified by dockside validation. The determination of retained and released catch by non-trawl sectors is achieved via fishery logbooks (with EM monitoring) and dockside validation of landed catch. The management plan (DFO 2010) specifies optional use of a measurement grid to determine if sablefish are of legal size for non-trawl sectors. Grids are designed to allow fishery-independent video verification of fish size prior to release however the extent to which they are used during commercial fishing is not reported. However, sablefish released on a directed sablefish trip (presumably under a K license) are assumed to be sub-legal and do not have to be measured. A new initiative for the trawl sector implemented for the 2010/2011 fishing season to increase responsibility for releases of fish that are below marketable size does not affect sablefish. This is because sablefish less than 55 cm fork length are deemed sub-legal by regulation, rather than unmarketable (see clause 17.1 of Appendix 8, Section 17 of DFO 2010).

COMMERCIAL CATCH CATEGORIES

Beginning in 2006 sablefish commercial catch can be divided into at least six categories: (*i*) legal retained, (*ii*) sub-legal retained, (*iii*) legal released, (*iv*) sub-legal released, (*v*) legal liced and (*vi*) sub-legal liced. The latter two “liced” categories result from sablefish subject to amphipod (colloquially called “lice”) predation while caught in fixed longline trap or longline hook gear. The liced catch categories are considered releases as these fish are not landed. Sablefish caught by trawl gear are not exposed to amphipod predation so the legal and sub-legal liced categories do not apply to that sector. This catch categorization was made possible by logbook and catch monitoring requirements introduced in 2006 as a result of commercial groundfish integration. However, fishery-independent 100% at-sea observer coverage applied to the trawl sector (Option A) predated groundfish integration by 10 years. Thus, estimates of retained and released sablefish are available for the trawl sector from 1996 to 2010. Groundfish sectors fishing with longline hook, longline trap and hand-line gears relied on voluntary logbooks to record at-sea retained and released catches prior to 2006. Observer coverage was sporadic for these sectors. In general, releases are thought to be under-estimated prior to 2006 for non-trawl sectors. Prior to 1996 at-sea releases reported in the GFCatch database are considered to be badly under-estimated for all sectors and do not represent reliable estimates of released catch (Fargo 2005).

RETAINED CATCH

Retained catch is summarized by calendar year rather than fishing year because of the various changes in the definition and duration of fishing years over the history of sablefish management (Table B-1). Data were obtained from the GFCatch, PacHarvSable, and FOS databases maintained by Fisheries and Oceans Canada, Pacific Region. Catches from seamount fishing were excluded where they could be identified since seamount harvest is not included within the coastal quota management area. From 1913 to 1965 only retained catch data (landings) are available. After 1920 and prior to 1965 when the Canadian domestic fishery increased effort on sablefish, retained catches averaged less than 1,000 t (Figure B-1, Table B-3, McFarlane and Beamish 1983). Total annual landings as high as 5,956 t were reported during World War I. However, landings were modest from 1920 to 1964, ranging between 209 t (1956) and 1,895 t (1949). Landings did increase during World War II, but not to the amounts reported during World War I. Exploitation increased significantly in the late 1960s with the arrival of foreign longline fleets from Japan, the US, the USSR and the Republic of Korea (McFarlane and Beamish 1983, Figure B-1, Figure B-2). The largest annual landings of sablefish occurred during this period with a peak 7,408 t reported landed in 1975. Some foreign fishing was allowed between 1977 and 1980 despite the establishment of the Economic Exclusion Zone in 1977 to utilize yield surplus to Canadian domestic fleet needs. Total landings have ranged from 2,287 t (2003) to 7,408 t (1975) since 1969 and averaged about 4,741 t over the 1969 to 1999 period. Landings have declined from 4,620 t in 2005 to 2,500 t in 2009 in response to TAC reductions over the same period (Table B-1, Figure B-1).

RELEASED CATCH

Sablefish encountered in commercial catches with fork lengths less than the 55 cm size limit must be released at sea by regulation regardless of gear type (DFO 2010). Furthermore, sablefish are encountered by all commercial gear types that include trawl, longline hook and longline trap gears. Mortality associated with releases of sub-legal sablefish is not deducted from the quota holdings for any sector. However, mortality attributable to releases of legal sablefish is deducted from IVQ holdings using mortality rates that depend on gear type (DFO 2009). For trawl gear, the IVQ deduction is calculated at a rate of 10% of legal-size releases for the first two hours of the tow and an additional 10% for each hour or portion of an hour thereafter. For example, a 2.25hr tow results in a mortality rate of 20% of the legal releases applied against the vessel's IVQ. Deductions of 9% and 15% of legal size releases are applied to IVQ for longline trap and longline hook gear, respectively.

Fishery-independent estimates of released catch have been available since 1996 for the trawl sector via 100% at-sea observer coverage and beginning in 2006 for other groundfish sectors when electronic video monitoring was introduced to audit fishery logbooks (Koolman et al. 2007, DFO 2009). Released catch prior to 1996 was voluntarily reported, primarily by the trawl sector, and included reports of very large releases in the few years following the occurrence of the 1977 year class (McFarlane and Beamish 1983, Figure B-1). Releases of sablefish reported by the trawl sector increased in 1996 when the at-sea observer program was implemented (Figure B-1). However, the level of sablefish releases reported by other groundfish sectors did not change until 2006 when auditing of at-sea electronic monitoring was broadly introduced.

TRAWL RELEASES

Estimates of released catch weight from the trawl sector (1996-2010) were taken directly from at-sea observer logbooks. Trawl releases can be further sub-divided into legal and sub-legal categories. Estimates of sablefish releases from trawl gear over the 1996 to 2010 period ranged from ~70 t (2008) to ~532 t (2002) and exceeded retained catch from 1996 to 2004 (Figure B-3). After 2004, retained catch exceeded releases, although incomplete data for 2010 indicate similar amounts of retained and released sablefish catch. Since the trawl sector is allocated 8.75% of the sablefish TAC, the general decline in retained catch and releases from

2006 can be attributed in part to reductions in TAC. In addition, trawl industry sources cite gear modifications and improved communication among fishing masters as a possible contributing factor to reduced interception and subsequent release of sub-legal sablefish over the past several years. The majority of releases are categorized as sub-legal sablefish and no liced sablefish are reported from trawl gear (Figure B-4). Trawl releases in 2010 have increased by about twofold in comparison to 2009 following a 7 year period of declining releases.

NON-TRAWL RELEASES

Estimates of released catch in this analysis were obtained from fishery logbook data archived in the FOS database maintained by Fisheries and Oceans Canada, Pacific Region and the GFFOS system maintained by the Groundfish Section, Pacific Biological Station. Fishery-independent release data are not available for non-trawl commercial groundfish sectors until 2006 (Figure B-5). Although the various non-trawl sectors joined the at-sea electronic monitoring program at different dates between March 2, 2006 and March 31, 2007, their reported release data are taken as reliable estimates for calendar years 2006 to 2010 for this analysis. The halibut and sablefish sectors joined March 2, 2006 and August 1, 2006, respectively, and account for most of the non-trawl releases of sablefish. Non-trawl releases are generally reported in logbooks by count rather than by estimated weight. Regardless of gear type, release counts were converted to weights using an average round weight of 1.5 kg for sub-legal sablefish and 3.0 kg for legal sablefish. These values were calculated from individual round fish weights obtained during sablefish trap surveys from 1990 to 2009. Note that the average legal weight differs from the value of 3.63 kg (8 lb) appearing in the management plan (DFO 2009); the management plan value is used for calculating mortality of legal-sized sablefish to be applied against IVQ for the non-trawl sectors (DFO 2009). The management plan weight was set at 3.63 kg (8 lbs) as a deterrent against releases of legal sablefish (pers. comm., Commercial Industry Caucus June 30, 2010).

The largest amounts of at-sea releases are reported from the sablefish longline trap fishery, halibut longline hook fishery, sablefish longline hook fishery and trawl fishery (Figure B-5, Table B-5). Note that longline hook fishing also includes combination fishing under both halibut and sablefish licenses. Longline hook fisheries by the outside rockfish, lingcod, dogfish, and inside rockfish hook fishery sectors represent minor contributions to total at-sea releases. Relatively large releases of sablefish were reported in the halibut sector during 2006. In this year of the Commercial Groundfish Integration Program, halibut license holders were accountable for enumerating sablefish catch but not responsible for accessing sablefish quota to cover these catches.

PRORATION OF RETAINED AND RELEASED CATCH FOR 2010

Simulation model fits require estimates of retained and released catches by gear type for 2010 (Table B-5, Table B-6). The following assumptions were applied to estimate the incomplete 2010 catch:

1. Assume 2010 retained catch will be approximately 2009 retained catch less 150 t, or about 2,350 t, which leaves approximately 275 t of retained catch to be caught after November 19, 2010;

2. Allocate the 275 t of retained catch to the commercial gear types by the average of the retained catch proportions observed from 2008 to 2010. This calculation yields

estimated retained catches of 115.6, 131.8, and 27.6 t for trap, longline hook and trawl gears, respectively;

3. Assume sablefish are released at the rate observed in 2010, i.e., the ratios of observed released catch to retained catch by gear type for 2010;

4. Apply the ratios in step (3) to the estimated retained catch by gear in step (2) to estimate releases by gear type. This calculation yields releases of 12.7, 18.1, and 22.8 t for trap, longline and trawl gears, respectively;

5. Add the estimated retained and released catches to the catches observed to date to estimate commercial fishery catches by gear;

6. Assume the 2010 standardized (7 t) and stratified random (12 t) trap surveys incur the same retained catches as in 2009.

ABUNDANCE INDICES

Stock abundance indices input to the operating model and assessment models are listed in Table B-8. These relative indices are based on trap catch per unit effort (CPUE) with units of kg/trap. The series include (*i*) annual nominal trap fishery CPUE (1979-2010), (*ii*) standardized trap CPUE (1990-2009), and (*iii*) stratified random trap survey CPUE (2003-2009).

Set by set trap fishery logbook data are not available until 1990. Prior to 1990 one fishing record may represent multiple sets. We elected to use a longer nominal sablefish trap fishery CPUE from 1979 to 2009 calculated as the sum of annual trap retained catches divided by the sum of trap effort subject to the following filtering:

1. Gear is restricted to longline trap;
2. Records with missing or out of range dates were excluded;
3. Sets reported to be at seamounts or in inlets are excluded, i.e., "offshore" records only were included;
4. Research or experimental sets are excluded;
5. Records with null catch values in the logbook data were excluded from the calculations rather than assigning zeros to those records, although there is little difference in the CPUE estimates if nulls are treated as zeros;
6. Only records with valid reported effort are included as null entries cannot be distinguished from zeros;
7. Beginning in 2006, retained weights per set recorded in logbooks were adjusted to correct for skippers entering product weight rather than round weight as required by the logbook program, which occurred frequently after the change in logbooks in 2006 under the Commercial Groundfish Integration Program. The adjustment was calculated as the ratio of the dockside monitoring program landed weight (converted to round weight) to the total logbook weight for each trip.

Nominal trap CPUE fluctuated around ~15 kg/trap until the late 1980s when historic highs from ~20 to ~25 kg/trap were recorded (Figure B-6). Catch rates subsequently declined until 2001. Trap fishery CPUE increased significantly in 2003. The 2003 observation can be attributed to the effects of (*i*) recruitment of the 2000 year class to the trap fishery, and (*ii*) the lack of trap activity from March to September of 2003 which meant that catch was taken during winter months when trap fishery CPUE is generally higher than average. The restricted trap activity in 2003 was due to low quota availability following an in-season TAC reduction in the FY 2001/2002 (Table B-1). Nominal catch rates declined from near 20 kg per trap in 2003 to ~10 kg/trap by 2009.

A "standardized" trap survey (Wyeth et al. 2006, 2007) was started in 1990 using consistent squid bait loading and has continued annually since implementation; similar survey work conducted in 1988 and 1989 used different baits (Figure B-7). The standardized survey is a fixed locality survey usually conducted by a chartered sablefish trap fishing vessel. Nine offshore survey localities have been consistently occupied in each year of the survey except in 1990 when only southern localities were surveyed. The localities were purposively selected because the areas were commercial fishing grounds and were spatially dispersed about 60 nm apart such that the coast-wide survey could be conducted in about 30 days given favourable weather. Survey localities typically include high-relief bathymetric features such as gullies or canyons, which reflects the original intention to index sablefish abundance in "core" fishing areas that represented prime habitat. Trap escape rings are sewn closed during survey fishing.

Over the course of the survey between 5 and 7 depth intervals have been fished within each locality, although only the five core depth intervals identified as D1-D5 have been fished consistently over the history of the survey and only D1-D5 have been occupied since 2008. These core depth intervals lie between 274 and 1189 m (or 150 to 650 fm). The depth intervals are designated D1 (274-457 m), D2 (457-641 m), D3 (641-824 m), D4 (824-1006 m), and D5 (1006-1189 m). Usually only one set is conducted within each depth interval at each survey locality. Thus, there is no replication of sets within each combination of depth and locality except for selected localities in 1990, 1991, and 1993 and three selected localities in 2002 (Wyeth et al. 2007). Also, the exact spatial position of each set is at the discretion of the fishing master rather than being selected at random. The lack of replicate sets within each combination of locality and depth zone means that only very simple linear model standardization is possible with no interaction terms. Haist et al. (2005) concluded that linear models with area and depth factors achieved little adjustment to year coefficients when compared to a model with only a year effect. The survey catch rate values reported in Table B-8 are the arithmetic mean of the catch per trap (kg/trap) for depth intervals D1-D5. Survey sets were included if their intended depth interval was D1-D5. In each of 2000-2002, three sets intended for depth interval D6 were actually deployed into depth interval D5. In 2003 one set intended for depth interval D0 was deployed into depth interval D1. These sets were not included for this analysis, although their inclusion has only a small effect.

The observed annual distributions of catch rates (kg/trap) are shown using boxplots in Figure B-7 (upper panel). Confidence intervals (95%) calculated using empirical likelihood methods (Owen 2001) are shown to represent the relative precision of survey index values (Figure B-7, lower panel). The coast-wide trends of survey catch rates show a decline from relatively high mean values in the early 1990s and fluctuated around 10 kg/trap beginning in the mid to late-1990s. The 2001 survey produced the lowest mean and median catch rates observed in the time series, with marked reduction of the variance. Catch rates improved from 2001 to 2002 to a level similar to catch rates observed in the mid-1990s. The catch rates in 2003 and 2004 were substantially higher than those observed during the previous nine years and comparable to those observed in 1992 and 1993. Catch rates consistently declined from 2003 to 2009.

A second annual fishery-independent trap survey that follows a depth and area stratified random sampling (StRs) design was initiated in 2003. The StRs survey was started for the purpose of distributing tags coast-wide at random locations over five area strata and three depth strata of the offshore habitat range of sablefish (i.e., 183 to 1372 m; Wyeth et al. 2006). The survey design allocates 90 sets equally distributed among the 15 strata. Catch is enumerated and weighed by species on each set. A sample of sablefish is retained from each set for (*i*) measurements of length, weight, sex and maturity, and (*ii*) extraction of otoliths. Finally, sablefish are tagged and released on each set. Fishing practices were standardized at the outset of the survey in hopes of yielding a second fishery-independent abundance index with statistical properties superior to the existing standardized survey. Like the standardized survey gear, trap escape rings are sewn shut however the StRS survey is baited with a combination of Pacific hake (*Merluccius productus*) and squid similar to that typically used by the commercial trap fishery. Survey data were inspected to determine if the beginning of set bottom depth, end of set bottom depth, or modal bottom depth was located in the target depth stratum; failure to achieve one of the three depth observations in the target stratum resulted in the set being reassigned to the achieved depth stratum, or eliminated from the survey if no valid stratum was achieved. Changes were made to six sets over the 2003-2009 period.

Stratified random sampling mean index values and 95% confidence intervals (Table B-9) were calculated by year using the classical survey stratified random sampling estimator (e.g., Cochran 1979) and the number of possible sampling units per stratum provided by Wyeth et al. (2007). The bootstrap means and 95% confidences intervals based on 1000 bootstrap replicates are also reported. The R Language library "survey" (Lumley 2010) was used for the computations. The StRS survey means and 95% confidence intervals shown in Figure B-8 and indicates a declining trend over the 2003-2009 time series punctuated by high observation in 2006 (see Hanselman et al. 2009 for a similar feature in the Gulf of Alaska longline survey).

Considerations for interpretation of these indices include:

1. Standardized survey: A key issue here is that the standardized survey places unknown sampling weights on the various areas formed by combinations of locality and depth interval. For example, over-representing certain habitats may cause index values to be overly sensitive to changes the shallow depths of the survey area as new fish recruit into the survey zone.
2. Standardized survey vs. stratified survey: The design differences, as well as increased sample size for the stratified random survey (75 to 90 sets per year), mean that the two surveys may react differently in response to changes in actual stock abundance. Potential differences between these surveys may not become apparent until major changes (increases or decreases) in abundance occur in the sablefish stock. The two surveys use different baits and follow very different designs.
3. Standardized survey vs. nominal fishery CPUE: The commercial fishery nominal CPUE and standardized survey show similar patterns and variability, consistent with the placement of standardized survey sets in core fishing areas.

PROPORTIONS AT AGE

Age proportions from the commercial trap fishery, standardized trap survey and stratified random trap survey are shown as Figure B-9 to Figure B-11, respectively. Specimens were assigned equal weight and pooled by sex for each of the three data sources. The first age class was set to 3 and a plus group was created for fish aged 35 and older. For all data sources, the following conditions were imposed:

1. Age readings were restricted to those obtained using the burnt-otolith section method (MacLellan 1997), e.g., surface readings were excluded;
2. Only samples collected using trap gear were included;

3. Samples were included if the sample type code was “total catch” or “random”, i.e., ages were excluded if the sample type code was “selected” or “stratified”;
4. Samples were excluded if the sample could be identified as collected at a seamount or inshore waters (e.g., mainland inlets).

Commercial trap fishery samples obtained from the voluntary sampling program were included if the trip type was “observed commercial” or “non-observed commercial”. In comparison to Cox et al. (2009) we excluded some commercial ageing data from 1980, 1981, 1982, and 1983 that were not coded as “random” or “total catch” samples, i.e., possibly samples selected for specific attributes or stratified samples. Ageing data for 1979, 1980 and1984 were removed from the analysis after visual inspection of the age proportions suggested that the samples were not random, (e.g., virtual lack of fish in the first 10 age classes, blocks of age classes missing where they should have been abundant, uniform distribution of proportions) or had small sample sizes. Standardized survey ages were included if the fish were derived from depth strata D1 through D5 (Wyeth et al. 2006). All ages obtained from the stratified random survey were included.

INDICES NOT USED

Although not used for assessment of the offshore component of sablefish in B.C., a directed sablefish longline trap survey has been conducted at mainland inlets since 1995. This survey deploys 5 sets in each of four inlets (Wyeth et al. 2007). Figure B-12 summarizes the distribution of annual catch rates for the combined inlet survey data. Mean catch rates recently peaked in 2004 then declined until 2008 before increasing in 2009 due to improved catches of sub-legal sablefish in the two northern inlets. The mainland inlets have been closed to directed sablefish fishing since 1995 although sablefish may now be intercepted and retained by non-directed fishing under the Groundfish Integration Pilot Program (DFO 2009a). This survey has not been used to date in assessments of B.C. sablefish.

A suite of synoptic multi-species bottom trawl surveys was initiated in 2003 as a collaborative effort between DFO and the Canadian Groundfish Research and Conservation Society (see for example, Olsen et al. 2008, Olsen et al. 2009a,b,c). These surveys provide high density coverage using depth-stratified random sampling designs for Queen Charlotte Sound (QCS, Major Areas 5AB, 233 tows in 2009, 37-543 m), Hecate Strait (HS, Major Areas 5CD, 156 tows in 2009, 11-230 m), West Coast Queen Charlotte Islands (WCQCI, Major Area 5E, 129 tows in 2010, 180-1800 m – renamed West Coast Haida Gwaii Synoptic Survey in 2010) and the West Coast of Vancouver Island (WCVI, Major Area 3CD, 137 tows in 2010, 46-750 m). Each survey is now conducted at a two year interval with the QCS and Hecate Strait surveys conducted one year and the WCVI and WCQCI surveys conducted the next year. However, the QCS survey benefited from three successive survey years from 2003 to 2005 before adopting a biennial schedule. Swept-area (relative) biomass estimates can be developed from these surveys for many species including sablefish. Although we do not yet include these indices in formal analyses due to the brevity of the time series and the additional parameters required to estimate survey selectivity, they are presented here in anticipation of future use in sablefish assessments as data accumulate.

Table B-10 lists the results of 1,000 bootstrap replications of synoptic survey catch rates expanded for area swept (courtesy Norm Olsen, Groundfish Section, Pacific Biological Station). The biomass estimates are bias-corrected and lower and upper confidence intervals are bounded by the 5th and 95th percentiles of the bootstrap distributions. The “Catch Weight” column of Table B-10 is the sum of the total sablefish catch (kg), with the total number of survey sets and the number of sets containing positive catches of sablefish shown. Roughly half the survey sets encounter sablefish across survey areas and years. The bootstrap relative biomass estimates and 95% confidence intervals are plotted in Figure B-13. The 2009 Hecate Strait survey shows the influence of several sets where significant amounts of young sablefish (approx. 38-40 cm fork length) were encountered.

Shrimp surveys are conducted off the West Coast Vancouver Island (1979-2010) and in Queen Charlotte Sound (1999-2010). These surveys were described in the context of sablefish by Kronlund et al. (2003), Haist et al. (2004) and in general by Sinclair et al. (2001). These authors noted differences in survey gear, set distribution and survey timing, and gaps in the identification and enumeration of finfish over the history of the surveys. No attempt to adjust for these factors was made for the results presented here. In general, when sablefish are encountered by the shrimp gear, the total catch may be a few fish per set. Fishing generally occurred at depths of 100 to 175 m in Pacific Fisheries Management Area (PFMA) 124 and 125 (West Coast Vancouver Island) and 125 to 225 m in PFMA 107 to 111 (Queen Charlotte Sound). Biomass estimates based on swept-area expansions shown in Figure B-14 are based on 1,000 bootstrap replicates. Estimates are bias-corrected and lower and upper confidence intervals are bounded by the 5^{th} and 95^{th} percentiles of the bootstrap distributions. Sablefish catch rates increased markedly in 2001 and 2002, and subsequently declined beginning in 2003. Coincident increases in catch rates were observed for the Queen Charlotte Sound shrimp survey. These observations coincided with higher than average sablefish catch rates observed from the continental U.S. shelf and slope surveys and bycatch rates in the U.S. Pacific hake (*Merluccius productus*) fishery (Schirripa 2002). Results obtained from US waters were attributed to the 1999 and 2000 year-classes, whereas results in B.C. were consistent with a 2000 year class. Due to the restricted shallow depth range of these surveys, newly recruited sablefish are exposed to survey gear for a period of 1-2 years before migration to deeper waters. Accordingly the shrimp surveys may signal the occurrence of above average year classes rather than serve as an index of stock abundance. However, the long-term West Coast Vancouver Island survey does not contain much evidence of the strong 1977 year class, or subsequent above average year classes observed by U.S. surveys during the 1980s and early 1990s.

Table B-1. Sablefish management history by sablefish fishing year. The 1999/2000 sablefish fishing year was 19 months in duration to accommodate a shift in the start date from Jan 1 to Aug 1. The 2008/2009 fishing year was shortened to 204 days to accommodate a change in the start date of the fishing year from Aug 1 to Feb 21. Beginning in 1999/2000 sablefish landings cannot be compared directly to the TAC due to the offset between K and T fishing years. Data for 2010/2011 are complete to October 31, 2010.

Year	Fishery	Assessment Yield Rec.	TAC	K Quota	T Quota	First Nations	Research	Landings FY	Date Open	Date Closed	Days Open	FY Days
1981	Derby		3500	3190	310			3830	01-Feb-81	04-Oct-81	245	245
1982	Derby		3500	3190	310			4028	01-Feb-82	22-Aug-82	202	202
1983	Derby		3500	3190	310			4346	01-May-83	26-Sep-83	148	148
1984	Derby		3500	3190	310			3827	01-Mar-84	22-Aug-84	174	174
1985	Derby		4000	3650	350			4193	01-Feb-85	08-Mar-85	35	92
									29-Mar-85	02-May-85	34	
									19-Jul-85	11-Aug-85	23	
1986	Derby		4000	3650	350			4449	17-Mar-86	21-Apr-86	35	63
									12-May-86	09-Jun-86	28	
1987	Derby		4100	3740	360			4630	16-Mar-87	10-Apr-87	25	45
									01-Sep-87	21-Sep-87	20	
1988	Derby		4400	4015	385			5403	06-Mar-88	26-Mar-88	20	140
									05-Apr-88	25-Apr-88	20	
									05-May-88	25-May-88	20	
									05-Jun-88	25-Jun-88	20	
									05-Jul-88	25-Jul-88	20	
									02-Aug-88	22-Aug-88	20	
									04-Sep-88	24-Sep-88	20	
1989	Derby		4400	4015	385			5324	14-Feb-89	28-Feb-89	14	112
									14-Mar-89	28-Mar-89	14	
									14-Apr-89	28-Apr-89	14	
									10-May-89	24-May-89	14	
									10-Jun-89	24-Jun-89	14	
									06-Jul-89	20-Jul-89	14	
									04-Aug-89	18-Aug-89	14	
									15-Sep-89	29-Sep-89	14	
1990	IVQ		4670	4260	410			4905	21-Apr-90	31-Dec-90	255	255

Year	Fishery	Assessment Yield Rec.	TAC	K Quota	T Quota	First Nations	Research	Landings FY	Date Open	Date Closed	Days Open	FY Days
1991	IVQ	2,900-5,000	5000	4560	440			5112	01-Jan-91	31-Dec-91	365	365
1992	IVQ	2,900-5,000	5000	4560	440			5007	01-Jan-92	31-Dec-92	366	366
1993	IVQ	2,900-5,000	5000	4560	440			5110	01-Jan-93	31-Dec-93	365	365
1994	IVQ	2,900-5,000	5000	4521	433			5002	01-Jan-94	31-Dec-94	365	365
1995	IVQ	2,725-5,550	4140	3709	356		29.48	4179	01-Jan-95	31-Dec-95	365	365
1996	IVQ	690-2,580	3600	3169	304		81.65	3471	01-Jan-96	31-Dec-96	366	366
1997	IVQ	6,227-16,285	4500	4023	386		45.36	4142	01-Jan-97	31-Dec-97	365	365
1998	IVQ	3,286-4,761	4500	4023	386		45.36	4592	01-Jan-98	31-Dec-98	365	365
1999/ 2000*	IVQ	2,977-5,052	4500	6395	386		45.36	7012	**01-Jan-99**	**31-Jul-00**	578	578
2000/ 2001	IVQ	3,375-5,625	4000	3555	350		45.36	3884	01-Aug-00	31-Jul-01	365	365
2001/ 2002	IVQ	4,000	2800	2657	342	45	45.36	3075	01-Aug-01	31-Jul-02	365	365
2002/ 2003	IVQ	4,000, revised to 2100-2800	2450	1883	206	45	45	2206	01-Aug-02	31-Jul-03	365	365
2003/ 2004	IVQ	Decision table	3000	2647	254	45	54	2983	01-Aug-03	31-Jul-04	365	365
2004/ 2005	IVQ	Decision table	4500	3995	384	45	75	4249	01-Aug-04	31-Jul-05	365	365
2005/ 2006	IVQ	Decision table	4600	4056	389	45	110	4498	01-Aug-05	31-Jul-06	365	365
2006/ 2007	IVQ	No Assessment	3900	3417	328	45	110	4004	01-Aug-06	31-Jul-07	365	365
2007/ 2008	IVQ	No Assessment	3300	2938	282	45	35	3429	01-Aug-07	31-Jul-08	365	365
2008/ 2009	IVQ	MSE Analysis	1509	1454		45	31	1514	01-Aug-08	20-Feb-09	204	204
2009/ 2010	IVQ	No Assessment	2450	2160	207	45	38	2159	21-Feb-09	20-Feb-10	365	365
2010/ 2011	IVQ	*MSE Analysis*	2300	2023	194	45	38	*1599*	21-Feb-10	20-Feb-11	365	365

Table B-2. Total allowable catches and allocations (nearest metric ton fresh round weight) for the sablefish 2001/02 fishing year to the 2010/11 fishing year. Dockside monitoring program (DMP) landings do not include seamount catch or experimental catches. An in-season quota reduction of the 4,000 t quota by 910 t in the 2001/02 fishing year is shown as a carry-forward into 2002/03. This change was designed to spread the reduction over two fishing years (light gray shading). Note that until July 31, 2008 the directed "K" sablefish fishing year was defined as Aug 1 to Jul 31 while the trawl "T" fishing year was defined as Apr 1 to Mar 31. The trawl "T" allocation was applied Apr 1 of each year until 2009. The 2008/09 directed "K" fishing year was shortened to 204 days to end on Feb 20, 2009 to coincide with a common groundfish fishery year for all sectors beginning Feb 21, 2009 (dark gray shading). Thus, the sum of "K" and "T" allocations will not equal the commercial allocation until the common 2009/10 fishing year. Total "K" allocation, carryover, and IVQ available provided courtesy of the Groundfish Management Unit, DFO and annual groundfish management plans (http://www-ops2.pac.dfo-mpo.gc.ca/xnet/content/mplans/mplans.htm?).

					Fishing	Year				
Sablefish Sector	01-Aug-01 31-Jul-02	01-Aug-02 31-Jul-03	01-Aug-03 31-Jul-04	01-Aug-04 31-Jul-05	01-Aug-05 31-Jul-06	01-Aug-06 31-Jul-07	01-Aug-07 31-Jul-08	01-Aug-08 20-Feb-09	21-Feb-09 20-Feb-10	21-Feb-10 20-Feb-11
TAC Coastwide	**2800**	**2450**	**3000**	**4500**	**4600**	**3900**	**3300**	**1509**	**2450**	**2300**
Scientific allocation	25	45	54	65	110	110	35	31	38	38
K scientific allocation	-	-	-	10	-	-	-	-	-	-
First Nations allocation	45	45	45	45	45	45	45	24	45	45
K allocation (91.25%)	*3567*	*973*	*2647*	*3995*	*4056*	*3417*	*2938*	*1454*	*2160*	*2023*
K carry forward	153-(910)	79+910	35	87	228	316	221		42	193
Total K IVQ available	2806	1940	2669	4080	4284	3733	2938	1454	2202	2216
K DMP landings	2790	1959	2671	3781	4016	3324	2802	1260	1738	1351

Trawl Sector	01-Apr-02 31-Mar-03	01-Apr-03 31-Mar-04	01-Apr-04 31-Mar-05	01-Apr-05 31-Mar-06	01-Apr-06 31-Mar-07	01-Apr-07 31-Mar-08	01-Apr-08 20-Feb-09		21-Feb-09 20-Feb-10	21-Feb-10 20-Feb-11
T allocation (8.75%)	*342*	*206*	*254*	*384*	*389*	*328*	*282*	-	*207*	*194*
T carry forward	*not available*	*not available*	*not available*	*not available*	100	62	85		50	40
Total T IVQ available					489	390	367		257	234
T DMP landings	301	253	355	315	366	308	316		221	163

Table B-3. Annual sablefish landings (t) in Canadian waters by source from 1913-1964.

Year	Canadian	Foreign	Longline	Other	Trap	Trawl	Total
1913	1988.0						1988.0
1914	3209.0						3209.0
1915	2441.0						2441.0
1916	4312.0						4312.0
1917	5956.0						5956.0
1918	2039.0						2039.0
1919	716.0						716.0
1920	1754.0						1754.0
1921	1383.0						1383.0
1922	1293.0						1293.0
1923	1135.0						1135.0
1924	1238.0						1238.0
1925	1017.0						1017.0
1926	705.0						705.0
1927	1118.0						1118.0
1928	911.0						911.0
1929	1042.0						1042.0
1930	1124.0						1124.0
1931	397.0						397.0
1932	436.0						436.0
1933	413.0						413.0
1934	435.0						435.0
1935	659.0						659.0
1936	490.0						490.0
1937	912.0						912.0
1938	576.0						576.0
1939	617.0						617.0
1940	948.0						948.0
1941	1188.0						1188.0
1942	835.0						835.0
1943	1426.0						1426.0
1944	1519.0						1519.0
1945	1428.0						1428.0
1946	1619.0						1619.0
1947	905.0						905.0
1948	1483.0						1483.0
1949	1895.0						1895.0
1950	648.0						648.0
1951			772.8	0.5		23.1	796.4
1952			453.2	0.6		34.0	487.8
1953			335.6	1.1		8.0	344.7
1954			432.3		0.3	26.4	459.0
1955			359.0			15.2	374.2
1956			172.8			36.5	209.3
1957			465.6		0.3	51.0	516.9
1958			167.1		0.6	117.6	285.3
1959			298.3			88.2	386.5
1960			423.3			65.5	488.8
1961			321.3			97.9	419.2
1962			277.7	1.1		113.7	392.5
1963			222.3	0.2		64.8	287.3
1964		83.0	274.5	0.1		125.2	482.8

Table B-4. Annual sablefish landings (t) in Canadian waters by source from 1965-2010. Data in italics for 2010 are complete to November 19, 2010.

Year	Trap	Longline Hook	Trawl	Other	Japan Longline	ROK Longline	USA Trawl	USSR Trawl	Research Trap	Total
1965	0	193	262	0	0	0	92	0	0	547
1966	0	326	312	0	174	0	95	0	0	907
1967	0	253	139	0	1189	0	65	0	0	1646
1968	0	292	167	15	2390	0	65	0	0	2929
1969	0	162	148	1	4720	0	43	0	0	5074
1970	0	142	166	0	5142	0	104	0	0	5554
1971	0	123	189	0	3050	0	161	0	0	3523
1972	0	400	688	0	4236	0	582	0	0	5906
1973	746	120	83	0	2950	0	82	6	0	3986
1974	327	41	122	2	3866	129	227	65	0	4779
1975	469	152	280	1	4702	1263	541	0	0	7408
1976	303	89	382	0	3494	2335	473	0	0	7077
1977	215	77	787	7	2961	186	571	0	0	4803
1978	635	57	131	8	2103	0	948	0	0	3881
1979	1480	277	276	6	1112	0	1236	0	0	4387
1980	3211	249	335	3	199	0	317	0	0	4314
1981	3275	326	229	0	0	0	0	0	0	3830
1982	3438	344	246	0	0	0	0	0	0	4028
1983	3611	451	274	11	0	0	0	0	0	4347
1984	3275	365	187	0	0	0	0	0	0	3827
1985	3501	458	233	0	0	0	0	0	0	4193
1986	3277	619	552	1	0	0	0	0	0	4449
1987	2954	1269	407	1	0	0	0	0	0	4630
1988	3488	1274	637	3	0	0	0	0	0	5403
1989	3772	929	623	0	0	0	0	0	0	5324
1990	3072	1372	461	0	0	0	0	0	0	4905
1991	3494	1179	439	0	0	0	0	0	0	5112
1992	3710	849	449	0	0	0	0	0	0	5007
1993	4142	424	543	0	0	0	0	0	0	5110
1994	4051	468	483	0	0	0	0	0	0	5002
1995	3282	474	427	5	0	0	0	0	0	4189
1996	2984	279	191	0	0	0	0	0	15	3469
1997	3554	431	156	0	0	0	0	0	2	4142
1998	3772	444	376	0	0	0	0	0	0	4592
1999	3677	628	403	0	0	0	0	0	6	4714
2000	2745	752	326	0	0	0	0	0	13	3836
2001	2743	564	300	0	0	0	0	0	8	3614
2002	2162	564	267	0	0	0	0	0	17	3010
2003	1419	641	228	0	0	0	0	0	68	2355
2004	2129	467	345	0	0	0	0	0	48	2989
2005	3197	1147	277	0	0	0	0	0	42	4662
2006	2679	1307	442	0	0	0	0	0	61	4489
2007	2132	1042	289	0	0	0	0	0	17	3481
2008	1432	1246	353	0	0	0	0	0	19	3051
2009	1164	1107	229	0	0	0	0	0	16	2516
2010	*671*	*1214*	*193*	*0*	*0*	*0*	*0*	*0*	*0*	*2078*

Table B-5. Annual sablefish retained catch (t) aggregated by gear as input to simulation analyses. Data in italics for 2010 are prorated to December 31, 2010.

Year	Time Step	Trap	Longline Hook	Trawl	Standardized Trap Survey	StRS Trap Survey	Total
1965	1	0	193.2	353.9	0	0	547.1
1966	2	0	499.7	406.9	0	0	906.6
1967	3	0	1441.9	203.6	0	0	1645.5
1968	4	0	2682.3	232.0	0	0	2914.3
1969	5	0	4882.3	191.3	0	0	5073.6
1970	6	0	5284.1	269.9	0	0	5554.0
1971	7	0	3173.0	350.3	0	0	3523.3
1972	8	0	4635.7	1270.3	0	0	5906.0
1973	9	745.8	3069.8	170.8	0	0	3986.4
1974	10	327.1	4036.3	413.8	0	0	4777.2
1975	11	469.4	6117.2	820.8	0	0	7407.4
1976	12	303.4	5918.4	855.0	0	0	7076.8
1977	13	214.6	3224.1	1357.5	0	0	4796.2
1978	14	634.6	2160.2	1078.5	0	0	3873.3
1979	15	1480.1	1388.8	1512.1	0	0	4381.0
1980	16	3210.8	447.6	652.3	0	0	4310.7
1981	17	3275.3	326.1	228.8	0	0	3830.2
1982	18	3437.8	343.6	245.9	0	0	4027.4
1983	19	3610.5	451.4	274.1	0	0	4336.0
1984	20	3275.4	365.1	187.0	0	0	3827.4
1985	21	3501.3	458.3	233.1	0	0	4192.7
1986	22	3277.1	619.2	551.8	0	0	4448.1
1987	23	2954.3	1268.6	406.9	0	0	4629.8
1988	24	3488.5	1273.6	637.3	0	0	5399.4
1989	25	3772.0	928.6	623.4	0	0	5324.0
1990	26	3072.4	1371.8	460.7	10.1	0	4915.0
1991	27	3494.4	1179.2	438.8	6.0	0	5118.4
1992	28	3710.2	848.6	448.7	9.5	0	5016.9
1993	29	4142.4	424.2	543.1	8.2	0	5117.9
1994	30	4050.7	467.7	483.1	7.0	0	5008.5
1995	31	3282.2	474.3	427.4	4.8	0	4188.7
1996	32	2984.3	278.5	190.9	4.9	0	3458.8
1997	33	3553.6	430.5	156.3	4.1	0	4144.5
1998	34	3772.0	443.6	376.1	5.6	0	4597.3
1999	35	3677.3	627.9	403.0	4.7	0	4713.0
2000	36	2745.3	751.9	326.1	7.3	0	3830.5
2001	37	2742.8	564.4	299.6	3.4	0	3610.3
2002	38	2161.9	564.4	267.1	16.1	0	3009.5
2003	39	1419.2	640.5	227.6	19.8	22.4	2329.5
2004	40	2128.5	467.4	344.7	16.2	8.6	2965.4
2005	41	3196.5	1146.5	277.1	13.6	8.2	4641.9
2006	42	2678.9	1307.3	441.8	12	22.7	4462.7
2007	43	2132.2	1042.3	288.9	9.1	10.4	3482.8
2008	44	1432.4	1246.2	352.9	9.6	12.3	3053.4
2009	45	1163.7	1107.1	228.8	6.3	11.9	2517.9
2010	*46*	*786.2*	*1346.1*	*220.1*	*7*	*12*	*2353.1*

Table B-6. Releases by gear 1974 to 2010. Data in italics for 2010 are complete to November 19, 2010. Releases are not reported prior to 1974. Data reported by at-sea trawl observers from 1996 to 2006 are shaded light gray. Data reported 2006-2010 under the at-sea electronic monitoring program are shaded dark gray. Only shaded releases are used for simulations. The year designation 2010 indicates estimated 2010 releases used for the simulations.*

Year	Time Step	Trap	Longline	Trawl	Total
1974	10	0.0	0.0	6.8	6.8
1975	11	0.0	0.0	61.2	61.2
1976	12	0.0	0.0	0.0	0.0
1977	13	0.0	0.0	14.8	14.8
1978	14	0.0	0.0	358.4	358.4
1979	15	32.0	1.7	2054.0	2087.7
1980	16	110.0	1.2	1391.3	1502.5
1981	17	32.3	0.0	315.6	347.9
1982	18	133.6	0.0	79.9	213.5
1983	19	5.3	0.0	12.8	18.1
1984	20	40.3	0.0	42.7	83.0
1985	21	0.0	0.1	1.9	2.0
1986	22	19.0	0.0	5.4	24.4
1987	23	13.2	0.0	5.6	18.8
1988	24	0.5	0.0	1.6	2.1
1989	25	1.3	0.0	6.2	7.5
1990	26	149.7	14.0	139.1	302.8
1991	27	75.2	7.5	68.0	150.7
1992	28	37.3	3.1	28.1	68.5
1993	29	43.0	0.4	10.5	53.9
1994	30	53.9	6.4	17.3	77.6
1995	31	85.3	7.2	11.9	104.4
1996	32	121.2	1.2	353.4	475.8
1997	33	124.4	2.7	452.9	580.0
1998	34	100.1	0.5	387.5	488.1
1999	35	40.7	2.6	422.7	466.0
2000	36	65.5	3.0	468.1	536.6
2001	37	73.7	3.3	341.8	418.8
2002	38	115.7	23.4	531.5	670.6
2003	39	68.4	21.7	362.2	452.3
2004	40	82.1	42.6	278.2	402.9
2005	41	259.8	100.6	189.2	549.6
2006	42	139.8	366.7	125.7	632.2
2007	43	180.7	165.5	119.6	465.8
2008	44	147.8	144.4	69.9	362.1
2009	45	85.6	136.1	81.7	303.4
2010	*46*	*73.8*	*167.0*	*159.9*	*400.7*
*2010**	*46*	*86.5*	*185.1*	*182.7*	*454.4*

Table B-7. Estimated catch (t) by category and sector, 1996-2010. Data in italics for 2010 are complete to November 19, 2010.

Sector	Year	Retained	Released	Legal Released	Legal Liced	Sublegal Released	Sublegal Liced	Legal Released Against Quota
GROUNDFISH TRAWL	2006	441.8	125.7	12.8	0	112.9	0	6.3
HALIBUT	2006	181.6	254.7	166.3	5.4	80.8	2.1	24.9
HALIBUT AND SABLEFISH	2006	560	54	2.8	3.2	46.1	1.9	0.4
LINGCOD	2006	0	0.1	0.1	0	0	0	0
ROCKFISH OUTSIDE	2006	0.5	0.2	0.1	0	0.1	0	0
SABLEFISH.LONGLINE	2006	557.9	54.6	0.5	1.6	51.7	0.9	0.1
SABLEFISH.TRAP	2006	2678.9	139.8	7	12.8	119	1.1	0.6
SPINY DOGFISH	2006	7.3	3.1	0.4	0.1	2.5	0.1	0.1
GROUNDFISH TRAWL	2007	289.4	119.6	24.4	0	95.2	0	7.2
HALIBUT	2007	249	64.9	22.8	5.3	34.6	2.3	3.4
HALIBUT AND SABLEFISH	2007	321.2	27.5	1.1	3.2	22.6	0.7	0.2
LINGCOD	2007	0	0	0	0	0	0	0
ROCKFISH INSIDE	2007	0	0	0	0	0	0	0
ROCKFISH OUTSIDE	2007	11.2	1.1	0.3	0.1	0.7	0	0
SABLEFISH.LONGLINE	2007	452	68.9	3.4	2.7	61.2	1.6	0.5
SABLEFISH.TRAP	2007	2132.2	180.7	8.6	10.7	154.9	6.5	0.8
SPINY DOGFISH	2007	10.2	3	0.2	0.3	2.2	0.4	0
GROUNDFISH TRAWL	2008	353	69.9	9.4	0	60.6	0	1.8
HALIBUT	2008	213.2	47.1	14.2	3.8	27.2	1.9	2.1
HALIBUT AND SABLEFISH	2008	636.4	52.8	4.5	5.8	41.2	1.3	0.7
LINGCOD	2008	0	0	0	0	0	0	0
ROCKFISH INSIDE	2008	0	0.1	0	0	0.1	0	0
ROCKFISH OUTSIDE	2008	16.9	10.4	6.9	0.7	2.7	0.1	1
SABLEFISH.LONGLINE	2008	373.4	32.5	0.4	1.2	30.3	0.6	0.1
SABLEFISH.TRAP	2008	1432.4	147.8	1.8	5.8	136.7	3.6	0.2
SPINY DOGFISH	2008	7.3	1.3	0.1	0.4	0.7	0.1	0

Sector	Year	Retained	Released	Legal Released	Legal Liced	Sublegal Released	Sublegal Liced	Legal Released Against Quota
GROUNDFISH TRAWL	2009	229.2	81.7	7	0	74.7	0	2
HALIBUT	2009	157.3	34.7	10.3	2.4	20.7	1.3	1.5
HALIBUT AND SABLEFISH	2009	415.5	37.3	2	5.9	28.3	1.1	0.3
LINGCOD	2009	0	0	0	0	0	0	0
ROCKFISH INSIDE	2009	0	0.1	0	0	0.1	0	0
ROCKFISH OUTSIDE	2009	23.5	7.2	3.1	0.5	3.5	0.1	0.5
SABLEFISH.LONGLINE	2009	508.9	54.8	0.5	4	49.4	0.9	0.1
SABLEFISH.TRAP	2009	1163.7	85.6	1.1	3.1	80.5	0.9	0.1
SPINY DOGFISH	2009	3.1	2.1	0.3	0.1	1.6	0.1	0
GROUNDFISH TRAWL	2010	190.4	156.1	8.3	0	147.8	0	5.8
HALIBUT	2010	107.8	35.4	6.6	1.7	26.1	0.9	1
HALIBUT AND SABLEFISH	2010	557.3	57.9	1.1	4.4	51.2	1.2	0.2
LINGCOD	2010	0	0	0	0	0	0	0
ROCKFISH INSIDE	2010	0	0.2	0	0	0.2	0	0
ROCKFISH OUTSIDE	2010	22.8	8	3.4	0.4	4.1	0.1	0.5
SABLEFISH.LONGLINE	2010	486.6	53.2	0.1	1.7	50	1.3	0
SABLEFISH.TRAP	2010	661.4	73.6	0.9	1.5	68.9	2.2	0.1
SPINY DOGFISH	2010	7.2	6.4	0.7	0	5.3	0.4	0.1

Table B-8. Sablefish relative stock indices: nominal trap fishery CPUE, standardized survey CPUE, and stratified random survey CPUE.

Year	Nominal Trap Fishery CPUE (kg/trap)	Std. Trap Survey CPUE (kg/trap)	Stratified Random Survey CPUE (kg/trap)
1968			
1969			
1970			
1971			
1972			
1973			
1974			
1975			
1976			
1977			
1978			
1979	17.661		
1980	15.312		
1981	15.056		
1982	16.973		
1983	16.819		
1984	13.059		
1985	17.687		
1986	15.602		
1987	16.160		
1988	24.736		
1989	25.695		
1990	19.222	20.017	
1991	24.600	19.336	
1992	24.363	25.569	
1993	20.380	36.509	
1994	18.397	15.571	
1995	15.020	13.665	
1996	14.087	11.258	
1997	12.956	7.721	
1998	13.020	12.037	
1999	13.426	7.720	
2000	12.667	8.912	
2001	10.082	3.016	
2002	9.899	8.206	
2003	19.222	27.590	28.364
2004	14.009	26.415	24.941
2005	11.615	19.432	23.725
2006	10.034	17.382	28.924
2007	9.705	10.348	20.474
2008	10.042	10.662	26.238
2009	10.090	7.087	18.329
2010	-	-	-

Table B-9. Sablefish stratified random survey statistics calculated using classical survey sampling method (StRS) and bootstrap methods (Boot). The design effect measures the efficiency of the stratified survey to a simple random sampling survey. Confidence intervals (CI) are calculated at the α = 0.05 for the StRS estimates. Bootstrap confidence intervals use the 2.5th and 97.5th quantiles of the bootstrap distribution. Bootstrap statistics are based on 1000 bootstrap replications.

Year	StRS Mean	StRS Variance	StRS Std. Err.	Design Effect	CV	Lower 95% CI	Upper 95% CI	Degrees of Freedom	Boot Mean	Boot Std. Err.	Boot Lower 95% CI	Boot Upper 95% CI
2003	28.364	5.137	2.266	0.806	0.080	23.831	32.898	60	28.377	2.296	23.865	32.864
2004	24.941	2.590	1.609	0.670	0.065	21.721	28.162	59	25.013	1.651	21.705	28.177
2005	23.725	2.887	1.699	0.690	0.072	20.325	27.125	59	23.769	1.669	20.454	26.996
2006	28.924	2.784	1.668	0.688	0.058	25.596	32.252	70	28.835	1.628	25.732	32.116
2007	20.474	1.739	1.319	0.774	0.064	17.847	23.101	75	20.486	1.356	17.817	23.131
2008	26.238	3.697	1.923	1.267	0.073	22.408	30.069	75	26.295	1.955	22.407	30.070
2009	18.329	1.073	1.036	0.571	0.057	16.266	20.393	74	18.330	1.061	16.250	20.409

Table B-10. Sablefish relative biomass indices for synoptic trawl surveys 2003-2010.

Year	Survey	Biomass (t)	Lower 95% CI	Upper 95% CI	Catch Weight (kg)	Total Sets	Number of Non-Zero Sets
2005	Hecate Strait	1083	616.2	1934.8	1498.5	203	68
2007		559.6	312.2	960.5	288.2	134	46
2009		4156.5	1014.2	13097.7	3939.4	156	55
2003	Queen Charlotte Sound	1131.3	918.2	1562.2	1966.3	233	133
2004		1846.5	1166.3	3039	2158.2	230	107
2005		1085.2	828.8	1504.5	1589.0	224	126
2007		840.3	684.9	1153.3	1180.6	257	114
2009		945.8	755.3	1205.5	1228.6	233	140
2006	West Coast Haida Gwaii (800-1300 m excluded)	802	297.1	2365.9	2394.7	97	64
2007		555.1	379.6	730.5	1314.6	112	68
2008		533.7	421.5	664.7	1914.1	110	65
2010		657.5	405.6	1227.6	2175.0	123	76
2006	West Coast Haida Gwaii	1638.4	1055.6	3284.5	3386.2	110	75
2007		554.1	379.7	740.3	1314.6	112	68
2008		1367.8	1034.5	1852.9	2711.1	118	73
2010		1056.7	758.2	1752.7	2394.2	129	82
2004	West Coast Vancouver Island	4237	2390.9	7562.9	5801.9	90	58
2006		1936.5	1481	2554.2	4826.2	166	81
2008		453	359.6	627.7	1740.6	163	89
2010		1309.5	801.8	2250.7	3697.4	138	103

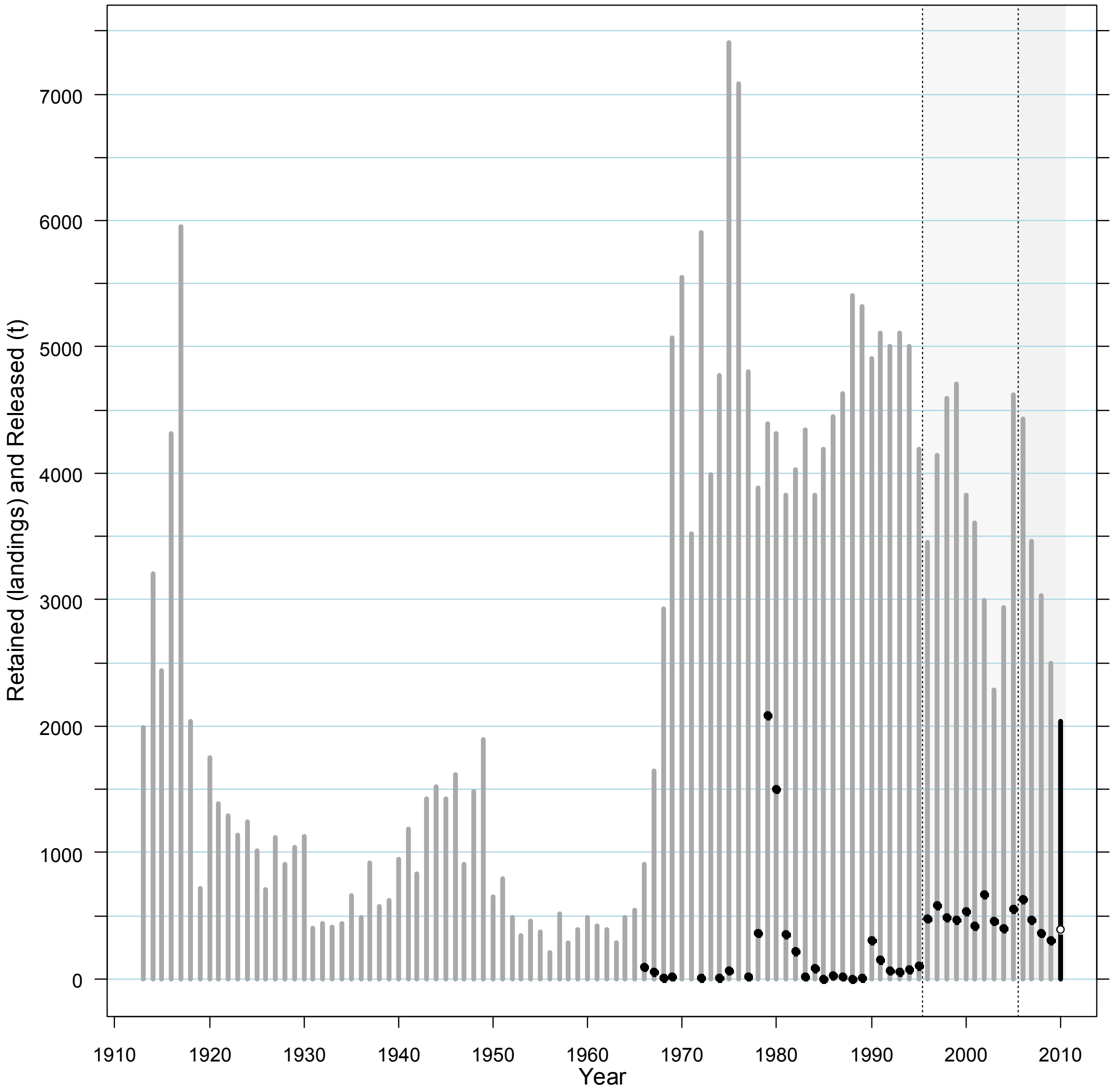

Figure B-1. Annual sablefish retained catch (t) from 1913 to 2010 from commercial sources (gray bars). Annual released catches are shown as reported. Vertical dotted lines demarcate the trawl at-sea observer period from 1996 to 2006 and the start of catch monitoring for all groundfish sectors in 2006. Catch data for 2010 are complete to October 31 for both retained catch (black bar) and released catch (open circle).

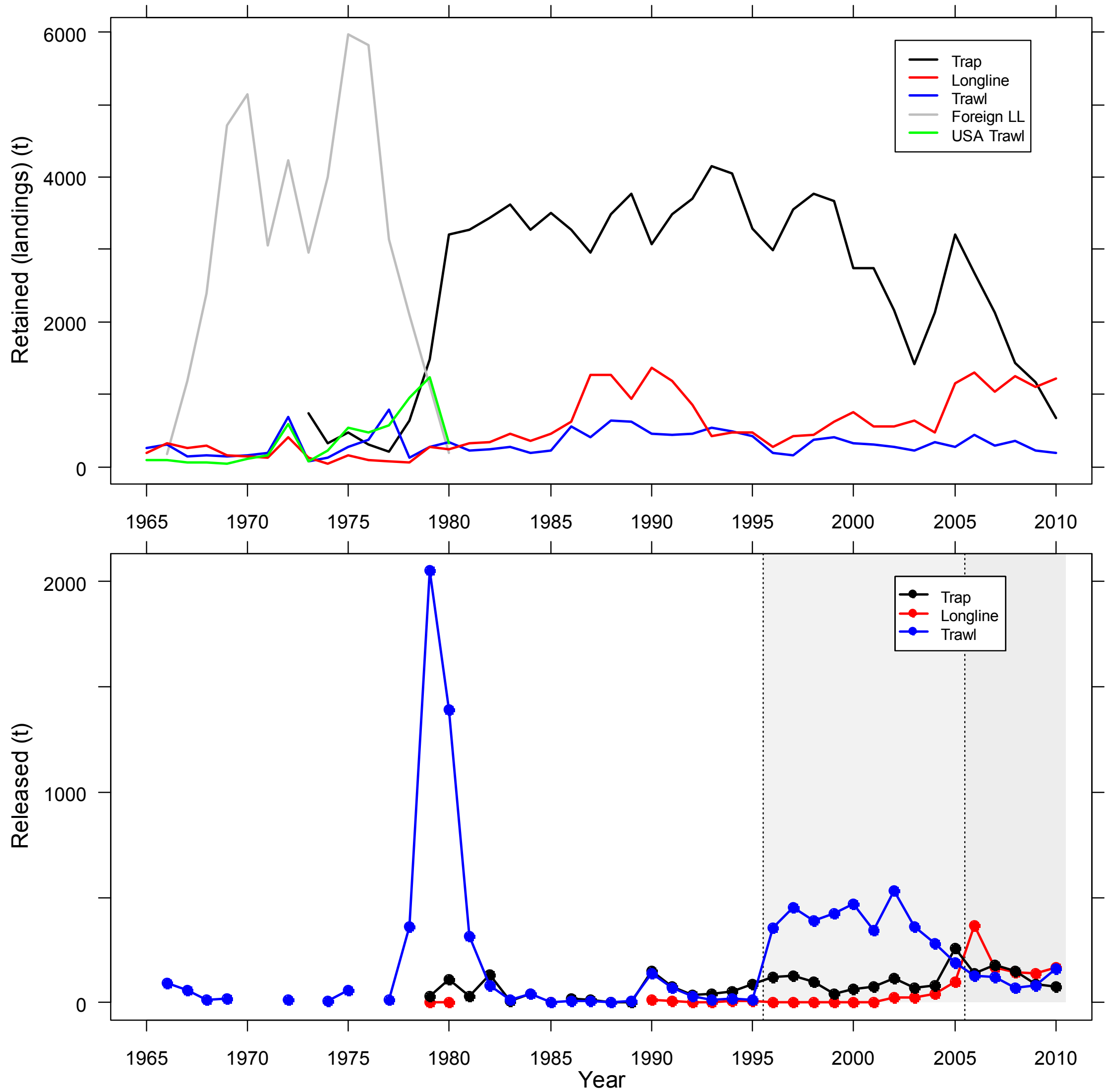

Figure B-2. Annual commercial retained catches from domestic Canadian and foreign fisheries from 1965 to 2010 (upper panel). Released catch is show for Canadian trap, longline hook and trawl fisheries (lower panel). Vertical dotted lines indicate the start of 100% at-sea observer coverage in 1996 for the trawl sector and start of 100% at-sea monitoring for all sectors in 2006.

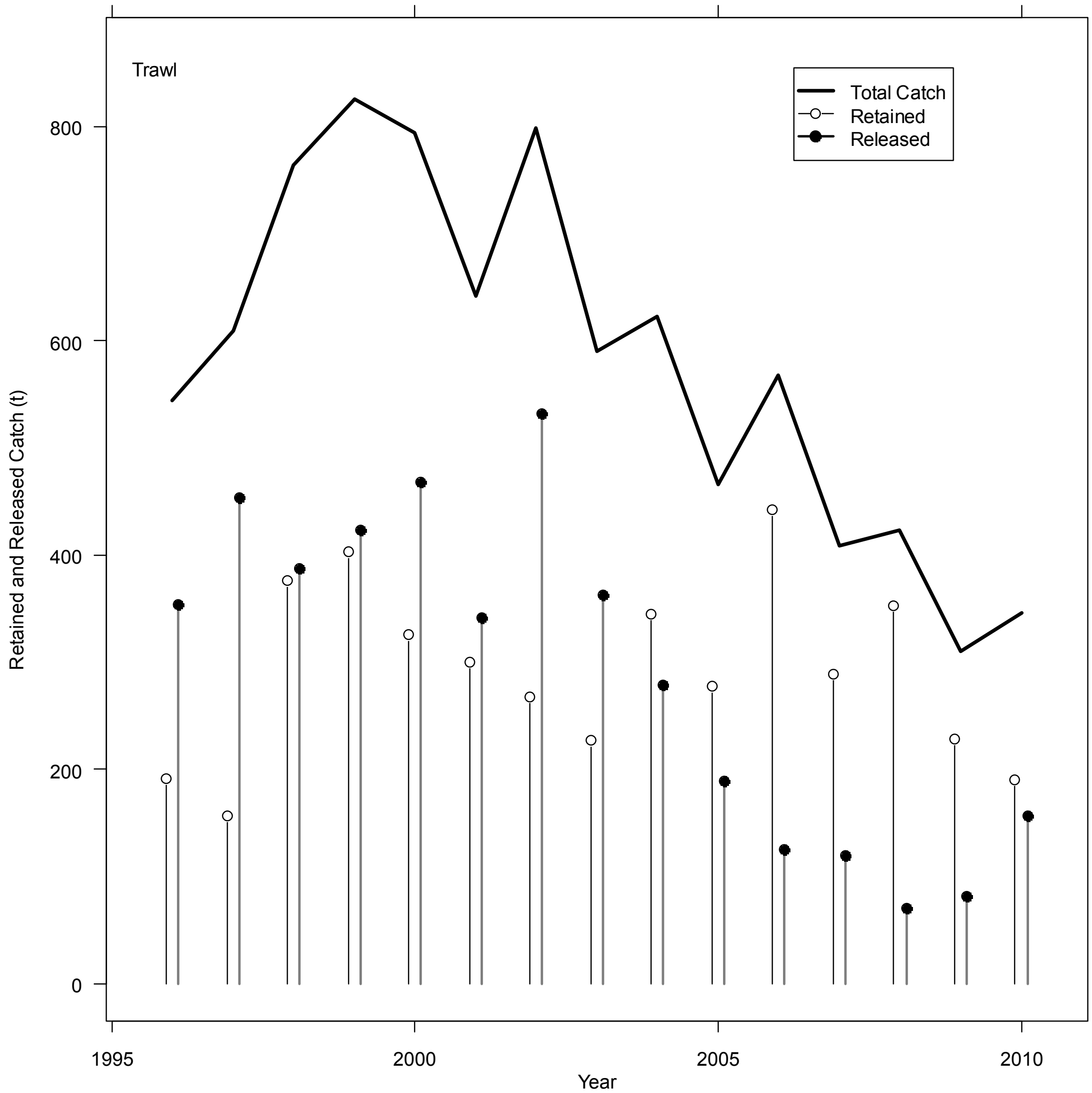

Figure B-3. Annual commercial trawl catches of sablefish showing the division of total catch (solid line) into retained (open circle) and released (filled circle) catches based on at-sea-observer estimates. Data for 2010 are incomplete.

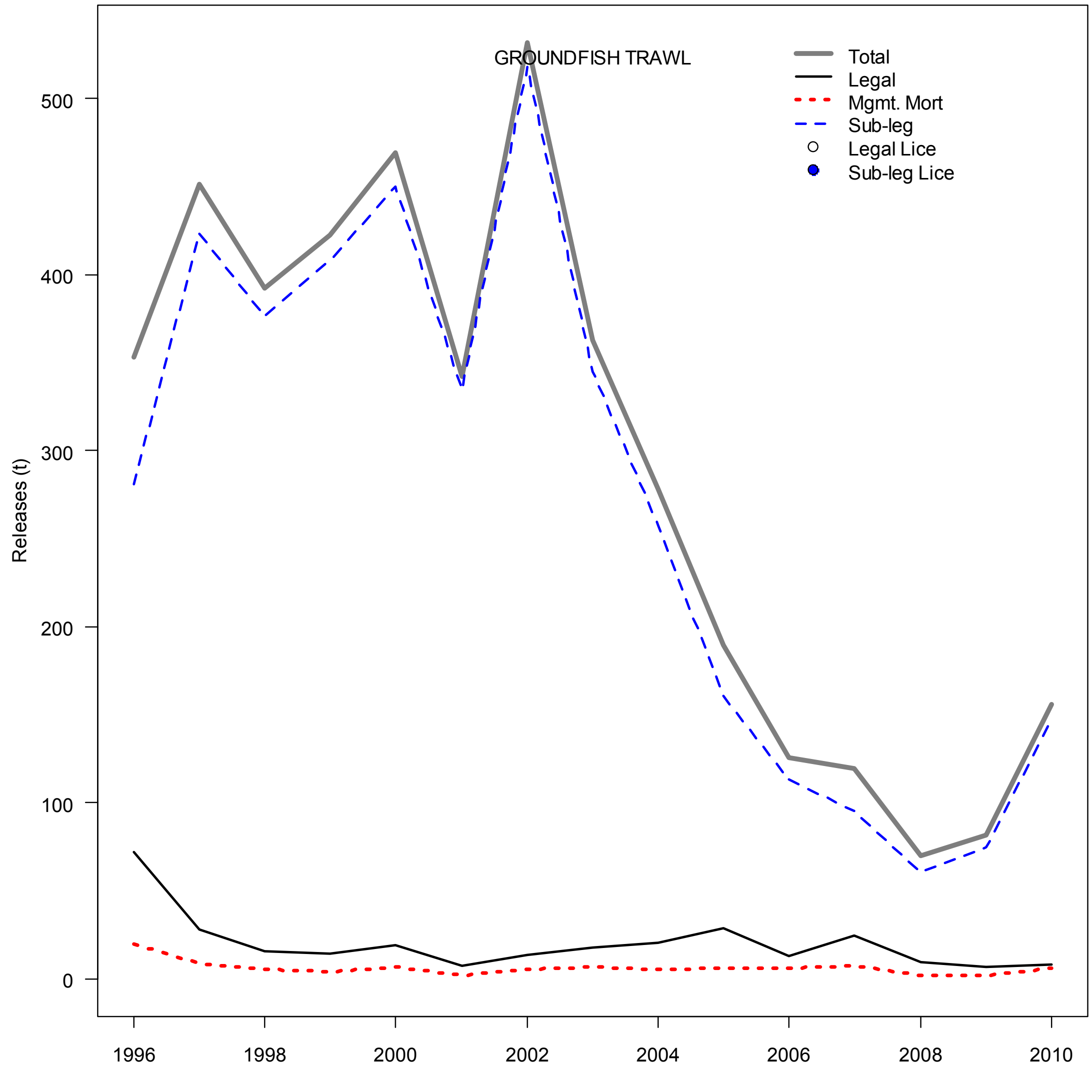

Figure B-4. Annual commercial trawl catches of sablefish showing the division of total catch (solid line) into retained (open circle) and released (filled circle) catches based on at-sea-observer estimates. Data for 2010 are incomplete.

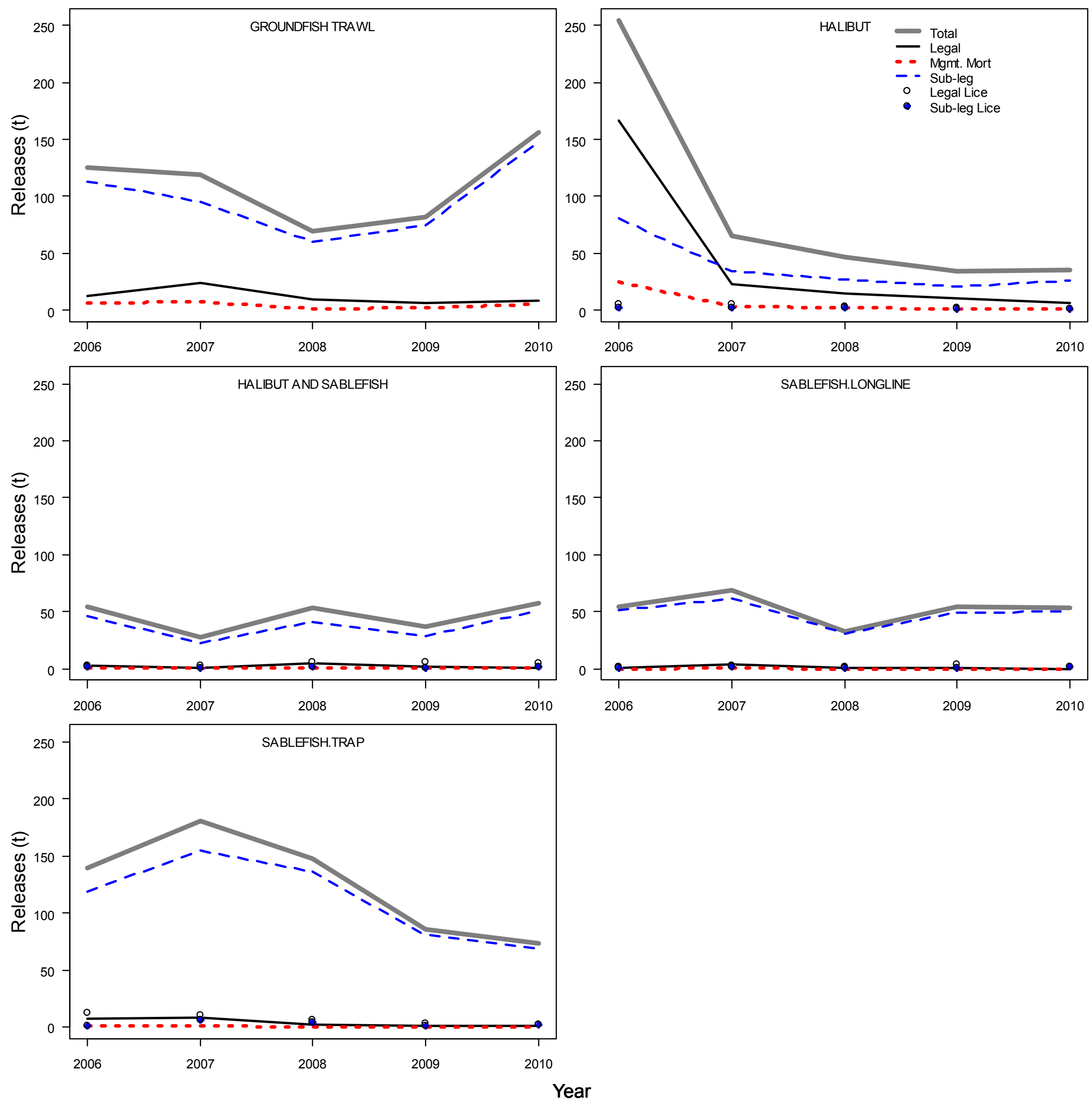

Figure B-5. Estimated releases by category for the trawl, sablefish trap, sablefish longline hook, and halibut longline hook sectors, and combined halibut and sablefish longline hook fishing. Liced legal and sub-legal release catches apply only to the fixed gears. Data for 2010 are incomplete.

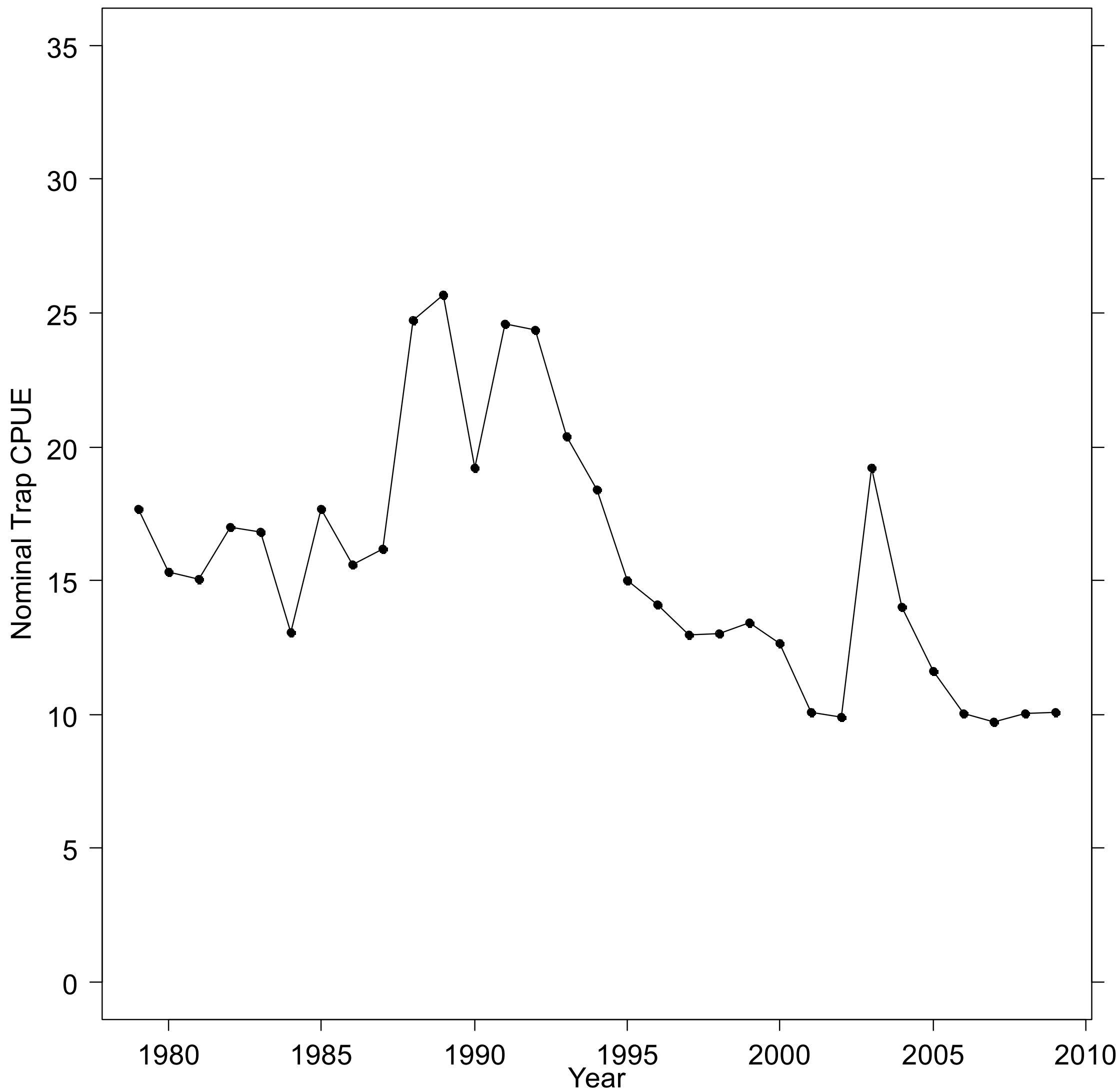

Figure B-6. Annual offshore nominal commercial trap fishery catch rates (kg/trap). The 2010 index value is not shown due to incomplete data.

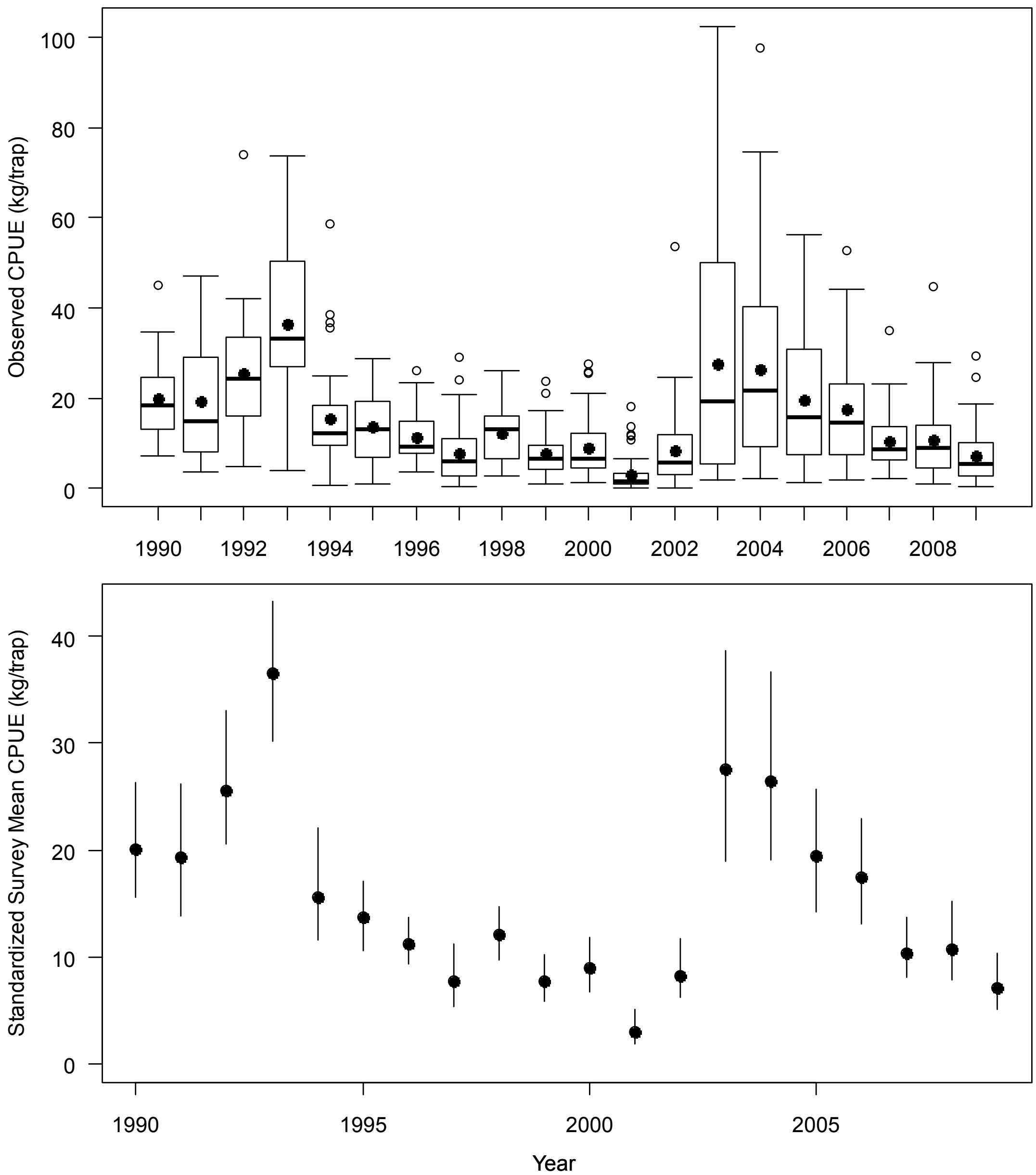

Figure B-7. Annual standardized survey catch rates (kg/trap) from 1990 to 2009. The annual distribution of catch rates for each year is summarized by boxplots (upper panel) where the solid circle indicates the mean. Annual mean catch rates are shown (lower panel) with empirical likelihood estimates of the 95% confidence interval to provide an indication of relative precision.

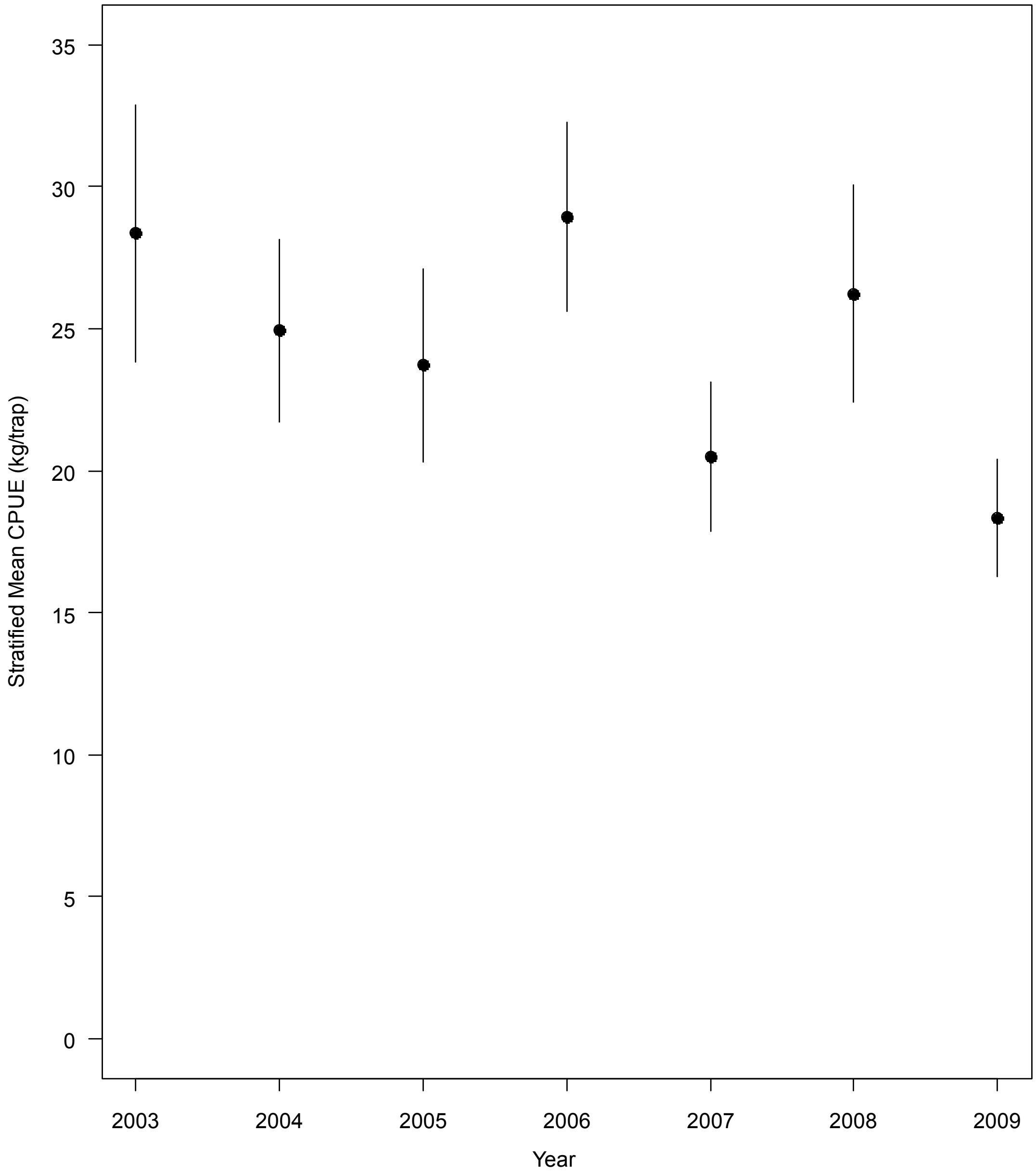

Figure B-8. Annual stratified random survey mean catch rates (kg/trap) from 2003 to 2009. Solid circles indicate the stratified mean. Vertical lines show the upper and lower 95% confidence limits.

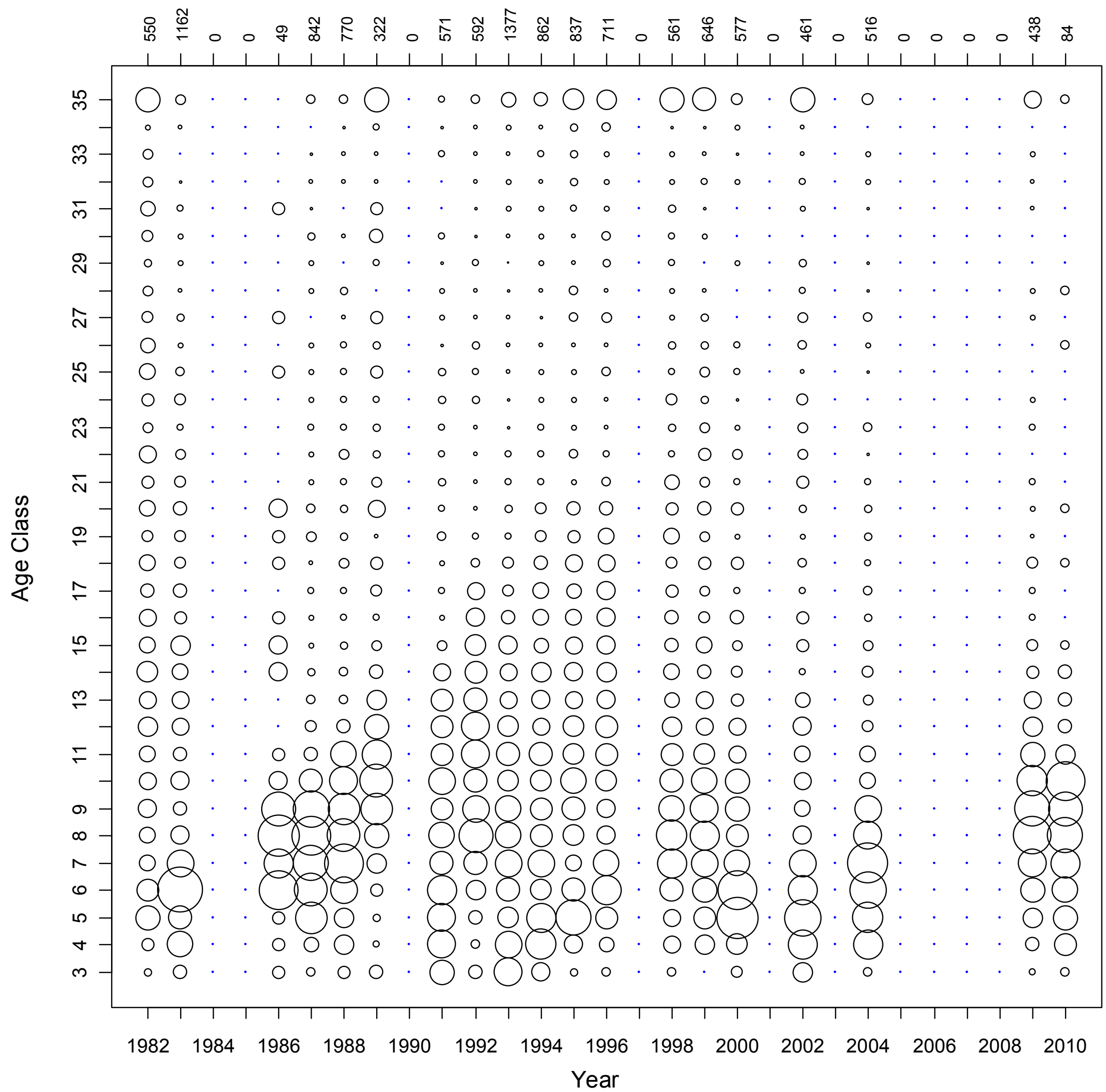

Figure B-9. Commercial trap fishery proportions at age for pooled sexes, 1982-2010. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers of fish are indicated along the top axis.

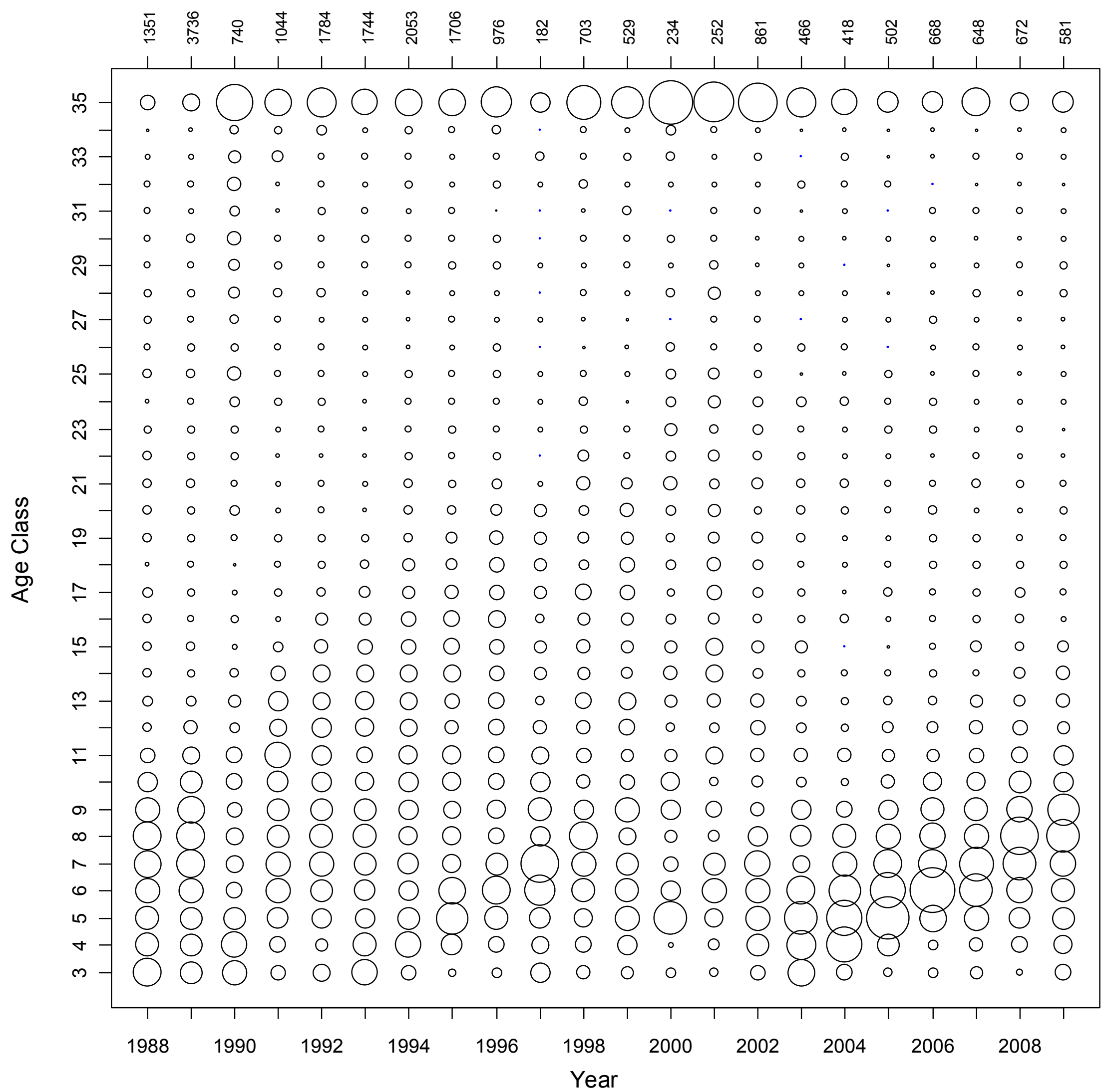

Figure B-10. Standardized trap survey proportions at age for pooled sexes, 1988-2009. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers of fish are indicated along the top axis.

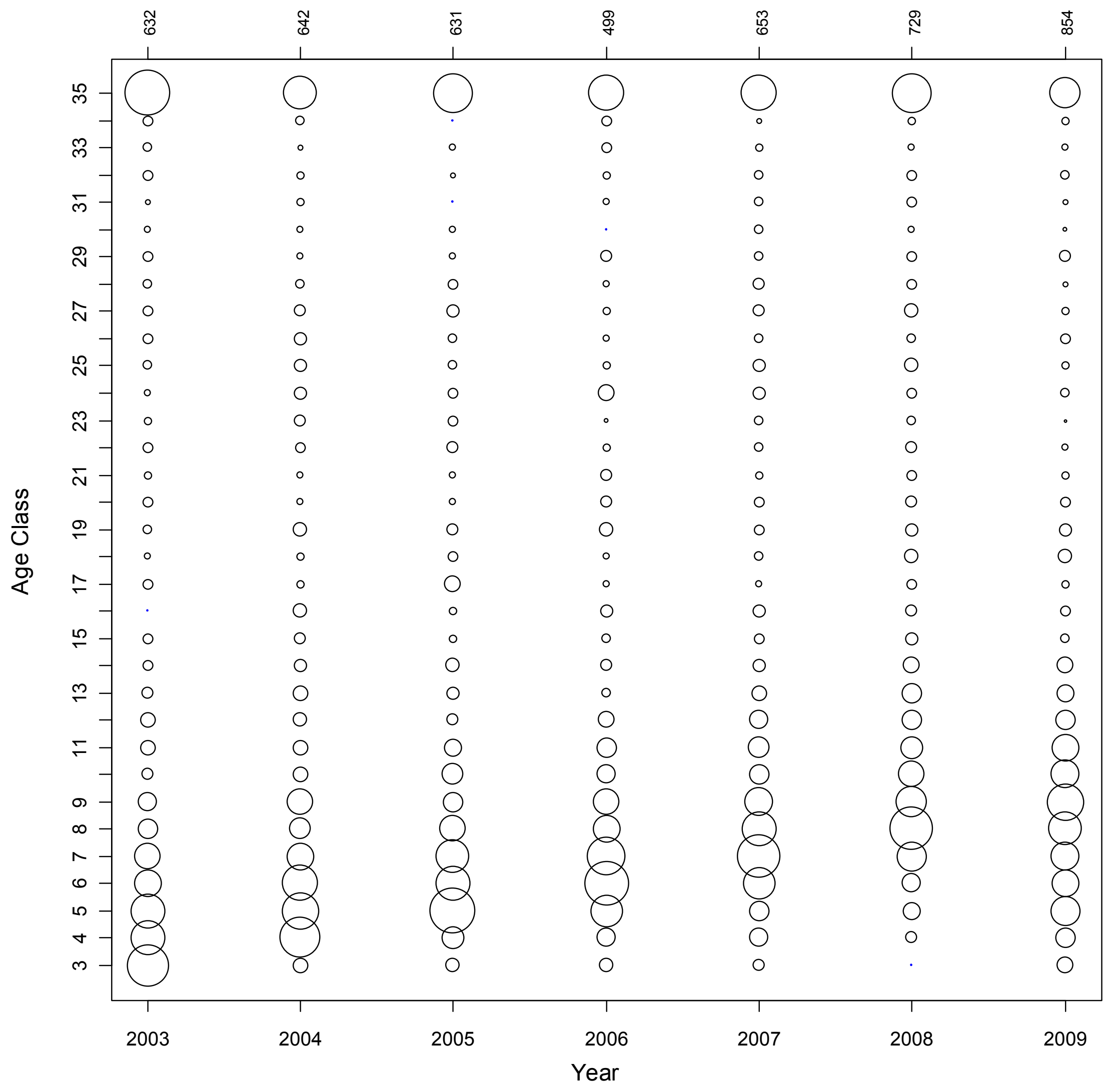

Figure B-11. Stratified random trap survey proportions at age for pooled sexes, 2003-2009. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers of fish are indicated long the top axis.

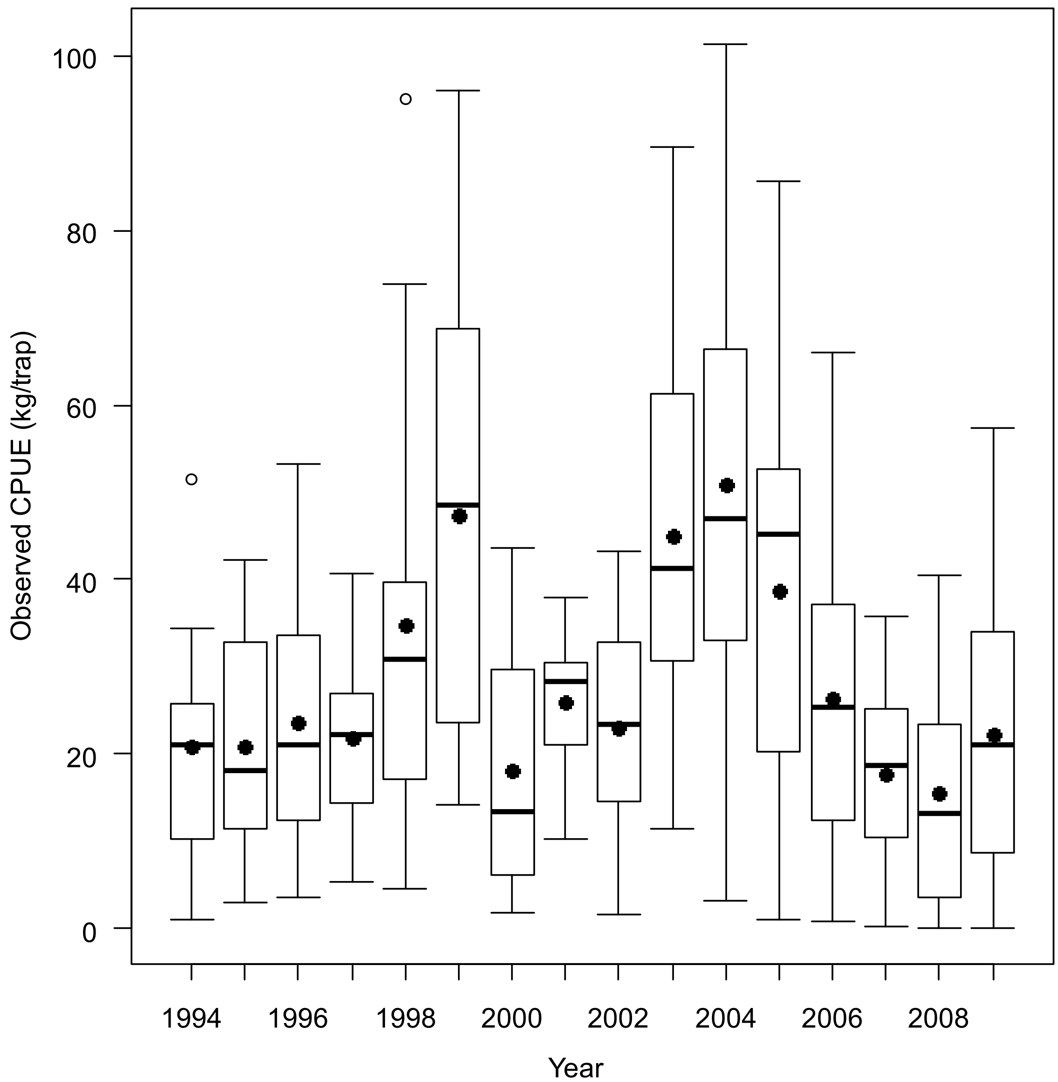

Figure B-12. Summary of observed catch rates (kg/trap) from annual mainland inlet surveys. Mean catch rates are indicated by filled circles and boxplots summarize the annual catch rate distributions. Outliers are indicated by open circles.

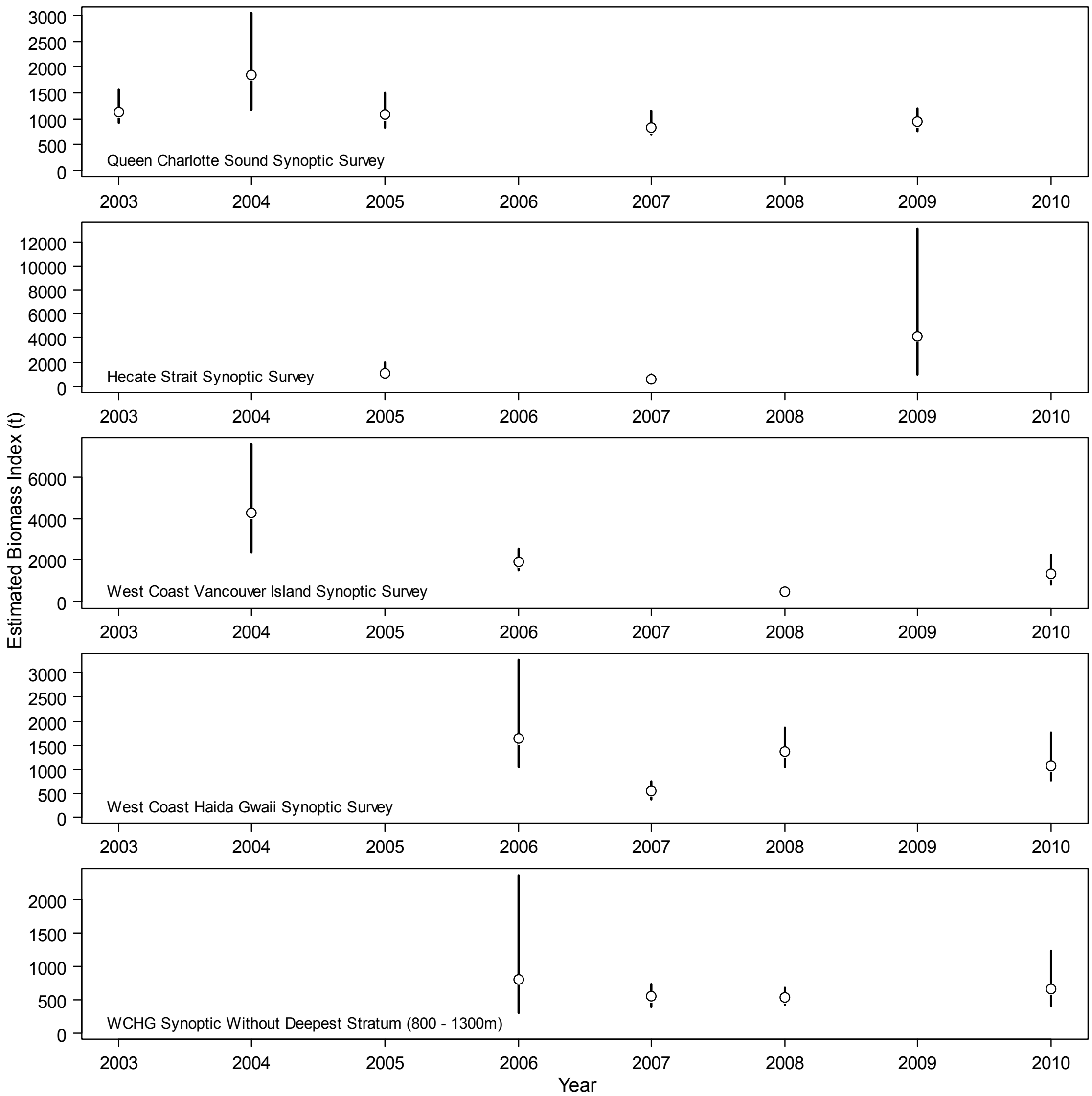

Figure B-13. Bootstrap estimates of relative sablefish biomass from groundfish synoptic trawl series 2003 to 2010 with 95% confidence intervals indicated by vertical solid lines. The 800-1300m stratum was not completed in 2006 for the West Coast Haida Gwaii survey hence results are presented with and without the deep stratum.

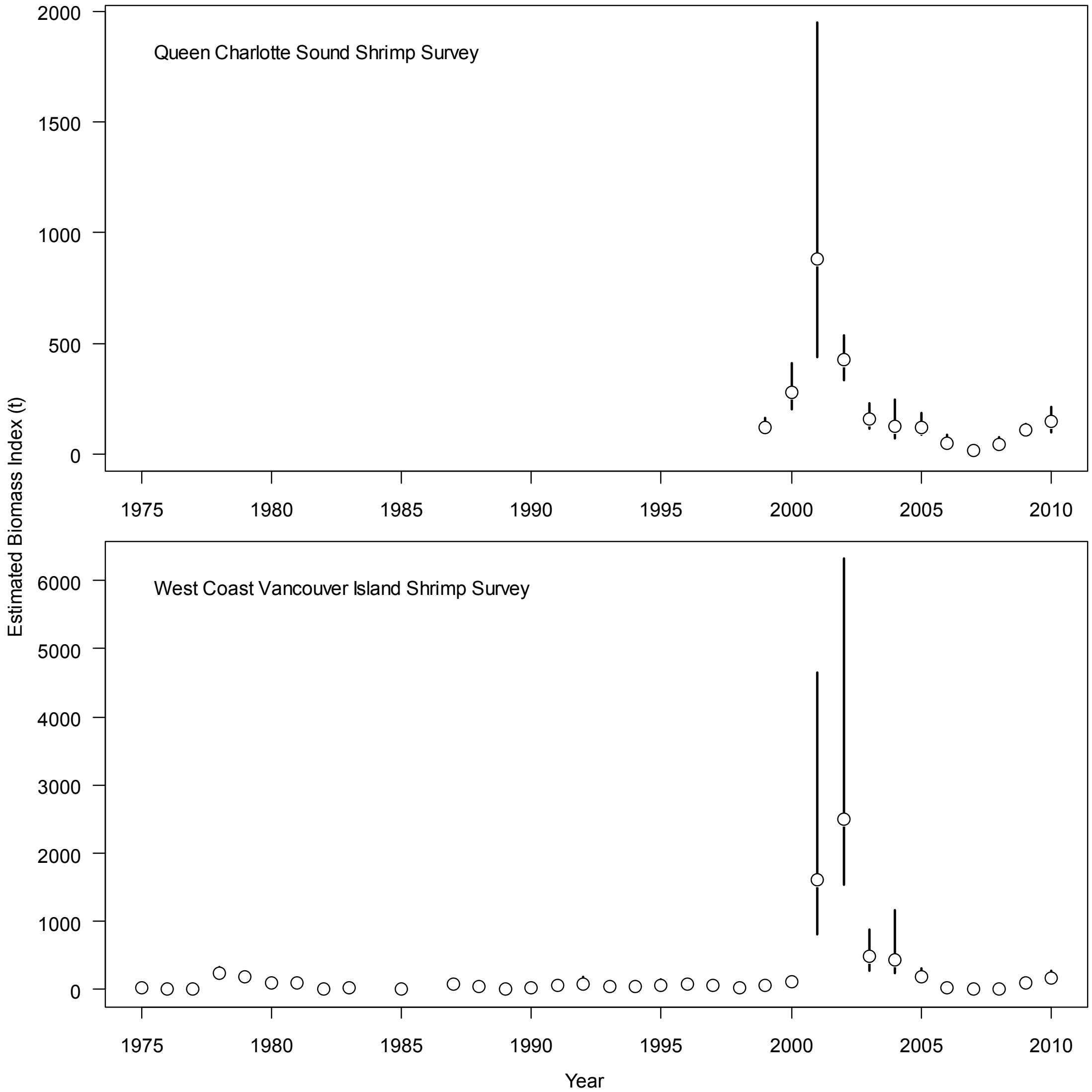

Figure B-14. Bootstrap estimates of relative sablefish biomass from the Queen Charlotte Sound (1999-2010) and west coast Vancouver Island (1975-2010) shrimp surveys with 95% confidence intervals indicated by vertical solid lines.

APPENDIX C QUANTITIES ESTIMATED INDEPENDENTLY

NATURAL MORTALITY

The reported maximum age for sablefish in Alaska is 94 years (Kimura et al. 1998), 87 years in British Columbia, and 85 years (female) along the U.S. west coast (Schirripa 2007). Stock assessments of Alaskan sablefish have generally assumed that natural mortality is about 0.1. For example, Funk and Bracken (1984) assumed M=0.112, with subsequent assessments assuming M=0.1 until 1999. From 1999 to 2003 natural mortality was estimated at about 0.1 but analysis of the Bayes posterior distribution of M in 2004 (Sigler et al. 2004) showed that these estimates were not well-supported. Stock assessments for Gulf of Alaska sablefish after 2004 were conducted with a very precise prior on M, or fixed M such that was set to M=0.1 (Hanselman et al. 2009).

Methot (1988) suggested that M=0.08 be adopted for the U.S. West Coast sablefish stock but M=0.15 was used in the first application of stock synthesis to sablefish (Methot 1988) based on arguments that model fit was improved. In 1989 (Methot and Hightower 1989) revised the value of M from 0.15 to 0.09 based on revised age determination criteria for sablefish and an increase in the observed proportion of older fish in the stock relative to previous assessments. The model used to generate harvest advice for 1989 set M=0.0875, as did assessments until 1992. Arguments based on application of the Hoenig (1983) estimator of total mortality led to M=0.07 being used in stock assessments from 1992 onwards (e.g., Schirripa 2007).

Stock assessments in British Columbia have assumed fixed M=0.08 over the last 10 years (eg., Haist et al. 2005, Cox et al. 2009, Cox and Kronlund 2009).

GROWTH AND MATURITY

McFarlane and Beamish (1983) noted the remarkable growth of sablefish in their first year based on observations from the large 1977 year class in British Columbia. Age 0+ fish from the 1977 year class averaged 28 cm fork length by the end of November and 31 to 33 cm fork length by the following spring at age 1+. By September of year 1+ sablefish from the 1977 year class averaged 37 cm fork length and averaged 40 cm fork length by November near the end of their second year of growth. Early life growth rates were estimated at 1.2 mm per day during the first spring and summer of life by Sigler et al. (2004) for Alaskan sablefish. Rapid growth was observed in aquaculture, where sablefish captured at about 3 cm fork length were grown to approximately 22 cm to 44 cm, depending on diet, over an 11 month period (McFarlane and Nagata 1987). Kimura et al. (1993) noted that sablefish are characterized by rapid growth at young ages, followed by extremely slow growth at older ages.

Specimens of age 1+ collected in B.C. averaged 40.7 cm fork length but were largely collected in the fall by trap gear and were therefore closer in size to an age-2+ fish early in their third year of life. Length at age-1 is reported as 38.4 cm for the U.S. west coast at age 1.66 in August for both sexes (Schirripa 2007). Length-at-age 1 reported in the literature for Gulf of Alaska sablefish ranges from 31 to 39 cm fork length (Sigler et al. 2001), with fish of age 2 averaging fork lengths of 48.1 cm for males and 46.8 cm for females (Hanselman et al. 2009).

Estimates of von Bertalanffy growth parameters published in the literature vary widely (Table C-1). The species exhibits sexual dimorphism with females larger at age than males after reaching maturity. However, published estimates are (*i*) sometimes based on fitting the growth curve to mean length-at-age rather than observations from individual fish, (*ii*) based on samples derived from various gear types which introduces different biases due to selectivity effects, and (*iii*) are based on samples taken from different depths, locations or time periods. For example, Hanselman et al. (2007) reported estimates of growth based on longline hook survey samples and compared estimates obtained from data collected during 1981-1993 to those obtained from data collected 1996-2004. They concluded that maximum length had increased over time and applied their growth estimates to the appropriate time periods as fixed inputs to the Gulf of Alaska (GOA) stock assessment. Estimates of growth rate and asymptotic length currently used as fixed inputs to the GOA stock assessments for female sablefish are *k*=0.222 and L_∞ =80.2 cm, respectively. Males growth parameters estimates are *k*=0.290 and L_∞ =67.8 cm (Hanselman et al. 2009). The corresponding estimates for the U.S. West Coast sablefish stock are *k*=0.246 and L_∞ =77.5 cm for females and *k*=0.298 and L_∞ =64.5 cm for males (Schirripa 2007).

Estimates of average growth rate derived from data collected in B.C. are at the high end of the range reported in the literature (Table C-2). We fit a von Bertanlanffy growth model with additive errors to data collected from the stratified random survey (2003-2009) which is thought to collect samples representative of the offshore population by virtue of the statistical survey design (Wyeth et al. 2007). In our growth formulation the average length at age a is given by

(1) $$L_a = L_\infty + \left(L_1 - L_\infty\right)\exp\left\{-k\left(a-1\right)\right\} \quad ,$$

where L_∞ is the average asymptotic size, L_1 is the length of a fish at age-1, and k is the average growth rate. We set $L_1 = 32.5$ cm, a reduction of 2.5 cm from the value used by Cox and Kronlund (2009) to better approximate fish size at the start of their second year of life. For observed individual length and age pairs $\left(L_i, A_i\right)$, the negative log-likelihood function for additive errors with a constant coefficient of variation can be stated as

(2) $$\Theta\left(k, L_\infty, \sigma\right) = n \log \sigma + \frac{1}{2\sigma^2}\sum_{i=1}^{n}\left(\frac{L_i - L_{A_i}}{L_{ia}}\right)^2 \quad ,$$

where L_i is the length if fish *i* in the sample, L_{A_i} is the average length of fish at age A_i, and σ^2 is the residual variance. The error structure implies the variance is proportional to fish length. Survey data are collected in October and November so ages were adjusted by adding the fraction of the year elapsed at the time of capture to the assigned age.

Although the sablefish operating model is not sex-structured, we fit the growth relationship described by equation (1) for data where the sexes are pooled and separately by sex (Table C-2, Figure C-1, Figure C-2). Comparison of these estimates with those listed in Table C-1 shows that estimates of growth rates for B.C. sablefish are among the highest reported. This result may be a function of the trap gear selectivity, which is likely to bias growth rate estimates upwards. Kimura et al. (1993) compared growth increments from sablefish collected by trawl and trap gear and showed that fish recovered by trap gear could have growth increments 3.7 cm larger than fish captured by trawl gear after adjustment for explanatory factors including sex, recovery gear, size-at-release, and time at liberty. We also obtained growth estimates for pooled sexes by depth by progressively extending the depth to 400 (Table C-3), 600 and 800 m. Estimates of *k* increase as specimens obtained from greater depths are included in the growth fit, while estimates of L_∞ decline due to the inclusion of small, old fish at age. Taylor et al. (2005) concluded that almost all capture methods favor the fast-growing individuals and over a period of exploitation lead to downward bias in estimates of mean asymptotic size and upward bias of estimates of the growth parameter, *k*, and the time of hatching, t_0. We consequently concluded that our estimates of the growth rate parameter were likely to be biased high and would therefore reduce the time that sablefish are exposed to release processes imposed by the size limit and produce optimistic estimates of fishery reference points. Instead, we chose values of k that approximate the range of estimates currently used for sablefish assessments in the U.S. In particular, we imposed the following assumptions:

1. Length at age-1 is fixed at L_1=32.5 cm;
2. Average growth rate is set to k=0.3 for the baseline configuration of the operating model and an alternative value of k=0.25 as a sensitivity test;
3. Asymptotic length is set to L_∞ =71 cm.

The same causes of bias in growth estimates can be anticipated for estimates of the maturity schedule. Our estimates of the age of 50% maturity based on stratified random survey samples are at the low end of the published range (Table C-3), which may be expected if trap gear selects for fast-growing sablefish. Thus, we set the age at 50% maturity to age 5 with the age of 95% maturity at age 8 as used by Cox and Kronlund (2009).

RELEASE MORTALITY

Mortality of fish released at sea represents a large uncertainty in estimates of fishing mortality. Release mortality rates are generally unmeasured and depend on the interaction of factors related to capture, environmental conditions, fish size, and susceptibility to stressors (Davis 2002, Davis et al. 2004, Davis et al. 2001, Olla et al. 1997). Determinants of release mortality for sablefish are related to (*i*) gear type, (*ii*) size-specific differences in sensitivity to stress due to interacting environmental factors, and (*iii*) delayed mortality after release due to cumulative stress effects or post-release predation. Gear-specific stressors include swimming exhaustion (trawl), crushing, punctures, suffocation (trawl, trap), hook injury, duration of fishing, predation by amphipods (fixed gear only), scale loss (trawl, trap, hook), and on-deck handling practices. The cumulative impact of these effects is difficult to quantify under the full range of fishing conditions, which explains why release mortality for sablefish has been studied primarily through controlled laboratory experiments (e.g., Davis et al. 2001, Davis and Olla 2001, Olla et al. 1998) with relatively few field studies (e.g., Erickson et al. 1997, Rutecki et al. 1992, Thorson 1972).

Rutecki et al. (1992) compared survival of jig-caught and trap-caught juvenile sablefish (22 to 30 cm fork length) and reported 19% mortality for jig-caught fish over the first week of holding compared to 75% mortality for trap-caught fish during the same period. Their results agreed with those reported by Thorson (1972) who concluded that mechanical injury from impact against trap walls and embolism from decompression led to petechial and ecchymotic hemorrhaging of the ventral abdomen and fins. Davis et al. (2001) conducted experiments to contrast the effects of hooked and trawl caught sablefish as a function of temperature change and exposure to air. Sablefish used for the experiments were captured at 20-40 mm fork length and raised for up to 3 years prior to use as age 2+ juvenile fish ranging from 32 to 48 cm fork length. Sablefish from the control group transferred from 4.7°C seawater to 12°C seawater and then exposed to air for 15 minutes survived for at least 60 days. Transfers to seawater at 16°C resulted in 100% mortality. Sablefish hooked using circle hooks for 4 h at 4.7°C and then transferred to 12°C seawater followed by 15 minutes air exposure all survived for at least 60 days. Those transferred to 14°C seawater experienced 50% mortality, while sablefish exposed to 16°C seawater experienced 100% mortality. Sablefish towed in a simulated cod end for 4 h and transferred to 12, 14, and 16°C seawater, held for 15 minutes in air experienced 33%, 83% and 100% mortality, respectively. However, sample sizes were small for both gears used in this study and industrial fishing conditions (e.g., longer exposure to air, higher temperatures, handling practices), were not replicated, so it is likely that mortality rates are under-estimated.

Davis and Parker (2004) and Davis (2005) suggest that changes to fish behaviour resulting from the accumulated effects of interacting stressors may reduce post-release predator avoidance, or increase vulnerability to infection via disturbed feeding. They exposed two size classes (small 32-49 cm and large 50-67 cm) of sablefish to air for 10-60 minutes at 10°C, 14°C and 18°C. Fish were not subjected to simulated fishing. Mortality increased more rapidly for the small size class after 30 minutes air exposure than for large sablefish, and also showed a threshold increase with temperature for small fish (Davis and Parker 2004). Ten minutes of air exposure impaired behavior of both small and large sablefish, but these effects declined when measured 1, 2, 3 and 24 hrs after exposure. Normal behaviour had not generally resumed by 24 hrs after exposure and small fish had more impairment than large fish at that time. Air exposure considerations are likely to impact trawl-caught fish more so than sablefish caught by hook and line gear because, in the latter case, under-sized fish are usually released at the rail whereas for trawl, fish are typically brought on deck, sorted, and then released. Trap gear may lead to air exposure times intermediate between hook and trawl gear, particularly when catch rates are high, because traps are highly selective for sablefish and thus sorting times are relatively short.

Erickson et al. (1997) trawled sablefish at depths from 177 to 223 m over 0.75 to 1.42 hrs and monitored mortality for up to six days. Sablefish 30 to 74 cm fork length were caged on the seabed at 138 to 148 m depth where bottom temperature was 6°C - 8°C and surface temperature was 15°C - 17°C. Deck handling time was decreased to 15 minutes during the study because handling times greater than 20 minutes led to 90% mortality after 2 days. The average mortality ranged from 37% (1 day) to 90% (4 days) implying daily mortality rates greater than 50% per day. Similar to other studies, mortality rates were greater for small sablefish over 1, 2, 4, and 6 days.

In general, the limited empirical data on at-sea release mortality of sablefish indicate that (*i*) release mortality is lowest for trap gear, intermediate for longline hook gear, and highest for trawling; (*ii*) small, sub-legal sablefish are more vulnerable to release mortality than larger fish because they are more susceptible to physical injury and more sensitive to rapid temperature change presumably due to their smaller body size; and (*iii*) behavioural changes and injury-related infection may cause substantial delayed mortality, particularly for small sablefish.

Under the current sablefish management plan (DFO 2010) deductions are made from quota holdings when legal-sized sablefish are released; no quota deductions are applied to releases of sub-legal fish because these fish must be released by regulation. Deduction rates vary by gear with trap and longline hook gears assigned mortality rates of 9% and 15%, respectively. The mortality rate for trawl gear is a function of tow duration with 10% mortality assigned for the first two hours and an additional 10% mortality hour for each subsequent hour or portion thereof. The trawl mortality rate typically assigned is roughly 20-30% based on the average annual tow duration (i.e., approximately 3 h) from 1996 to 2010, which is substantially lower than what might be expected based on the literature review described above.

At-sea release mortality rates used in B.C. fishery management plans may substantially under-estimate the actual mortality of released sablefish. In particular, management plan rates do not acknowledge that most at-sea releases are small, sub-legal fish that are the most susceptible to release mortality. In addition, fish released at sea are likely to be behaviorally or physiologically impaired and therefore subject to, for example, increased predation by marine mammals or other fish. Release mortality rates for the U.S. West Coast sablefish fishery, which has a minimum size limit of 55.88 cm (22 inches) fork length, are calculated as a function of sea-surface temperature based on relationships derived in Davis et al. (2001) (Schirripa and Colbert

2005, Schirripa 2007). It therefore appears that sablefish management plan mortality rates are too low to be used in model evaluations of the impacts of at-sea releases. Instead, we set at-sea release mortality rates (per year because they are additive to natural and fishing mortality rates) to 0.15/yr for trap gear, 0.30/yr for longline hook gear, and 0.80/yr for trawl. These equate to total annual mortality rates of 14%, 26%, and 55%, respectively.

Table C-1. Published growth estimates for sablefish from B.C., Gulf of Alaska (GOA), and the U.S. West Coast including time of hatching, t_0, average growth rate, k, and asymptotic size, L_∞. Estimates shaded gray are currently used as fixed inputs to U.S. sablefish stock assessments.

Sex	t_0 (years)	*k*	L_∞ (cm)	Source
Males Females	-1.07 -0.77	0.290 0.249	66.7 81.5	BC, Stocker and Saunders (1997)
Males Females		0.338 0.263	65.9 76.2	Northern B.C. Saunders et al. (1995)
Males Females		0.29 0.249	66.7 81.4	Southern B.C. Saunders et al. (1995)
Males Females	-2.35 -2.89	0.23 0.16	69.1 83.0	GOA 1981-1985 Hanselman et al. (2007)
Males Females	-0.716 -0.959	0.379 0.265	67.3 79.3	GOA 1996-2004 Hanselman et al. (2007)
Males Females		0.033-0.243 0.112-0.204	66.5-74.8 78.5-95.4	Sigler et al. (1997) for Gulf of Alaska slope (ranges)
Males Females		0.069-0.344 0.169-0.403	63.7-70.9 70.7-75.6	Sigler et al. (1997) for Gulf of Alaska shelf (ranges)
Males Females	-8.06 -6.15	0.12 0.106	70.2 86.7	GOA longline hook survey samples from 1987-1989 Kimura et al. (1993)
Males Females	-4.5 to -1.62 -2.81 to 0.48	0.193-0.357 0.183-0.314	66.6-70.1 77.2-81.3	GOA 1996-2004 Ranges by management area (Hanselman et al. (2007)
Males Females	-1.82 -0.81	0.472 0.499	54.7 61.0	U.S. West Coast trawl and trap survey samples from 1983 and 1989, Kimura et al. (1993)
Males Females	-4.092 -3.629	0.227 0.208	65.269 75.568	GOA 1981-1993, Hanselman et al. (2007)
Males Females	-2.273 -1.949	0.290 0.222	67.774 80.220	GOA 1996-2004, Hanselman et al. (2007)
Males Females		0.298 0.246	64.5 77.5	U.S. West Coast Schirripa (2007)

Table C-2. Growth estimates for sablefish collected during the stratified random survey, 2003-2009, for pooled sexes, separate sexes and pooled sexes by depth interval. Parameters include asymptotic average length, L_{∞}, growth rate, k, and standard error, σ. Sample is indicated by n. All growth fits set length at age-1 to $L_1 = 32.5$ cm.

Sample	Depth	L_{∞} (cm)	*k*	σ	n
Sexes Pooled	All	65.925	0476	0.119	4659
Males	All	61.172	0.504	0.093	2279
Females	All	70.914	0.390	0.107	2374
Sexes Pooled	0-400 m	72.280	0.312	0.102	988
Sexes Pooled	0-600 m	68.794	0.389	0.104	2011
Sexes Pooled	0-800 m	65.757	0.489	0.115	3031

Table C-3. Published estimates of age and length at 50% maturity for sablefish.

Source	Age at 50% Maturity (years)	Length at 50% Maturity (cm)	Source
British Columbia			
Males	5	52	Mason et al. (1983)
Females	5	58	
Males	4.3	52.6	McFarlane and Beamish (1983)
Females	4.9	62.4	
Males	4.8		Stocker and Saunders (1997)
Females	5.1		
Males	3.8 to 5.9	53.6-53.9	McFarlane and Beamish (1990)
Females	3.8 to 5	51.7-54.0	
Pooled sexes	2.95	49.47	B.C. stratified random survey estimates
Males	2.63	48.24	
Females	3.14	57.00	
Alaska			
Males	5	57	Sasaki (1985)
Females	6.5	65	Hanselman et al. (2009)
U.S. West Coast			
Males	5-7		Parks and Shaw (1987)
Females		55.3	Schirripa (2007)
Males	3-8	49.0	Fujiwara and Hankin (1988)
Females	3-8	56.4	

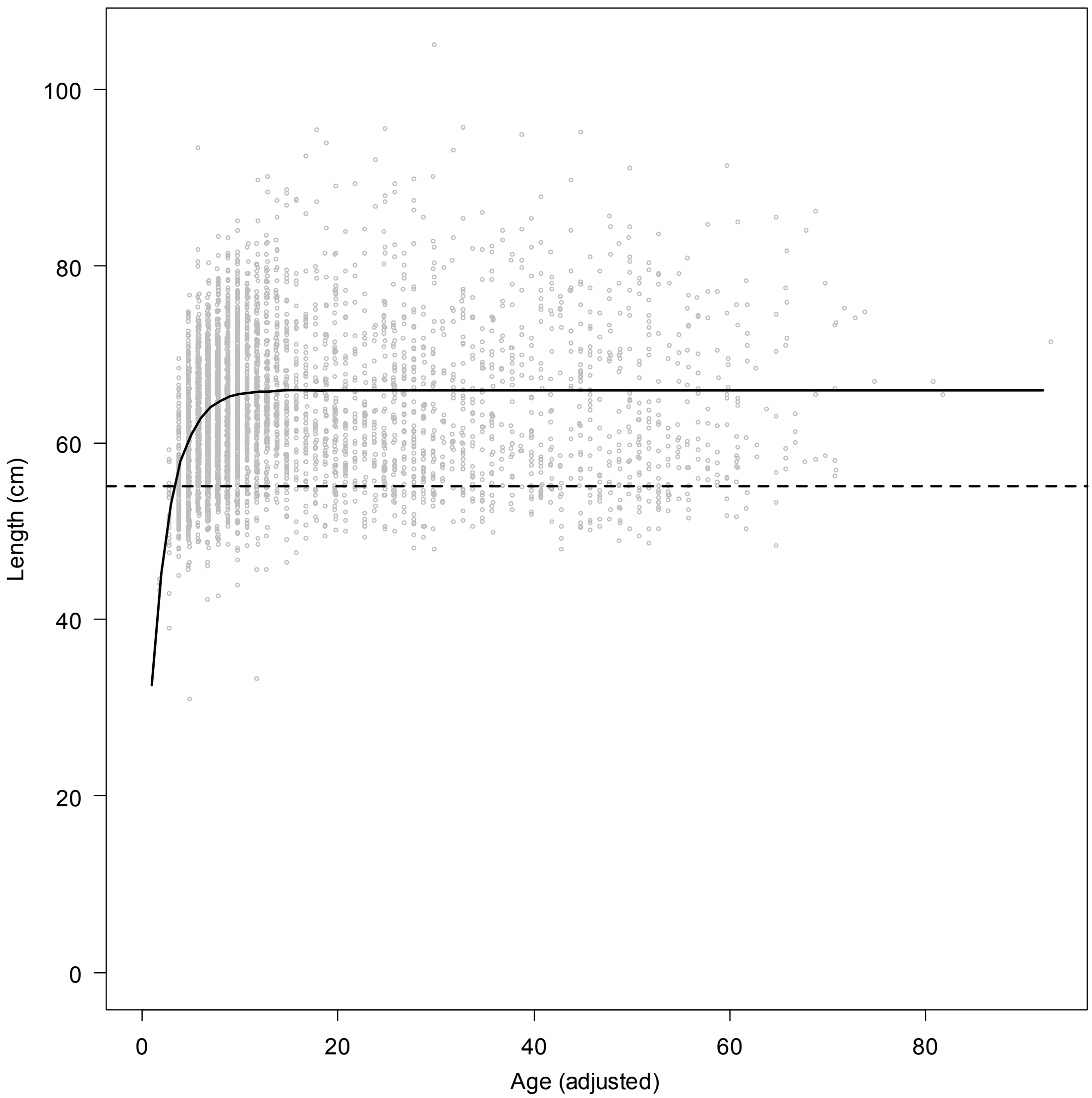

Figure C-1. Sablefish length at age observations obtained from the stratified random survey, 2003-2009, for pooled sexes. The solid black line indicates the fitted growth model predictions of length at age. The horizontal dashed line indicates the 55 cm size limit.

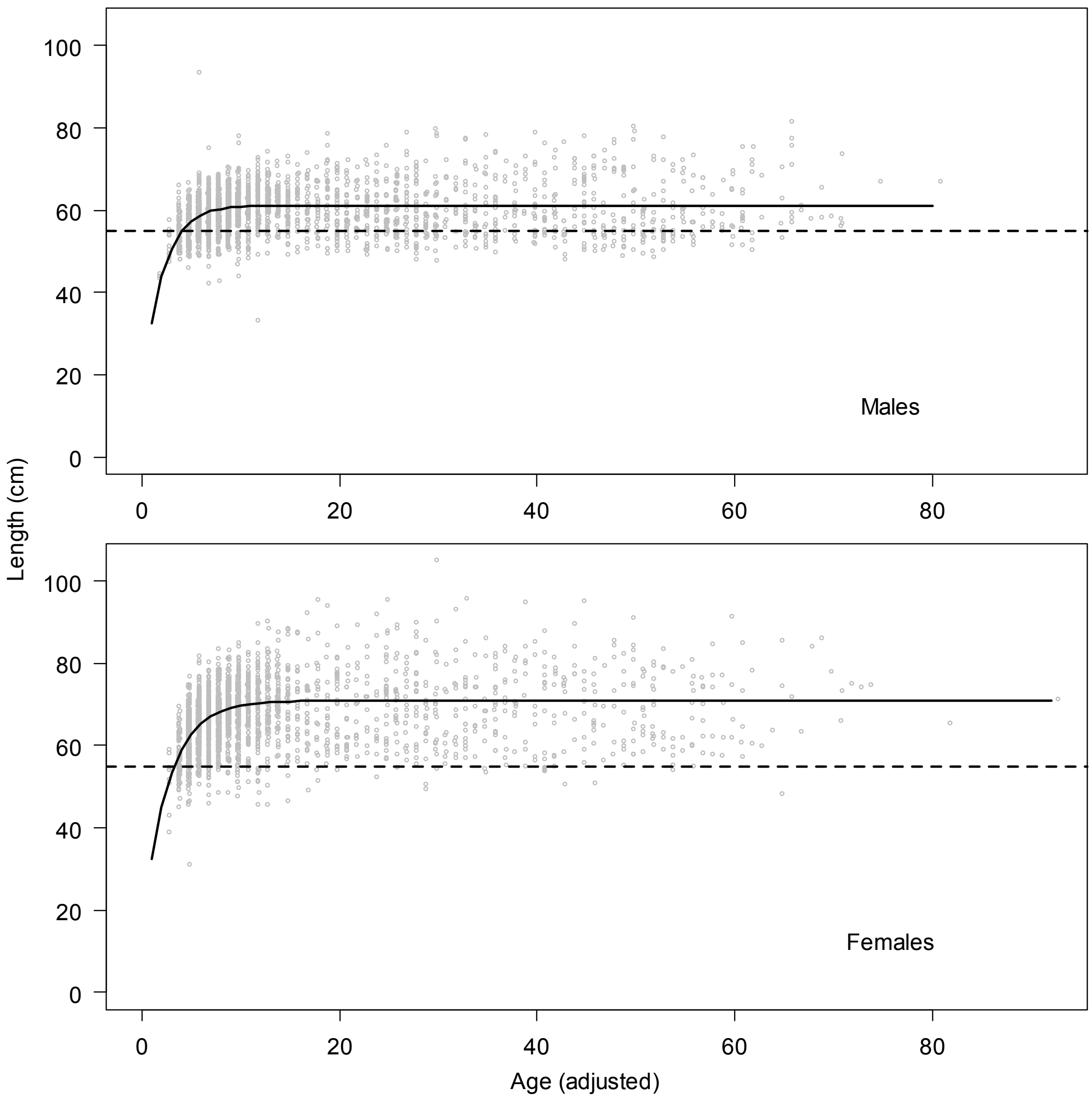

Figure C-2. Sablefish length at age observations obtained from the stratified random survey, 2003-2009, for males and females. The solid black line indicates the fitted growth model predictions of length at age. The horizontal dashed line indicates the 55 cm size limit.

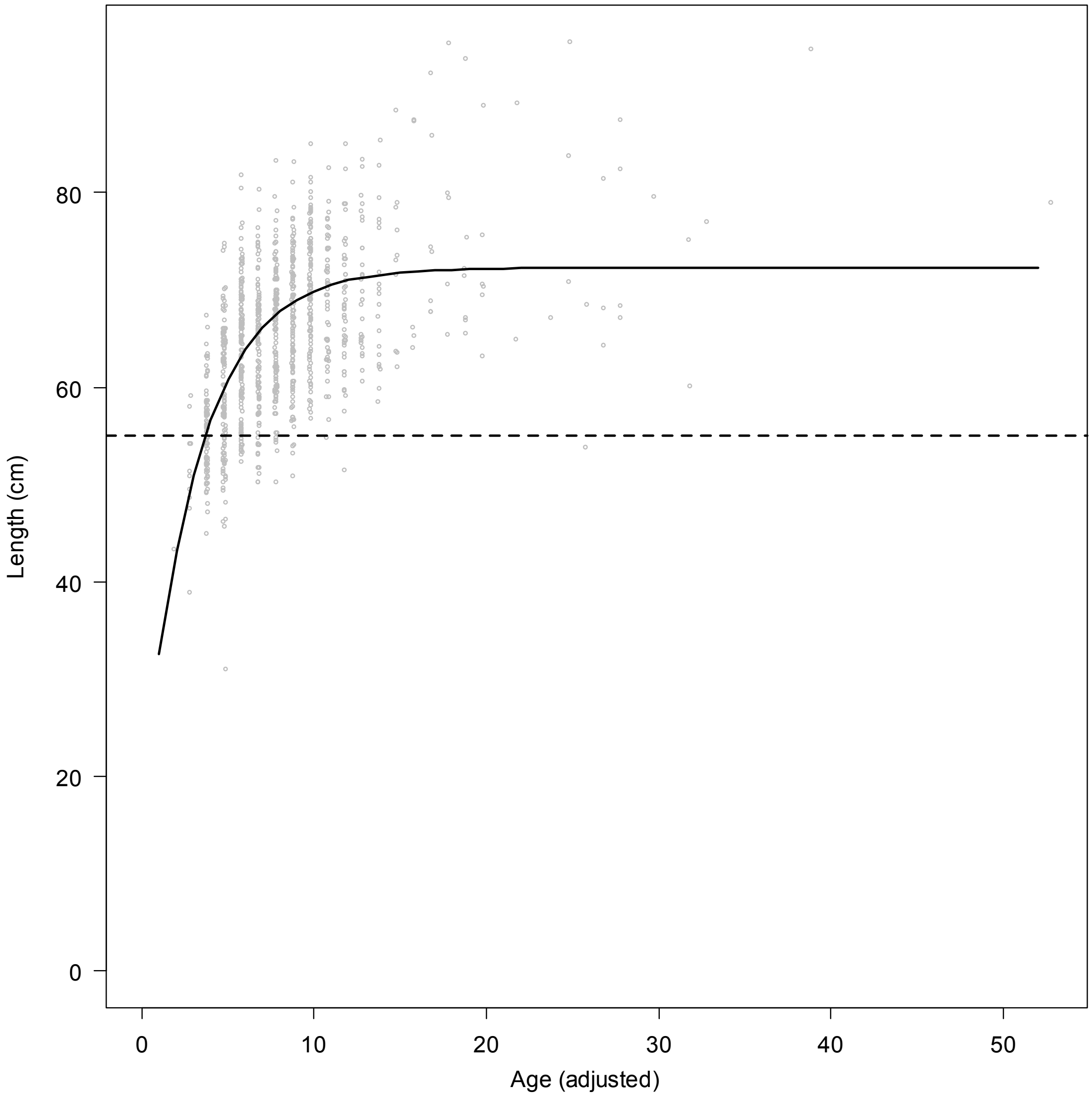

Figure C-3. Sablefish length at age observations obtained from the stratified random survey, 2003-2009, for pooled sexes and fish sampled from 0 to 400 m depth. The solid black line indicates the fitted growth model predictions of length at age. The horizontal dashed line indicates the 55 cm size limit.

APPENDIX D SABLEFISH OPERATING MODEL

The sablefish fishery operating model was developed to represent alternative hypotheses about sablefish population dynamics, at-sea release mortality rates, individual growth rate, and recruitment autocorrelation. The model is structured by age and also by growth group, where the latter dimension is added as part of our evaluation of size-based discarding, high-grading at sea, and potential regulatory changes aimed at reducing these activities. Here we describe the general structure of the operating model, with notation and equations given in Table D-1 and Table D-2, respectively. Note that in describing equations we use the prefix "O" to indicate those involved in the operating model (Table D-2) and "E" for equilibrium and reference point calculations (Table D-3).

All operating model scenarios assume that the B.C. sablefish spawning stock was at unfished, deterministic equilibrium B_0 in 1965 prior to the development of directed fisheries and that the B.C. population is closed to immigration and emigration.

GROWTH, MATURITY, AND FISHERY SELECTIVITY

Sablefish mean length (cm) for age-*a* and growth group *l* is modeled using a von Bertalanffy growth function with parameters (L_l^{∞} , *k*) (O2.2). All operating model scenarios use 12 growth groups, where the mean asymptotic length for each group is assigned using an inverse cumulative distribution function approach in which each group is assigned a unique quantile from a $Normal\left(\bar{L}^{\infty},\sigma_{L^{\infty}}\right)$ distribution. This procedure works by first dividing the central 95% of the $Normal\left(\bar{L}^{\infty},\sigma_{L^{\infty}}\right)$ distribution into 12 equally spaced probabilities p_1, p_2, …, p_{12} and then choosing quantiles (i.e., L_l^{∞} values) of the normal distribution corresponding to these probabilities. We set the mean and coefficient of variation of the asymptotic lengths to their maximum likelihood estimates based on length-at-age data from the Stratified Random Survey (2003-2009). The resulting growth patterns show that fish recruit to legal size between ages 3 and 15 for k = 0.25/yr and between ages 3 and 13 for k = 0.30/yr (Figure D.1). Also, at least one growth group never grows much above the commercial size limit of 55 cm, which is consistent with fishery and survey observations of very small and very old sablefish in some locations.

Because age, length, and maturity data for B.C. sablefish are largely derived from specimens captured by trap gear, it is likely that estimated age-at-50% maturity is biased downwards relative to the population, estimated growth rate (k) is biased upwards, and asymptotic size (L_{∞}) is biased downwards. This conclusion led us to reject estimates of age-of-50% maturity obtained from trap gear-based samples (Appendix C) and instead fix these parameters at values selected from review of the available literature (Appendix Table C-1). We use the alternative growth rate value k = 0.25/yr to reflect the potential upward bias in k = 0.3/yr arising from our use of trap-based length-at-age.

We model the size-based at-sea release process in two parts. In the first, fish are brought onboard fishing vessels according to gear-specific selectivity functions that depend on length (Equation O2.6, Figure D-3). Note that the relationships in O2.6 use a proportionality operator because each selectivity value is divided by the maximum gear-specific selectivity value over all ages and growth groups (not shown). Once onboard, fish smaller than the legal size limit (55 cm) are all released, whereas fish greater than the size limit are released according to a descending logistic function of length (Equation O2.5, Figure D-4). It is important to note that these are assumed relationships developed in consultation with the multi-sectoral Commercial Industry Caucus, DFO managers, and Wild Canadian Sablefish, Ltd. At the present time, monitoring programs in non-trawl sectors have no mandate to sample fish released at-sea, and sampling of species by at-sea observers is not directed at sablefish.

STOCK-RECRUITMENT

We assume that recruitment of age-1 individuals occurs in a single pulse on January 1st each year. Inter-annual variability in this recruitment has two components: (*i*) a deterministic Beverton-Holt relationship between spawning biomass in year *t*-1 and expected recruitment in year t; and (*ii*) log-normally distributed, lag-1 autocorrelated random variation around the expected recruitment. Parameters B_0 and h (the unfished spawning stock biomass and steepness, respectively) of the Beverton-Holt stock-recruitment relationship are the leading parameters estimated in the operating model conditioning step. The unfished spawning stock biomass, in combination with equilibrium unfished spawning biomass-per-recruit $\phi^{\mathrm{SSB}}_{\tilde{F}=0}$ (E3.4) determine the unfished recruitment R_0 (O2.7), as well as the initial slope (O2.8) and density dependence (O2.9) of the stock-recruitment relationship.

OPERATING MODEL REFERENCE POINTS AND GENERATION TIME

Life history schedules, fishery selectivity, and stock-recruitment parameters determine how the landed yield-per-recruit (E3.3), spawning stock biomass-per-recruit (E3.4), average biomass (E3.6), and average total landed yield (E3.7) vary in response to a particular combination of gear-specific equilibrium fishing mortality rates, $\tilde{\mathbf{F}}$ (Beverton and Holt 1957). Population and fishing mortality reference points are derived by (*i*) computing particular equilibrium functions, say total landed yield, over a grid of 50 F values ranging from 0 to 4 times the natural mortality rate, M; (*ii*) for each F, solving for the vector of gear-specific multipliers f_g that minimize the sum-of-squared differences between the modeled catch allocation among gear types, i.e., $C^{\mathrm{L}}_g \Big/ \sum_{j=1}^{G} C^{\mathrm{L}}_j$, and the predetermined target proportions (i.e., our assumed future allocation of catch among gear types); (*iii*) fitting a cubic spline between fishing mortality rates F (i.e., giving $\tilde{\mathbf{F}} = f_1 F, f_2 F, \ldots f_G F$) and the resulting total landed yield values $\sum_{g=1}^{G} C^{\mathrm{L}}_g$; and (*iv*) using the first derivative of the cubic spline in optimization procedures to solve for reference points, such as F^{MSY} (or U^{MSY}), MSY, B^{MSY}, etc. In practice, we only complete step (*ii*) once because the optimal multipliers are only weakly dependent on the values of F.

We use sablefish generation time as the timeframe over which to compute certain performance measures. Calculation of generation time varies depending on the available information, so we adopted the average age of the spawning stock[2], i.e.,

[2] IUCN Standards and Petitions Subcommittee. 2010. Guidelines for Using the IUCN Red List Categories and Criteria. Version 8.1. Prepared by the Standards and Petitions Subcommittee in March 2010. Downloaded from; http://intranet.iucn.org/webfiles/doc/SSC/RedList/RedListGuidelines.pdf.

$$G = \frac{\sum_{a=1}^{A} a l_a m_a}{\sum_{a=1}^{A} l_a m_a} \quad ,$$

where m_a is given by Equation O2.4 and the survivorship-at-age l_a is defined by Equation E3.2 for $F = 0$ (and ignoring growth groups). Because we estimate the natural mortality rate for some scenarios, the generation time will vary between 16 and 18 years.

INITIAL POPULATION AND STATE DYNAMICS

The population at time $t = 1$ is initialised in the deterministic, unfished equilibrium state using equations O2.10 - O2.11. Recruitment is assumed to be uniformly distributed among the 12 growth groups so that $\pi_{1,l} = 1/12$ and the normally distributed asymptotic lengths of each group are retained. State dynamics are then driven by recruitment (O2.12-13) and fishing mortality.

Annual recruitment deviations δ_t for the historical period 1965 – 2009 are estimated as part of the model conditioning step. As noted below, we do not include age classes $a < 3$ in the operating model fitting procedures, which means that recruitment deviations are only estimable for years 1966 – 2006. Therefore, in management strategy simulations, recruitment deviations for 2007 – 2009 are generated using Equation O2.12 in the same manner as future recruitment deviations for 2010 and beyond.

In calculating the catch (O2.18) and at-sea releases (O2.19), both fishing and natural mortality are assumed to operate continuously and simultaneously throughout the year. Note that the equilibrium computations in Table D-3 make the same assumption. For both the historical and future periods, we solve the catch equation for $F_{t,g}$ given the landed catch by gear (historical) or landed quota by gear (future projections). Four iterations of a Newton-Raphson algorithm are used to solve the catch equations to within 2-4% of the observed catches. The total at-sea releases are then computed based on the resulting $F_{t,g}$ values and at-sea release relationships to body length-at-age (O2.19).

We use legal biomass along with legal and sub-legal harvest rates to provide a common frame of reference for reporting harvestable stock biomass and total fishery exploitation. These quantities are easily derived from the fundamental catch and at-sea release quantities in O2.17-2.18, so we do not provide explicit equations for them here.

ABUNDANCE INDICES AND AGE-PROPORTION OBSERVATIONS

We assume that gear-specific indices of abundance are linearly proportional to the gear-specific available biomass, where availability is determined by the population size composition and gear selectivity (Equation O2.20). For the historical period and in future projections, we use a log-normal error structure on all indices of abundance, where the gear-specific standard errors ($\tau_{1,g}$) are estimated in the operating model conditioning step. In future projections, we only consider fishery-independent surveys (g = 4, 5). In our previous assessment (Cox and Kronlund 2009), we allowed for hyperstability in the fishery-dependent (i.e., trap catch-per-unit-effort, CPUE) index. We no longer include this scenario because (*i*) estimates of the hyperstability parameter were likely sensitive to two large anomalies in the Standardized Survey and (*ii*) a re-analysis allowing for time-varying catchability did not substantially improve the model fit to fishery CPUE; that is, a lack of systematic pattern in catchability deviations suggests that there is no information contradicting the assumption of a linear observation model. The end result of including hyperstability in our 2009 paper was a relatively low spawning biomass depletion and low steepness. Both of these results appear in our current suite of scenarios, so we concluded it was not necessary to include an additional hyperstability dimension.

In our management strategy projections, the operating model appends either one (Stratified Random Survey) or two (Standardized Survey and Stratified Random Survey) abundance index observations to the existing sablefish monitoring dataset. All historical index observations remain in the dataset, while indices not considered in the future are treated as missing in the future. Projections of abundance indices are also corrected for bias because simulated future surveys must have the same expected values as historical surveys for the same biomass levels. We do not generate age-proportion data (Equations O2.23-2.24) in future projections because we do not simulate management procedures involving catch-age stock assessment models.

Operating model conditioning based on historical data

Operating model scenarios were individually fitted to historical abundance indices, age composition, total at-sea releases, and tag recovery-at-length data (Appendix B). As noted above, we developed these scenarios around uncertainties about natural mortality rate, at-sea release mortality rates, individual growth rate, and recruitment autocorrelation. We use the term "conditioning" to represent the process of fitting four operating models to represent the cross-combinations of two particular hypotheses. Specifically, to represent the alternative growth rate hypothesis in which the von Bertalanffy parameter k = 0.25 instead of k = 0.30, we fix this parameter and re-fit the model to observed data. Similarly, we either fix the natural mortality rate at 0.08, or estimate its value given an informative prior distribution (described below). The conditioning procedure, therefore gives 4 operating models. To represent recruitment autocorrelation, we simply use the value γ = 0.40 for the projection period instead of γ = 0 as we do in the fitting the model to historical data. We don't estimate this parameter because its value will partly reflect the effects of ageing errors on estimated annual recruitments.

LIKELIHOODS

Abundance index likelihoods

Abundance index data consisted of (*i*) nominal trap fishery CPUE (1979-2009), (*ii*) standardized trap survey CPUE (1990-2009), and (*iii*) the stratified random trap survey CPUE (2003-2009). As described above, the observation model for each index is described by Equation O.20 with Equation O.21 specifying a log-normal error structure with variances $\tau^2_{1,g}$. The residual function for gear-type g is

$$\xi_{g,i} = \log\left(\frac{I_{g,i}}{B^*_{g,i}}\right) - \log\hat{q}_g \quad ,$$

where $\log\hat{q}_g$ is the conditional maximum likelihood estimate (MLE) of log-catchability, i.e.,

$$\log \hat{q}_g = \frac{1}{n_{1,g}} \sum_{i=1}^{n_{1,g}} \log\left(\frac{I_{g,i}}{B_{g,i}^*} \right)$$

and the vulnerable biomass is

$$B_{g,i}^* = \sum_{a=1}^{A} \sum_{l=1}^{12} w_{a,l} S_{a,l,g} N_{a,l,i} \quad .$$

Note that in these formulas and the ones below, we use the subscript *i* to index years for which a given datum is not missing and $n_{1,g}$ to represent, for example, the total number of observations contributing to the variance of dataset 1 for gear-*g*. The corresponding conditional MLE for the survey variance is

$$\hat{\tau}_{1,g}^2 = \frac{1}{n_{1,g}} \sum_{i=1}^{n_{1,g}} \xi_{g,i}^2 \quad .$$

Age composition likelihoods

Proportion-at-age data are available for the trap fishery (1979-2009, some years are either missing or treated as missing), standardized survey (1990-2009), and stratified random survey (2003-2009) (Appendix B). For each gear type and year, the predicted proportion-at-age *a* is defined by Equation O2.22. For a multivariate logistic likelihood function (Schnute and Richards 1995), the age-proportion residuals are defined by

$$\eta_{g,a,i} = \log p_{g,a,i} - \log u_{g,a,i}^C - \frac{1}{A} \sum_{a=3}^{A} \left[\log p_{g,a,i} - \log u_{g,a,i}^C \right]$$

and the conditional MLE for the age-proportion variance is

$$\hat{\tau}_{2,g}^2 = \frac{1}{(A-3) n_{2,g}} \sum_{a=3}^{A} \sum_{i=1}^{n_{2,g}} \eta_{g,a,i}^2 \quad .$$

Total at-sea release likelihoods

The total biomass of fish released at-sea has been estimated from piece counts for trap and hook fisheries since 2006 and biomass estimated by at-sea observers for trawl fisheries since 1996. The predicted releases at age-a for gear-*g* in year *t* is defined by Equation O2.18 and therefore, the total releases for gear-*g* are $D_{\bullet,t,g} = \sum_{a=1}^{A} D_{a,t,g}$, where the "dot" notation indicates summation over the subscript *a*. Assuming log-normally distributed errors, the residuals for total at-sea releases by gear-*g* are given by

$$\chi_{g,i} = \log D_{\bullet,t,g} - \log D_{\bullet,t,g}^{OBS} \quad ,$$

which gives the variance estimate

$$\hat{\tau}^2_{3,g} = \frac{1}{n_{3,g}} \sum_{i=1}^{n_{3,g}} \chi^2_{i,g} \quad .$$

Tag recovery-at-length likelihoods

We used gear- and length-specific tag recovery data as auxiliary information about selectivity-at-length parameters for trap, hook, and trawl fisheries. We did this because both hook and trawl fisheries lack age-composition sampling programs, and the trap fishery age-compositions were typically imprecise for much of the time-series. The tag recovery-at-length data, which we pooled over years 1996-2009, is therefore equivalent to informative prior information about length-based selectivity parameters.

If R_l represents the total number of fish released that are in length-class *l*, then the predicted proportion recovered by gear-*g* is

$$\pi_{l,g} = \mu_g S_{l,g} R_l \quad ,$$

where μ_g is the average proportion of tags recovered and reported by gear-*g*, and $S_{l,g}$ is the selectivity for length-class *l* by gear-*g* as defined by Equation O2.6 (ignoring the subscript for age). Note our assumption that tag reporting is independent of length. Assuming that recoveries are binomially distributed, the log-likelihood for the number recovered is

$$\ell\left(y_{l,g} \mid \pi_{l,g}\right) = y_{l,g} \log\left(\pi_{l,g}\right) + \left(R_l - y_{l,g}\right) \log\left(1 - \pi_{l,g}\right) \quad ,$$

where the dependence on gear-specific selectivity parameters is implicit in the definition of $\pi_{l,g}$ via $S_{l,g}$ and O2.6. Taken over all three fisheries, the total log-likelihood is

$$\ell_{\text{tag}} = \sum_{g=1}^{3} \sum_{l=1}^{n_l} \ell\left(y_{l,g} \mid \pi_{l,g}\right) \quad .$$

Prior distributions

We included the following prior distributions on the natural mortality rate *M* and the unfished spawning stock biomass B_0,

$M \sim N\left(0.08, 0.005\right)$, and

$$B_0 \sim 1/B_0 \quad .$$

Total objective function

Because we assumed that the individual variance components are unknown, the total objective function is given by sum of the concentrated log-likelihoods and log-priors, i.e.,

$$\ell_{\text{total}} = \sum_{g=1}^{G} n_{1,g} \log \hat{\tau}_{1,g}^2 + \sum_{g=1}^{G} (A-3) n_{2,g} \log \hat{\tau}_{2,g}^2 + \sum_{g=1}^{3} n_{3,g} \log \hat{\tau}_{3,g}^2 + \ell_{\text{tag}}$$
$$+ \frac{1}{2\sigma^2} \sum_t \omega_t^2 + 1/B_0 + 20000(M - 0.08)^2 .$$

OPERATING MODEL SCENARIOS

During MSE consultations[3], both industry and DFO managers expressed the desire to avoid specifying multiple operating model scenarios. Their concern was that decision-makers put too much weight on the most pessimistic model in Cox and Kronlund (2009; Scenario S1 in that paper), even though that particular model was not the most likely. Such behaviour is known as max-min utility, in which a decision maker seeks to get the best performance for the worst possible outcome or scenario. In fisheries, the max-min approach seems inevitable given the abundance of alternative models, and the high risk of management procedure failure in the most pessimistic cases.

Although our previous assessment (Cox et al. 2009) used a fixed *M* = 0.08, historically, both B.C. and U.S. stock assessment used natural mortality values ranging from *M* = 0.06/yr to *M* = 0.12/yr (Appendix B). Fixing the natural mortality rate based estimates external to stock assessment models is common practice in stock assessment modeling. However, such practice causes biases in estimated exploitation rates and stock abundance, especially if the fixed natural mortality rate over-estimates the true value (Clark 1999). Although it is possible to estimate the natural mortality rate from catch-age data, results are typically poor unless age-composition data exist for the early fishery development period in which the stock was unfished, or only lightly fished (Schnute and Richards 1995). For assessment models that include stock-recruitment functions, mis-specification of a fixed natural mortality may also cause unknown side-effects in estimated parameters contributing to the species life history. For instance, Mangel et al. (2010) demonstrate that any particular combination of growth, fecundity, and natural mortality parameters will favor some stock-recruitment steepness parameters over others. Thus, specifying a fixed natural mortality rate typically has a strong effect on estimates of stock-recruitment steepness, productivity, and fishery reference points.

We dealt explicitly with uncertainty about sablefish natural mortality, *M*, by estimating this parameter as part of the operating model conditioning step. We used an informative $N(0.08, 0.005)$ prior on *M* to overcome the well-established difficulties in estimating *M* along with other production parameters, and to guard against implausible values. This approach integrates over the uncertainty in natural mortality value and the resulting effect on other parameters. The operating model defined by an estimated natural mortality is therefore our baseline operating model scenario, which we refer to as S1. At the present time, we do not apply this approach to other parameters that we consider uncertain and potentially important. These additional parameters include the body growth rate *k* and the recruitment auto-correlation γ. Future operating models may further disaggregate the age/growth group model by sex, which would alleviate some of the uncertainty in applying a *k* = 0.3/yr growth rate to a unisex model. On the other hand, it is unlikely that we will resolve uncertainty about γ because of

[3] Sablefish Advisory Committee Minutes, 26 May 2010, SFU Segal School of Business, Vancouver, B.C.

unknown ageing errors that tend to smear historical age-classes over several years. Such smearing is known to create an erroneous appearance of high recruitment auto-correlation (Bradford 1992).

We developed seven secondary scenarios as tests of sensitivity and potential robustness of sablefish management procedures to a fixed natural mortality rate, alternative growth rate, and moderate recruitment autocorrelation (Table D-4). The first of these models (S2) is identical to S1, except that the natural mortality is fixed at the prior mean M = 0.08/yr. This scenario is expected to generate an operating model similar to that used in our previous work (Cox et al. 2009). Scenarios S3 and S4 are identical to S1 and S2, respectively, except that each uses a growth rate parameter k = 0.25/yr, which is closer to the growth rate used in U.S. sablefish assessments. Scenarios S5 and S6 are also identical to S1 and S2, respectively, except that recruitment autocorrelation is fixed at γ = 0.4 for projection years 2008 – 2047. We chose this low/moderate value because recruitment estimates from Alaskan sablefish assessments (that assume annual recruitment deviations are independent) did not appear to be highly correlated.

Finally, scenarios S7 and S8 address parameter uncertainty for scenario S1. Scenario S7 sets operating model parameters to their posterior means, while scenario S8 sets model parameters based on the 10th percentile of the posterior distribution for MSY. The posterior means that form the basis of scenario S7 are based on sample of 2,000 draws taken from an MCMC chain of length 100,000. Similarly, parameters required for scenario S8 were obtained by taking the particular draw from the sample of 2,000 points corresponding to the 10th percentile of the posterior distribution of MSY. The pair-wise joint distributions of selected leading and management parameters are shown in Figure D-15.

Operating model scenarios S1-S4 are the only ones fitted to sablefish fishery data (Table D-5). Models S1 and S3 estimate 15 leading parameters, while models S2 and S4 fix the natural mortality rate and thus estimate only 14 leading parameters. All four models involve an additional 43 recruitment deviations; however, the variance of these is assumed known at $\sigma_R^2 = 0.6$. Therefore, the effective number of recruitment deviation parameters is smaller.

Estimating the natural mortality rate (S1) generates the lowest negative log-likelihood value (Table D-5), although it is only 10 units smaller than fixed M. Note that the prior is still calculated even though M is fixed so that the likelihoods can be compared (otherwise the difference would include the negative log-prior computed for S1 only). The estimated data standard errors provide an indication of the fit quality for each data source. For instance, the estimated standard error for the StRS survey index $\tau_{1,5}$ = 0.16 is invariant under the alternative models, mainly because the time-series is so short (Figure D-6, row 3). This standard error is approximately double the within-year survey standard error of approximately 0.07-0.08. The estimated standard error for the Std survey index $\tau_{1,4}$ = 0.50 is also invariant under the alternative models, but in this case, probably because the survey is too noisy (Figure D-6, row 2). In contrast, the standard errors for releases in both trap and hook fisheries show relatively high sensitivity to M with values 0.52 and 0.26, respectively when M is estimated to 0.33 and 0.46 when M is fixed (Figure D-7, row 1 and 2). The standard error for trawl releases is only slightly sensitivity to M because the model only fits the latter half of the time-series. Since 1996, when the trawl release series originated, this fishery has undergone changes in gear (e.g., change from 4 ½ - inch to 5 ½ - inch cod-end mesh size in Hecate Strait and Dixon Entrance by regulation and in Queen Charlotte Sound on a voluntary basis) and catch accounting that likely reduced encounter rates with sub-legal sablefish. In addition, trawl industry members recently cite a higher degree of communication among fishing masters when encounters with sablefish occur, which may indicate active “avoidance behavior” in response to declining sablefish quotas. Because we do not take these changes into account, the model can only fit the latter part of the time-series. Under some extremely narrow parameterizations (and much trial-and-error model fitting), the model will fit the earlier releases instead, but the resulting parameter estimates (especially recruitments) were not particularly plausible. In the future, we could split the trawl sector into two separate fisheries to account for differences in size-selectivity over time. None of the fits to age-composition data were sensitive to M, which is not surprising given that we did not expect these to contain much information about M anyway (Schnute and Richards 1995). Age-composition fits were worst for trap fishery ages (Table D-5; Figure D-8), whereas Std and StRS were similar. The Std (Figure D-9) and StRS (Figure D-10) surveys showed similar age-frequencies during the period over which they coincide (i.e., 2003-2009).

Model parameters, stock status, and fishery reference points differed substantially when M was estimated rather than fixed. First, stock productivity as indicated by the recruitment steepness was much higher and unfished biomass was lower when natural mortality was estimated at M = 0.06/yr rather than fixed at M = 0.08/yr (Table D-6). These parameter combinations represent the well-known small/productive vs. large/unproductive stock uncertainty that arises from stock assessment models based on one-way trip data (Hilborn and Walters 1992). Although it may seem like this assessment is data-rich, there is little contrast in historical catch and biomass indices (Figure D-6). Information appears to be generated mainly by the extent of stock depletion, which is near the estimated B^{MSY} for (S1, S3) or just below B^{MSY} for (S2, S4) (Figure D-11; Table D-6).

In some stock assessments, particularly those in the U.S., the state of a fishery is characterized by the specific combination of biomass relative to B^{MSY} and fishing mortality rate relative to F^{MSY}. Stocks are characterized as "over-fished" ($B < B^{MSY}$) or "not over-fished" ($B > B^{MSY}$), and fishing mortality rates are characterized as "over-fishing" ($F > F^{MSY}$) or "not over-fishing" ($F < F^{MSY}$). Therefore a fishery with $B < B^{MSY}$ and $F > F^{MSY}$ would be "over-fished and over-fishing". If fishing mortality rates are reduced below F^{MSY}, then the state of the fishery can change quickly to "over-fished but not over-fishing". These states appear as the four quadrants of a plot of B/B^{MSY} versus F/F^{MSY}. For sablefish, the current state of the fishery differs by scenario: (S1) - slightly over-fished, but not over-fishing (Figure D-12, row 1); (S2) – over-fished and slightly over-fishing (Figure D-12, row 2); (S3) – slightly over-fished, but not over-fishing (Figure D-12, row 3); and (S4) – over-fished and slightly over-fishing. The legal harvest rate at MSY appears to have been exceeded since at least 1993 and possibly since 1987; however the current legal harvest rate appears to be very near the optimal level for all scenarios (Figure D-13). The harvest rate on sub-legal sablefish as a result of discard mortality ranges from 1.5% (fixed M) to 2.0% (estimated M). Finally, inter-annual variability in recruitment was nearly identical across scenarios, while the mean recruitment was higher for fixed M compared to estimated M (Figure D-14).

The estimate of maximum sustainable yield (MSY) was practically identical across scenarios, even though all other fishery referent points were markedly different. For instance, the legal harvest rate at MSY was nearly twice as high (0.11), and B^{MSY} nearly twice as low (27.68) for the estimated M scenario compared to fixed M (0.06 and 53.13, respectively). Spawning biomass depletion estimates at the limit reference points were not as dissimilar among scenarios, although all were at, or below 15%, of the unfished level (Table D-6).

Table D-1. Notation for the age-structured population, survey and fishery operating model. The "Symbol" column gives notation used in subsequent equation tables. Many parameters will have base values and then alternatives under different model configurations.

Symbol	Value	Range	Description
Indices			
T_1	47	$1 < T_1 < T_2$	Year in which the management procedure begins
T_2	83	$T_2 > T_1$	Total number of years to simulate
t		$1,2,...,T_2$	Time step
A	35	$A > 2$	Number of age-classes
a		$1,2,...,A$	Age-class
l		$1,2,...n_l$	Growth-group index
n_l	12		Number of growth groups
g		$1,2,...G$	Fishery/gear index
Parameters			
B_0	Est	$B_0 > 0$	Unfished spawning biomass (1,000s tonnes)
h	Est	$0.2 < h < 1.0$	Recruitment function steepness
q_g	Est	$q_g > 0$	Survey catchability for gear g
σ_R	0.60	$\sigma_R \geq 0$	Standard error of log-recruitment
γ_R	0.0	$-1 \leq \gamma_R \leq 1$	Lag-1 autocorrelation in log-recruitment deviations
M	(0.08, Est)	$M > 0$	Instantaneous natural mortality rate (/yr)

Symbol	Value	Range	Description
L_l^{∞}	$Normal\left(\bar{L}^{\infty}, \sigma_{L^{\infty}}\right)$	$L_l^{\infty} > 0$	Asymptotic length (cm) for growth-group *l* - value is mean
$\sigma_{L_{\infty}}$	7.8	$\sigma_{L_{\infty}} > 0$	Standard error of asymptotic length (cm)
$L_{1,l}$	30	$L_{1,l} > 0.0$	Length-at age-1 for all growth-groups (cm)
k	(0.25, 0.30)	$0 < k < 1.0$	von Bertalanffy growth constant
c_1	8.48e-6	$c_1 > 0$	length- weight scalar
c_2	3.05	$c_2 > 0$	length- weight power
$\tilde{A}_{50}$	5	$\tilde{A}_{50} > 1$	Age-at-50% maturity
$\tilde{A}_{95}$	8	$\tilde{A}_{95} > \tilde{A}_{50}$	Age-at-95% maturity
$\tilde{L}_{\text{lim}}$	55	$\tilde{L}_{\text{lim}} > 0$	Minimum size limit (cm)
$\tilde{L}_{50,g,1}^{\text{C}}$	Est	$\tilde{L}_{50,g,1}^{\text{C}} > 0$	Length-at-50% selectivity - ascending limb
$\tilde{L}_{95,g,1}^{\text{C}}$	Est	$\tilde{L}_{95,g,1}^{\text{C}} > \tilde{L}_{50,g,1}^{\text{C}}$	Length-at-95% selectivity - ascending limb
$\tilde{L}_{95,g,2}^{\text{C}}$	Est	$\tilde{L}_{95,g,2}^{\text{C}} > \tilde{L}_{95,g,1}^{\text{C}}$	Length-at-95% selectivity - descending limb
$\tilde{L}_{50,g,2}^{\text{C}}$	Est	$\tilde{L}_{50,g,2}^{\text{C}} > \tilde{L}_{95,g,2}^{\text{C}}$	Length-at-50% selectivity - descending limb

Symbol	Value	Range	Description
$\tilde{L}^{\mathrm{D}}_{95,g}$	Est	$\tilde{L}^{\mathrm{D}}_{95,g} > 0$	Length-at-50% discard probability
$\tilde{L}^{\mathrm{D}}_{50,g}$	Est	$\tilde{L}^{\mathrm{D}}_{50,g} > \tilde{L}^{\mathrm{D}}_{95,g}$	Length-at-95% discard probability
$\pi_{1,l}$	$1/n_l$	$0 < \pi_{1,l} \leq 1$ $\sum_l \pi_{1,l} = 1$	Proportion of age-1 recruits assigned to growth-group *l*
d_g	(0.15,0.30,0.8,0,0)	$0 \leq d_g \leq 1$	discard mortality rate (/yr)
Derived variables, states, and observations			
$L_{a,l}$			Length-class of growth-group *l* at age-*a* (cm)
$w_{a,l}$			Weight-at-age for fish in growth-group *l* (units determined by c_1)
m_a			Proportion mature-at-age
$P_{a,l,g}$			Proportion of age-*a*, growth-group-*l* discarded
$S_{a,l,g}$			Selectivity for age-*a*, growth-group-*l* by gear-*g*
R_0			Unfished recruitment
$\phi^{\mathrm{SSB}}_{\tilde{\mathbf{F}}}$			Spawning biomass per recruit given fishing mortality vector $\tilde{\mathbf{F}}$
ϕ^{L}_{g}			Landed yield per recruit for gear-*g*

Symbol	Value	Range	Description
ϕ_g^{D}			Discarded yield per recruit for gear-*g*
$N_{a,l,t}$			Number of age *a* fish in growth-group *l* in year *t*
$\omega_{R,t}$			Auto-correlated log-normal error in recruitment
B_t			Spawning biomass in year *t*
$C_{a,t,g}$			Landed catch-at-age in fishery *g*
$D_{a,t,g}$			At-sea releases-at-age fishery *g*
$F_{t,g}$			Fishing mortality rate for gear *g* in year *t*
$Z_{a,l,t}$			Total mortality rate for age-*a*, growth-group-*l* in year *t*
$I_{t,g}$			Deterministic biomass index for gear *g*
$\hat{I}_{t,g}$			Observed biomass index for gear *g*
$u_{a,t,g}^{\mathrm{C}}$			Proportion of age-*a* in year *t* landed catch
$u_{a,t,g}^{\mathrm{D}}$			Proportion of age-*a* in year *t* dead discarded catch

Symbol	Value	Range	Description
$\mathbf{X}_g$			Matrix of true age-proportions for gear-*g*
$\tilde{\mathbf{X}}_g$			Matrix of observed age-proportions for gear-*g*
δ_t	$Normal(0,1)$		Standard normal error in log-recruitment
$\varepsilon_{t,g}$	$Normal(0,1)$		Standard normal error for index *i*

Table D-2. Age-/growth-structured fish population and fishery operating model used to evaluate management procedures. This table sequentially defines the population and fishery dynamics for a given set of input parameters as defined in Table D-1. The subset of parameters given by Θ in O2.1 is estimated during operating model conditioning.

Parameters

O2.1 $$\Theta = \left\{ B_0, h, M, \{\delta_t\}_{t=2}^{T-3}, \left\{\tilde{L}^{\mathrm{C}}_{50,g,1}\right\}_{g=1}^{5}, \left\{\tilde{L}^{\mathrm{C}}_{95,g,1}\right\}_{g=1}^{5}, \tilde{L}^{\mathrm{C}}_{50,g=3,2}, \tilde{L}^{\mathrm{C}}_{95,g=3,2} \right\}$$

Growth, maturity, and selectivity

O2.2 $$L_{a,l} = L_l^{\infty} + \left(L_{1,l} - L_l^{\infty}\right) e^{(-k(a-1))}$$

O2.3 $$w_{a,l} = c_1 L_{a,l}^{c_2}$$

O2.4 $$m_a = \left(1 + \exp\left[-\log(19)\left(a - \tilde{A}_{50}\right) \middle/ \left(\tilde{A}_{95} - \tilde{A}_{50}\right)\right]\right)^{-1}$$

O2.5 $$P_{a,l,g} = \begin{cases} 1.0 & L_{a,l} < L_{\mathrm{lim}} \\ \left(1 + \exp\left[-\log(19)\left(L_{a,l} - \tilde{L}^{\mathrm{D}}_{50,g}\right) \middle/ \left(\tilde{L}^{\mathrm{D}}_{95,g} - \tilde{L}^{\mathrm{D}}_{50,g}\right)\right]\right)^{-1} & L_{a,l} \ge L_{\mathrm{lim}} \end{cases}$$

O2.6 $$\begin{aligned} S_{a,l,g} \propto & \left(1 + \exp\left[-\log(19)\left(L_{a,l} - \tilde{L}^{\mathrm{C}}_{50,g,1}\right) \middle/ \left(\tilde{L}^{\mathrm{C}}_{95,g,1} - \tilde{L}^{\mathrm{C}}_{50,g,1}\right)\right]\right)^{-1} \\ & \times \left(1 + \exp\left[-\log(19)\left(L_{a,l} - \tilde{L}^{\mathrm{C}}_{50,g,2}\right) \middle/ \left(\tilde{L}^{\mathrm{C}}_{95,g,2} - \tilde{L}^{\mathrm{C}}_{50,g,2}\right)\right]\right)^{-1} \end{aligned}$$

Stock-recruitment relationship

O2.7 $$R_0 = B_0 / \phi^{\mathrm{SSB}}_{\tilde{\mathrm{F}}=0}$$

O2.8 $$a = \frac{4hR_0}{B_0\left(1-h\right)}$$

O2.9 $$b = \frac{5h-1}{B_0\left(1-h\right)}$$

Initial population

O2.10 $$N_{1,l,1} = \pi_{1,l} R_0 e^{-M(a-1)} \quad 1 \le a \le A-1$$

O2.11 $$N_{A,l,1} = N_{A-1,l,1} \middle/ \left(1 - e^{-M}\right)$$

State dynamics

O2.12 $$\omega_{R,t} = \begin{cases} \dfrac{\sigma_R}{\sqrt{1-\gamma_R^2}}\delta_t & t=1 \\ \gamma_R \omega_{R,t-1} + \sigma_R \delta_t & t>1 \end{cases}$$

O2.13 $$N_{1,l,t} = \pi_{1,l} \frac{aB_{t-1}}{1+bB_{t-1}} \exp\left[\omega_{R,t} - 0.5\sigma_R^2 \big/ \left(1-\gamma_R^2\right)\right]$$

O2.14 $$N_{a,l,t} = N_{a-1,l,t-1} e^{-Z_{a-1,l,t-1}} \qquad 2 \le a \le A-1$$

O2.15 $$N_{A,l,t} = N_{A-1,l,t-1} e^{-Z_{A-1,l,t-1}} + N_{A,l,t-1} e^{-Z_{A,l,t-1}}$$

O2.16 $$B_t = \sum_{a=1}^{A} m_a \sum_{l=1}^{n_l} w_{a,l} N_{a,l,t}$$

O2.17 $$C_{a,t,g} = \sum_{l=1}^{n_l} w_{a,l} N_{a,l,t} \frac{S_{a,l,g} F_{t,g} (1-P_{a,l,g})}{Z_{a,l,t}} \left[1 - e^{-Z_{a,l,t}}\right]$$

O2.18 $$D_{a,t,g} = \sum_{l=1}^{n_l} w_{a,l} N_{a,l,t} \frac{S_{a,l,g} F_{t,g} P_{a,l,g}}{Z_{a,l,t}} \left[1 - e^{-Z_{a,l,t}}\right]$$

O2.19 $$Z_{a,l,t} = M + \sum_{g=1}^{G} S_{a,l,g} F_{t,g} \left(d_g P_{a,l,g} - P_{a,l,g} + 1\right)$$

Observations

O2.20 $$I_{t,g} = q_g \sum_{a=1}^{A} \sum_{l=1}^{n_l} w_{a,l} S_{a,l,g} N_{a,l,t}$$

O2.21 $$\hat{I}_{t,g} = I_{t,g} \exp\left[\tau_{1,g} \varepsilon_{t,g} - \tau_{1,g}^2 / 2\right]$$

O2.22 $$u_{a,t,g}^{\mathrm{C}} = C_{a,t,g} \Big/ \sum_{a'=1}^{A} C_{a,t,g}$$

O2.23 $$x_{a,t,g}^{\mathrm{C}} = \log u_{a,t,g}^{\mathrm{C}} + \tau_{2,g} \eta_{a,t,g}^{\mathrm{C}} - \frac{1}{A} \sum_{a'=1}^{A} \left[\log u_{a',t,g}^{\mathrm{C}} + \tau_{2,g} \eta_{a',t,g}^{\mathrm{C}}\right]$$

O2.24 $$X_{a,t,g}^{\mathrm{C}} = \exp\left[x_{a,t,g}^{\mathrm{C}}\right] \Big/ \sum_{a'=1}^{A} \exp\left[x_{a',t,g}^{\mathrm{C}}\right]$$

Table D-3. Equilibrium functions of a fishing mortality rate vector $\tilde{\mathbf{F}} = \left(\tilde{F}_1, \tilde{F}_2, ..., \tilde{F}_G\right)$.

Equation	Formula	Description
E3.1	$\Omega = \left(\tilde{\mathbf{F}}, \Theta\right)$	parameters
	$Z_{a,l} = M + \sum_{g=1}^{G} S_{a,l,g} \tilde{F}_g \left(d_g P_{a,l,g} - P_{a,l,g} + 1\right)$	total mortality-at-age/growth group
E3.2	$\ell_{a,l} = \begin{cases} 1 & a = 1 \\ \ell_{a,l} e^{-\tilde{Z}_{a-1,l}} & 2 \le a < A \\ \ell_{A-1,l} e^{-\tilde{Z}_{A-1,l}} \Big/ \left(1 - e^{-\tilde{Z}_{A-1,l}}\right) & a = A \end{cases}$	survivorship to age *a*
E3.3	$\phi_{\mathrm{g}}^{\mathrm{L}} = \sum_{a=1}^{A} \sum_{l=1}^{n} \ell_{a,l} w_{a,l} S_{a,l,g} \tilde{F}_g \left(1 - P_{a,l,g}\right)\left(1 - e^{-Z_{a,l}}\right) \Big/ Z_{a,l}$	landed yield per recruit
	$\phi_{g}^{\mathrm{D}} = \sum_{a=1}^{A} \sum_{l=1}^{n} \ell_{a,l} w_{a,l} S_{a,l,g} \tilde{F}_g P_{a,l,g} \left(1 - e^{-Z_{a,l}}\right) \Big/ Z_{a,l}$	discarded yield per recruit
E3.4	$\phi_{\tilde{\mathrm{F}}}^{\mathrm{SSB}} = \sum_{a=1}^{A} \sum_{l=1}^{n} \ell_{a,l} m_a w_{a,l}$	spawning stock biomass per recruit
E3.5	$R = \left(a\phi_{\tilde{\mathbf{F}}}^{\mathrm{SSB}} - 1\right) \Big/ b\phi_{\tilde{\mathbf{F}}}^{\mathrm{SSB}}$	age-1 recruitment
E3.6	$B = R\phi_{\tilde{\mathbf{F}}}^{\mathrm{SSB}}$	spawning stock biomass
E3.7	$C_{\mathrm{g}}^{\mathrm{L}} = R \sum_{g=1}^{G} \phi_g^{\mathrm{L}}$	total landed yield
	$C_g^{\mathrm{D}} = R \sum_{g=1}^{G} \phi_g^{\mathrm{D}}$	discarded total yield

Table D-4. Operating model scenarios for B.C. sablefish. Release mortality rates are given in order for trap, longline hook and trawl gears. Scenarios S7 and S8 are based on parameters obtained from the mean of the Bayes posterior distribution of scenario S1 (S7) or on a draw from the posterior corresponding to the 10th percentile of the distribution of MSY (S8). The S-R column indicates the value of stock-recruitment auto-correlation $\left(\gamma_R\right)$ simulated in the projection period.

Scenario	Release mortality	Natural mortality (*M*)	MSY quantile	Growth rate (*k*)	S-R $\left(\gamma_R\right)$	Label
S1	(0.15,0.30,0.80)	Estimated	--	0.30	0	S1:Baseline
S2	(0.15,0.30,0.80)	Fixed 0.08	--	0.30	0	S2:FixedM
S3	(0.15,0.30,0.80)	Estimated	--	0.25	0	S3:S1+Growth
S4	(0.15,0.30,0.80)	Fixed 0.08	--	0.25	0	S4:S2+Growth
S5	(0.15,0.30,0.80)	Estimated	--	0.30	0.40	S5:S1+AR
S6	(0.15,0.30,0.80)	Fixed 0.08	--	0.30	0.40	S6:S2+AR
S7	(0.15,0.30,0.80)	Estimated	--	0.30	0	S7:S1-Mean
S8	(0.15,0.30,0.80)	Estimated	10th	0.30	0	S8:S1-10th

Table D-5. Model fit statistics for scenarios S1-S4 (S5-S8 are derived from these). The number of estimated model parameters (N) does not include 43 recruitment deviations that are common to all models. Values of τ are maximum likelihood estimates of the standard errors for data sources listed in the headers, while the second subscript indexes gear type.

				Indices			**Ages**			**Releases**		
Scenario	**Description**	*N*	ℓ_{total}	$\tau_{1,1}$	$\tau_{1,4}$	$\tau_{1,5}$	$\tau_{2,1}$	$\tau_{2,4}$	$\tau_{2,5}$	$\tau_{3,1}$	$\tau_{3,2}$	$\tau_{3,3}$
S1	Baseline: model uncertainty	15	51095	0.29	0.49	0.16	2.84	1.27	1.39	0.52	0.26	0.87
S2		14	51105	0.24	0.50	0.16	2.88	1.28	1.40	0.33	0.46	0.93
S3	Growth rate parameter uncertainty.	15	51124	0.27	0.50	0.16	2.91	1.40	1.40	0.66	0.20	0.80
S4		14	51132	0.24	0.50	0.16	2.94	1.40	1.40	0.50	0.26	0.83

Table D-6. Distinguishing features of operating model scenarios S1-S8. Leading model parameters for each scenario are stock-recruitment steepness (h), the natural mortality rate (M), and the unfished spawning biomass (B_0). Equilibrium characteristics include the maximum sustainable yield (MSY), optimal legal harvest rate (U^{MSY}), spawning biomass (B^{MSY}), spawning biomass depletion (D^{MSY}), and depletion at the limit reference point $0.4B^{MSY}$ (D^{LRP}). The remaining two columns give projections for Year 2011 of spawning biomass (B_{2011}) and depletion (D_{2011}). Biomass units are thousands of metric tonnes.

Scenario	h	M	B_0	MSY	U^{MSY}	B^{MSY}	D^{MSY}	D^{LRP}	B_{2011}	D_{2011}
S1: Baseline	0.88	0.06	114.77	3.23	0.11	27.68	0.24	0.10	21.09	0.18
S2: FixedM	0.50	0.08	147.73	3.21	0.06	53.13	0.36	0.14	34.85	0.24
S3: S1+Growth	0.85	0.06	122.10	3.31	0.10	32.21	0.26	0.10	27.25	0.22
S4: S2+Growth	0.51	0.08	152.65	3.22	0.06	55.68	0.36	0.15	39.07	0.26
S5: S1+AR	0.88	0.06	114.77	3.22	0.11	27.68	0.24	0.10	21.18	0.18
S6: S2+AR	0.50	0.08	147.73	3.21	0.06	53.13	0.36	0.14	34.96	0.24
S7: S1-Mean	0.75	0.06	120.05	3.06	0.09	33.70	0.28	0.11	22.74	0.20
S8: S1-10th	0.59	0.06	121.08	2.53	0.06	40.02	0.33	0.13	24.59	0.19

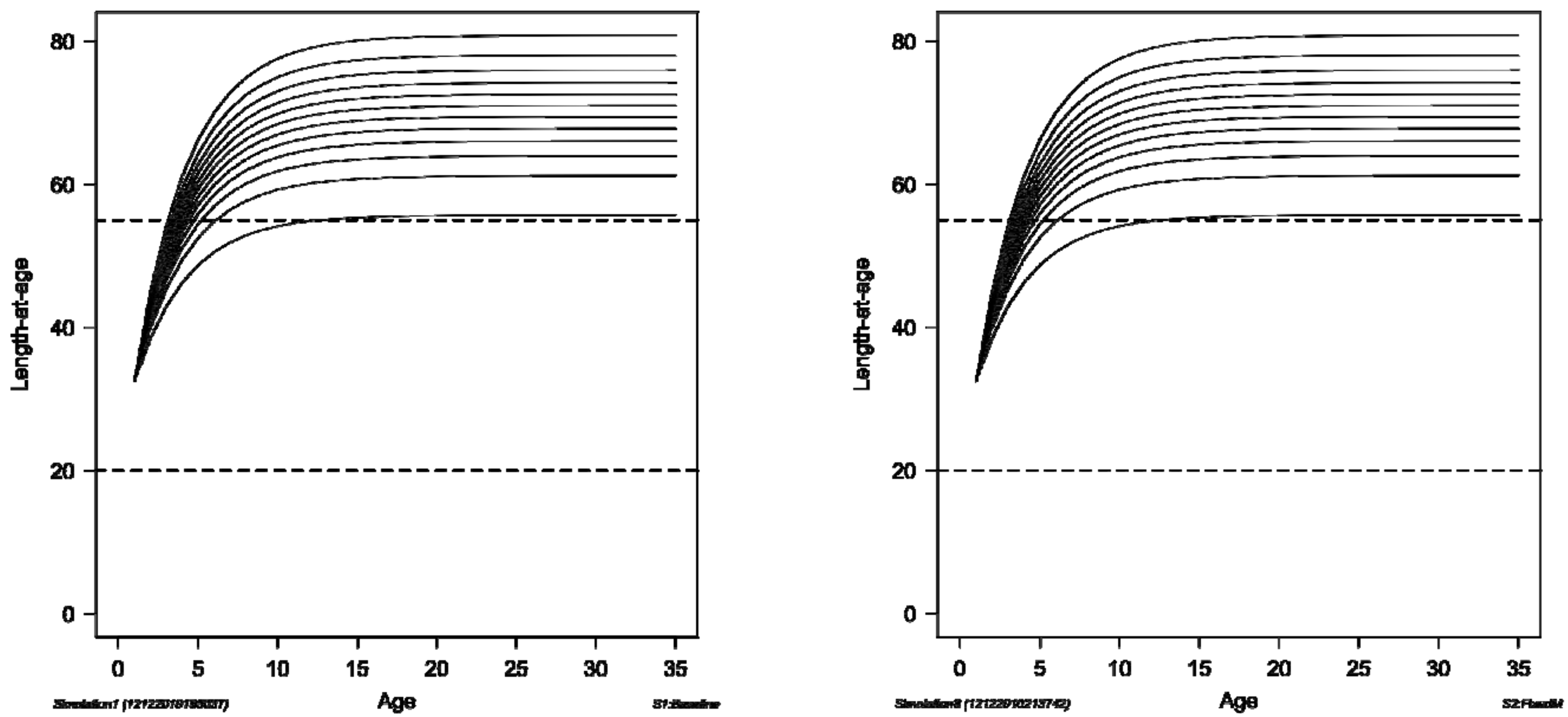

Figure D-1. Length-at-age (cm) by growth group for two growth rate scenarios involving k = 0.25/yr (left) and k = 0.30/yr (right)

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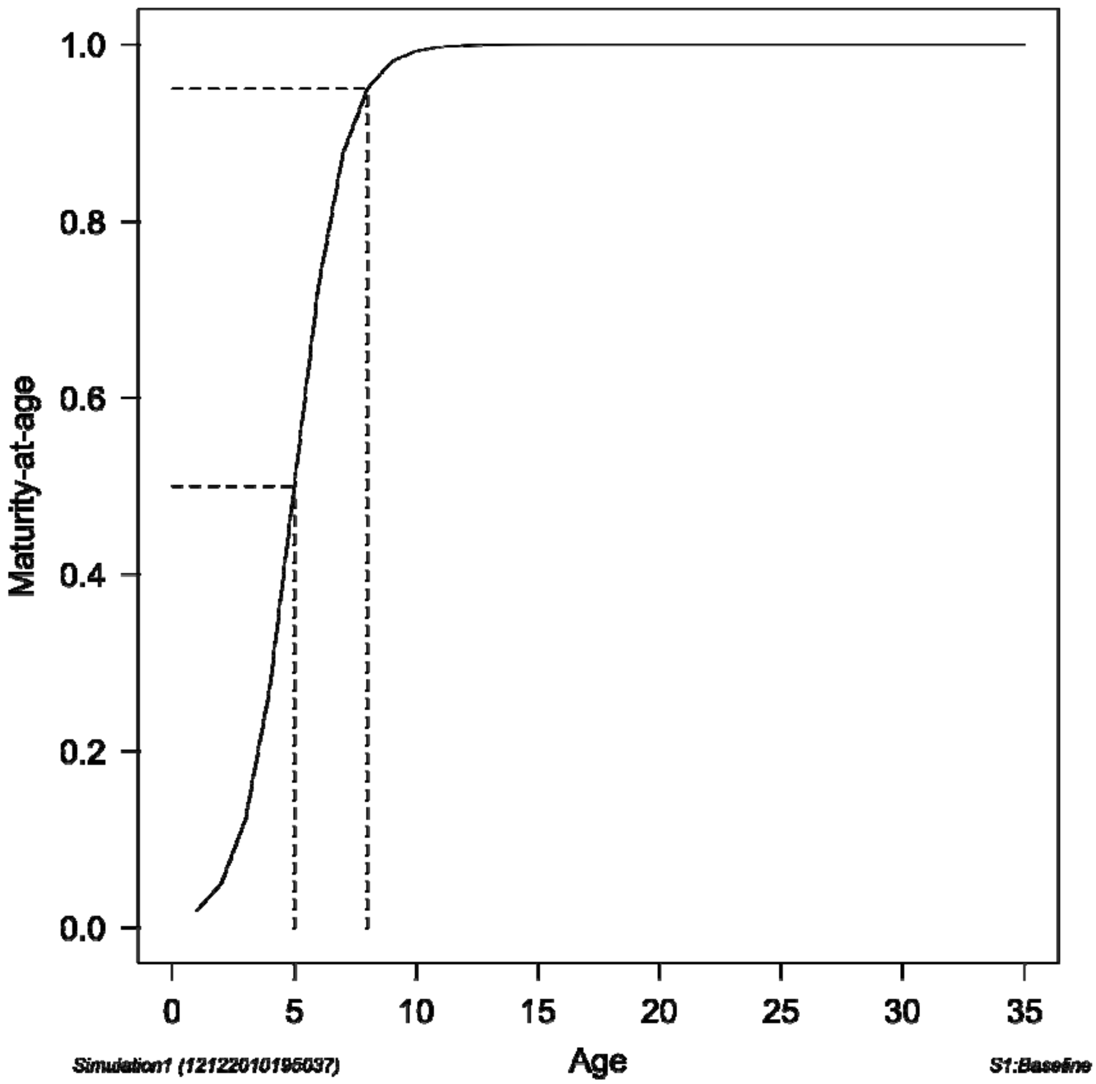

Figure D-2. Sablefish proportion mature-at-age. Dashed lines indicate the ages at 50% and 95% mature.

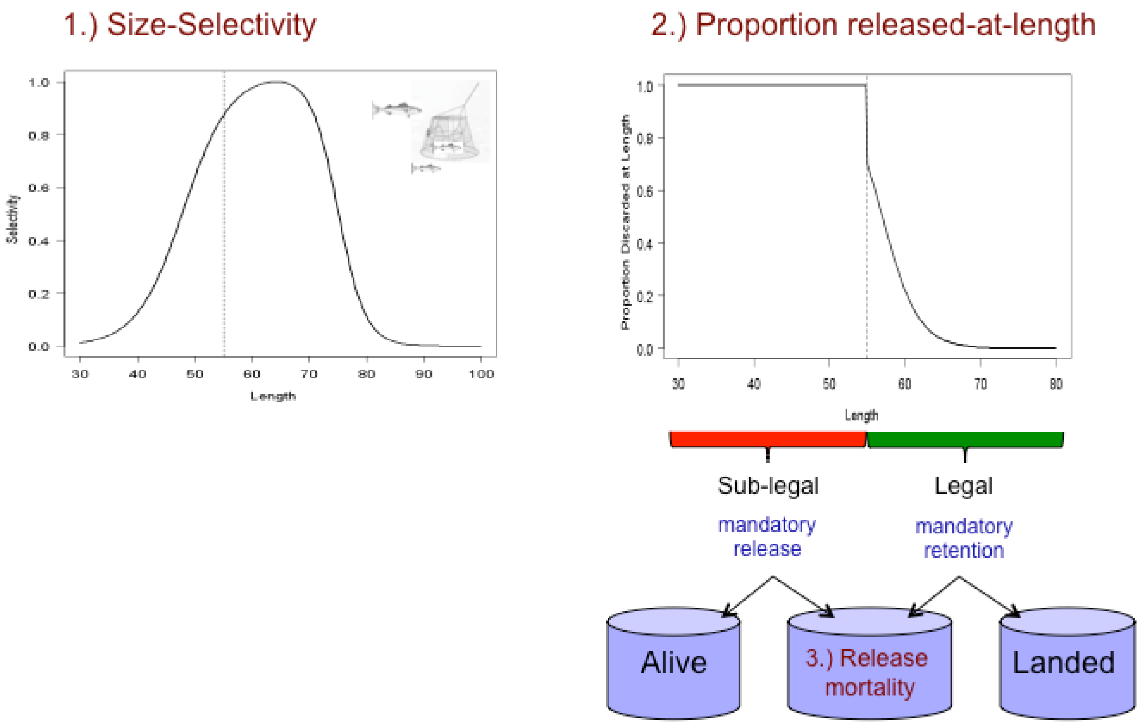

Figure D-3. Two-part process leading to retention and release of sablefish in the operating model. Sablefish encounter the fishing gear and are selected according to a gear-dependent size-selectivity function (1). Fish brought onboard the vessel are released according to a function of the legal size limit (2). Released fish are then subject to gear-specific post-release mortality (e.g., wound infection, stress, marine mammal predation).

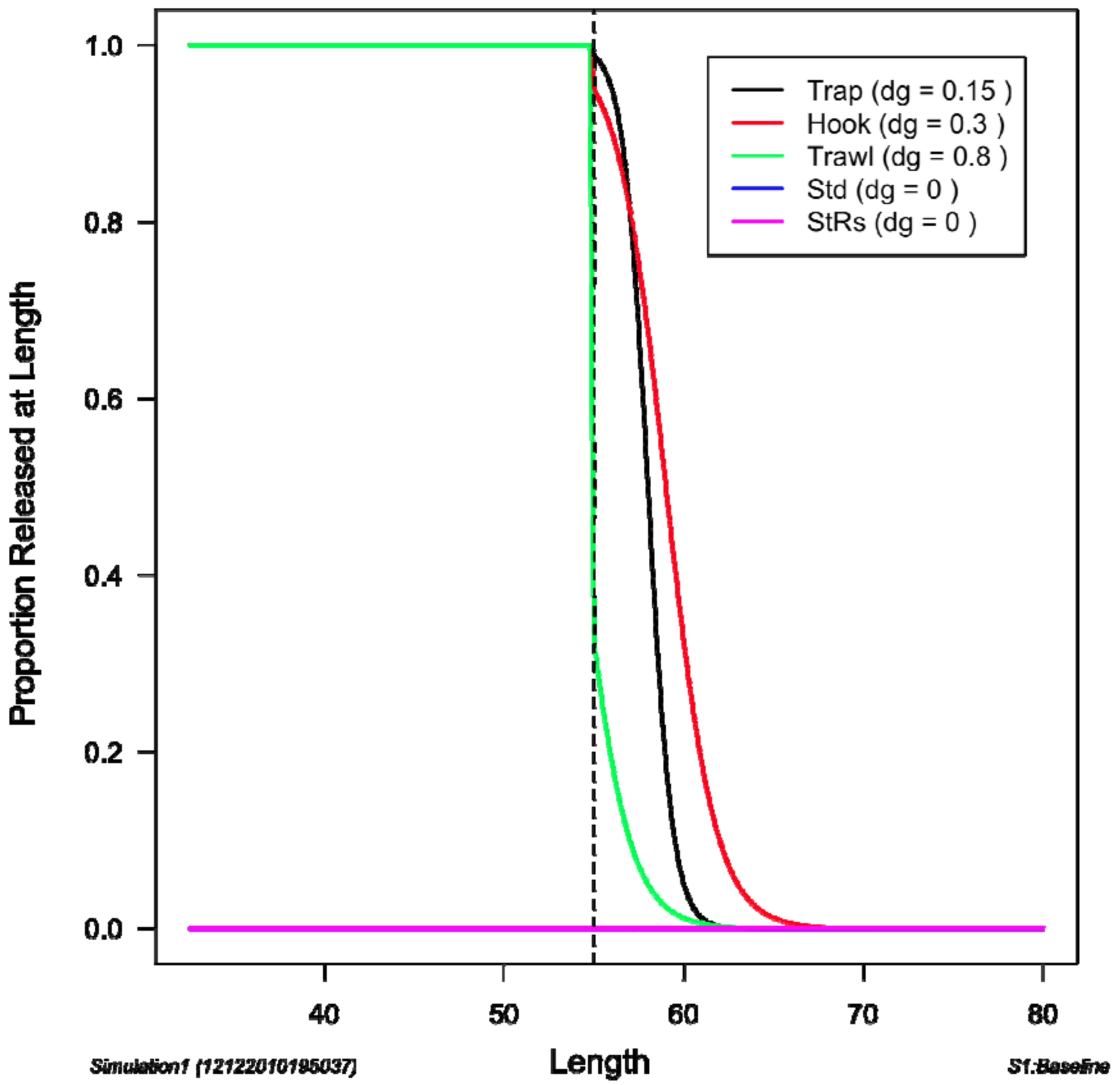

Figure D-4. Fishery and survey at-sea release rates as functions of length. Note: for black-and-white images, the order of gear types in the top panel (Proportion released = 0.2, left-to-right) is Trawl, Trap, and Hook. The flat lines along the bottom are for surveys that do not release fish at-sea. Values of "dg" in legend are assumed at-sea release mortality rates for this scenario.

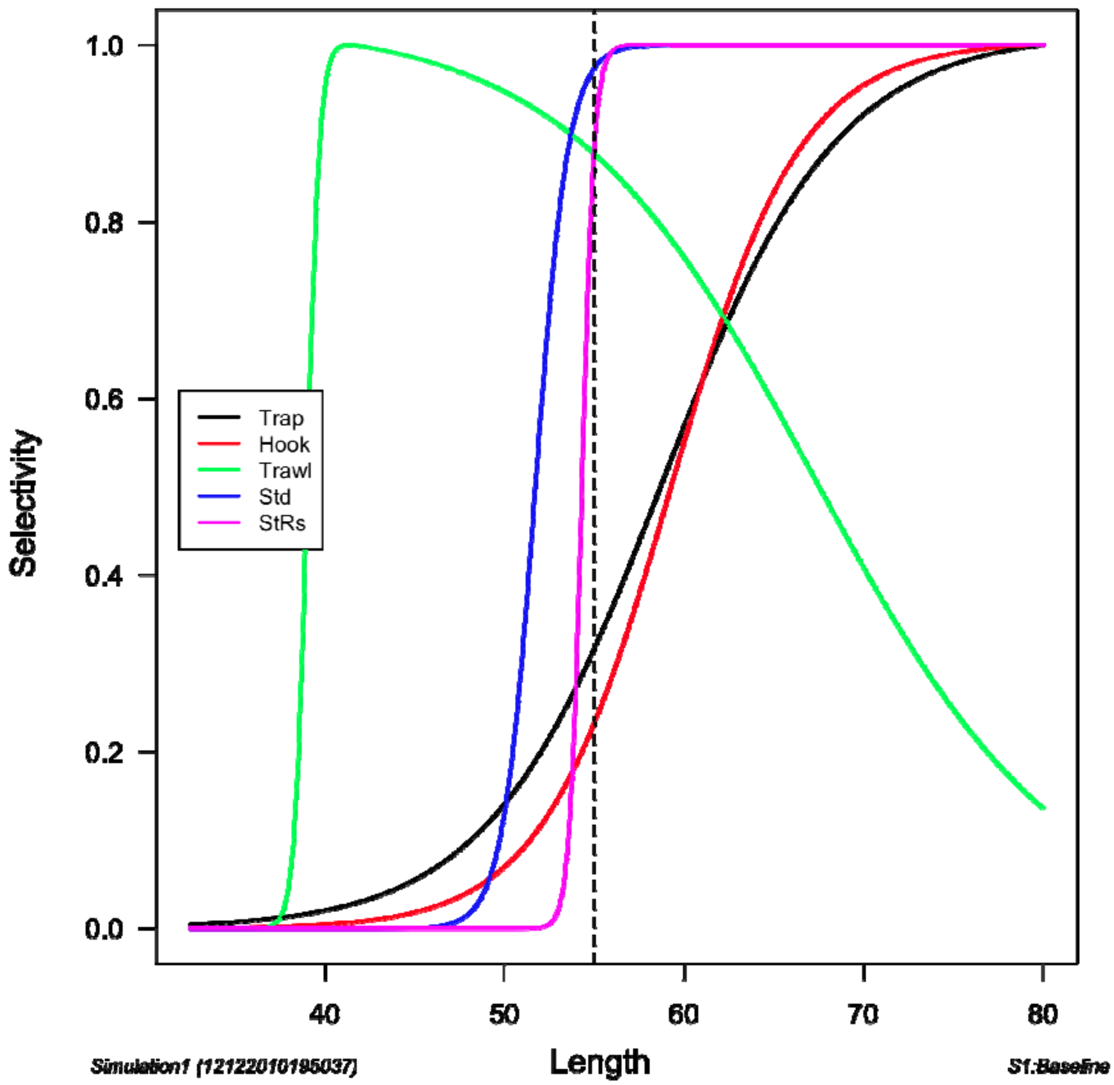

Figure D-5. Fishery and survey selectivity as a function of length. The order of gear types in the figure is Trawl, Std, StRs, Trap, and Hook from left to right at Selectivity=0.2.

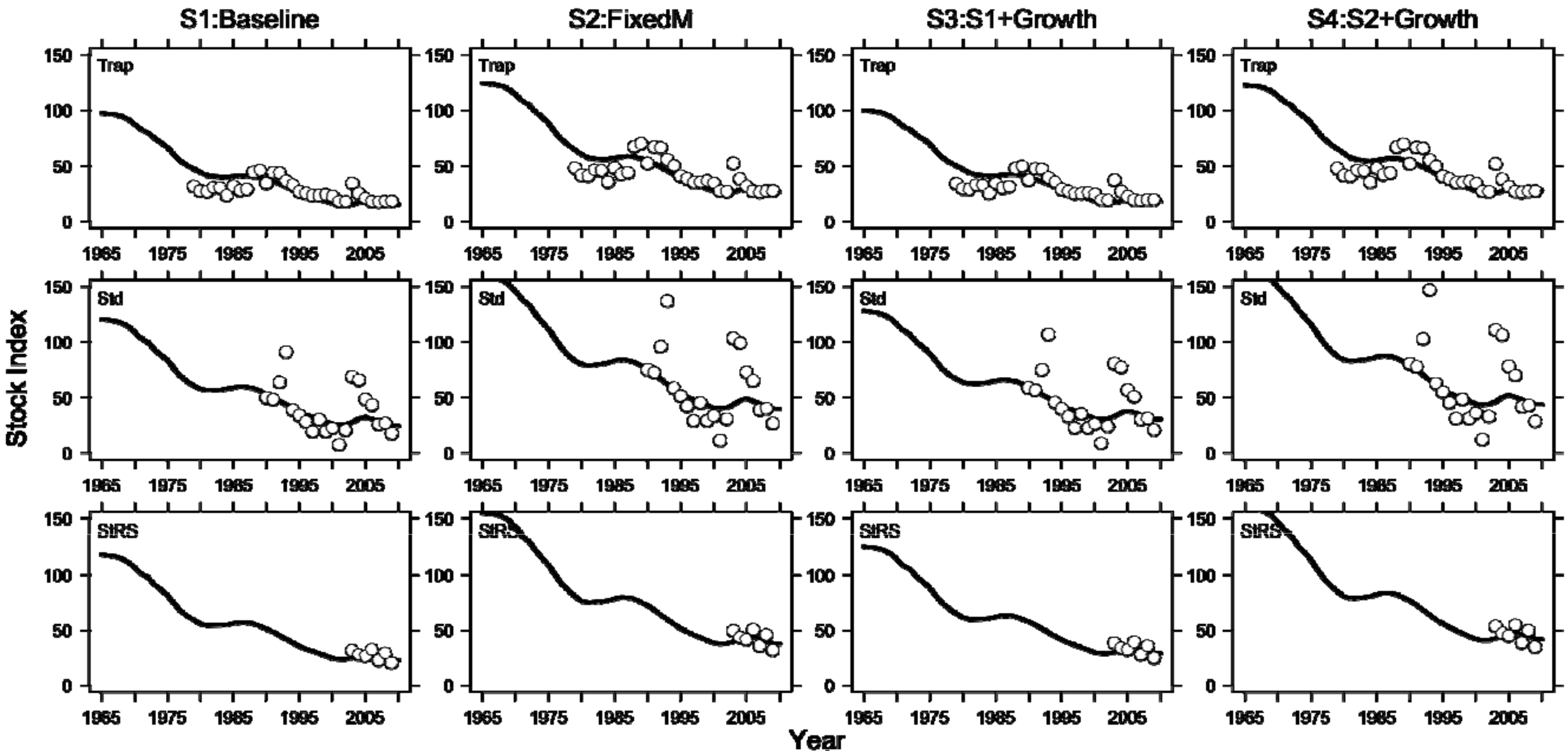

Figure D-6. Four operating model (columns) scenario fits to biomass index data obtained from the trap fishery (Row 1), standardized survey (Row 2), and stratified random survey (Row 3).

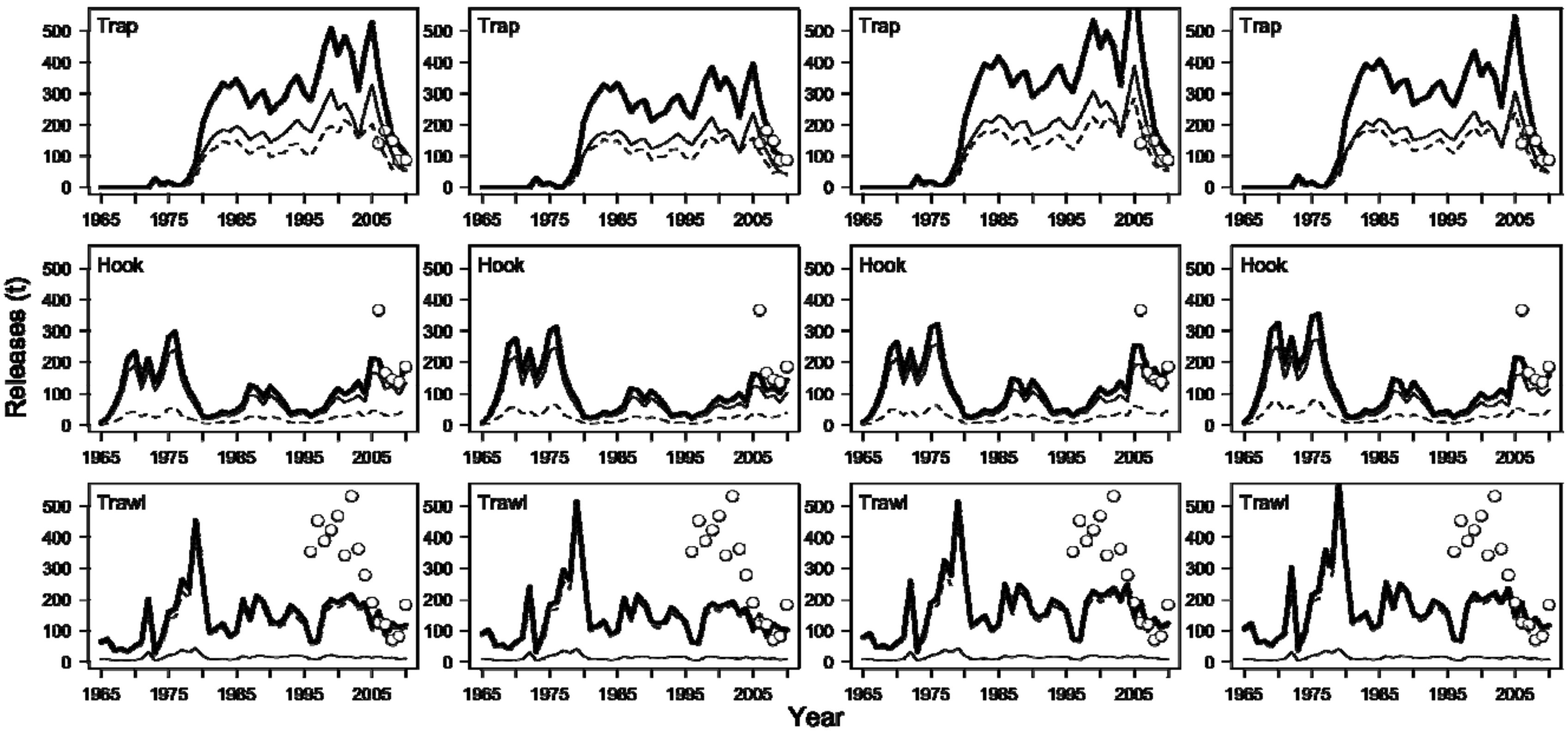

Figure D-7. Four operating model (columns) scenario fits to at-sea release data obtained from commercial fisheries – Trap (Row 1), Hook (Row 2), and Trawl (Row 3). At-sea release estimates are from electronically audited logbooks for Trap and Hook fisheries and at-sea observers for Trawl.

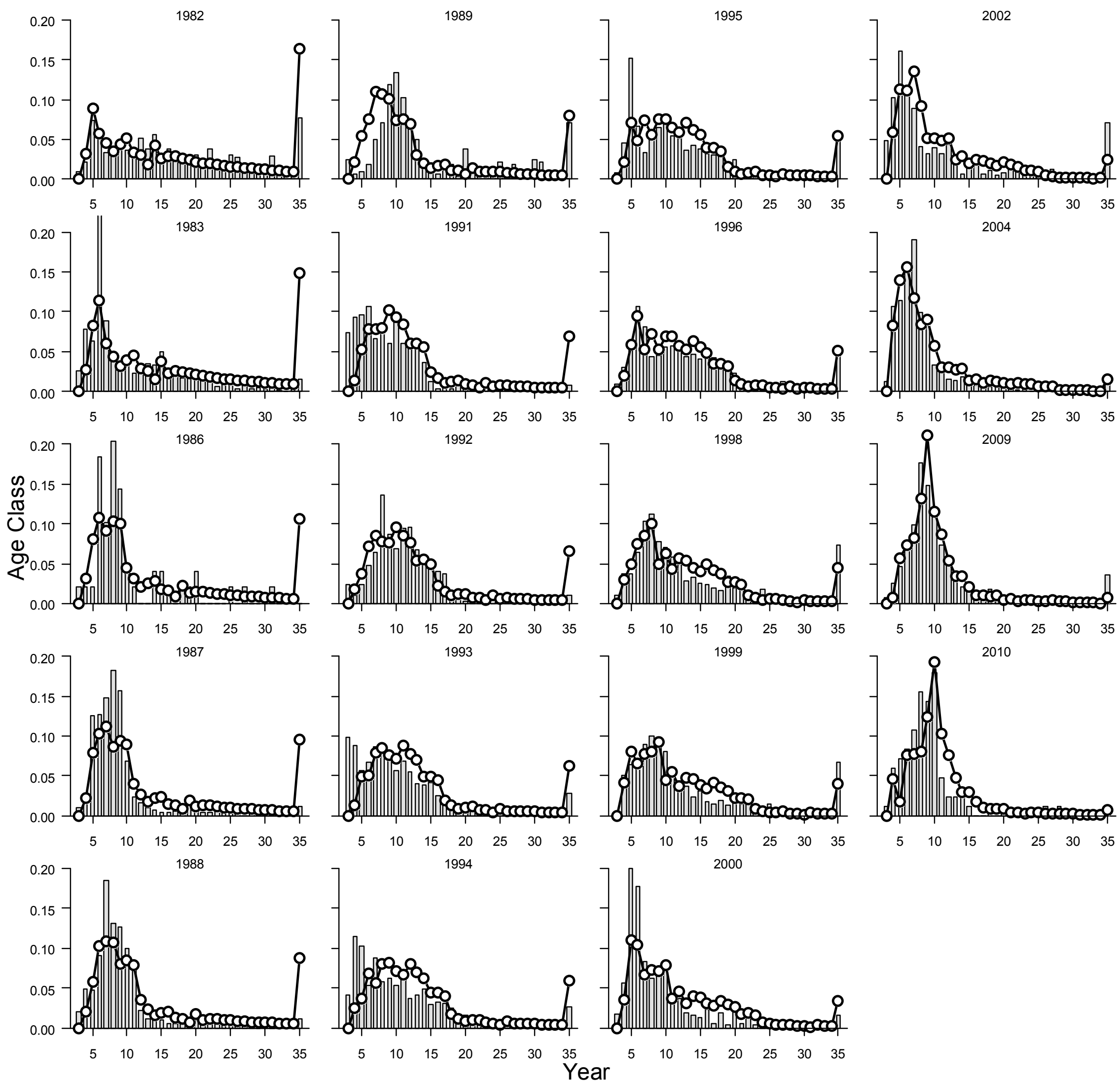

Figure D-8. Observed (bars) and predicted (lines and circles) proportion-at-age in the commercial Trap fishery.

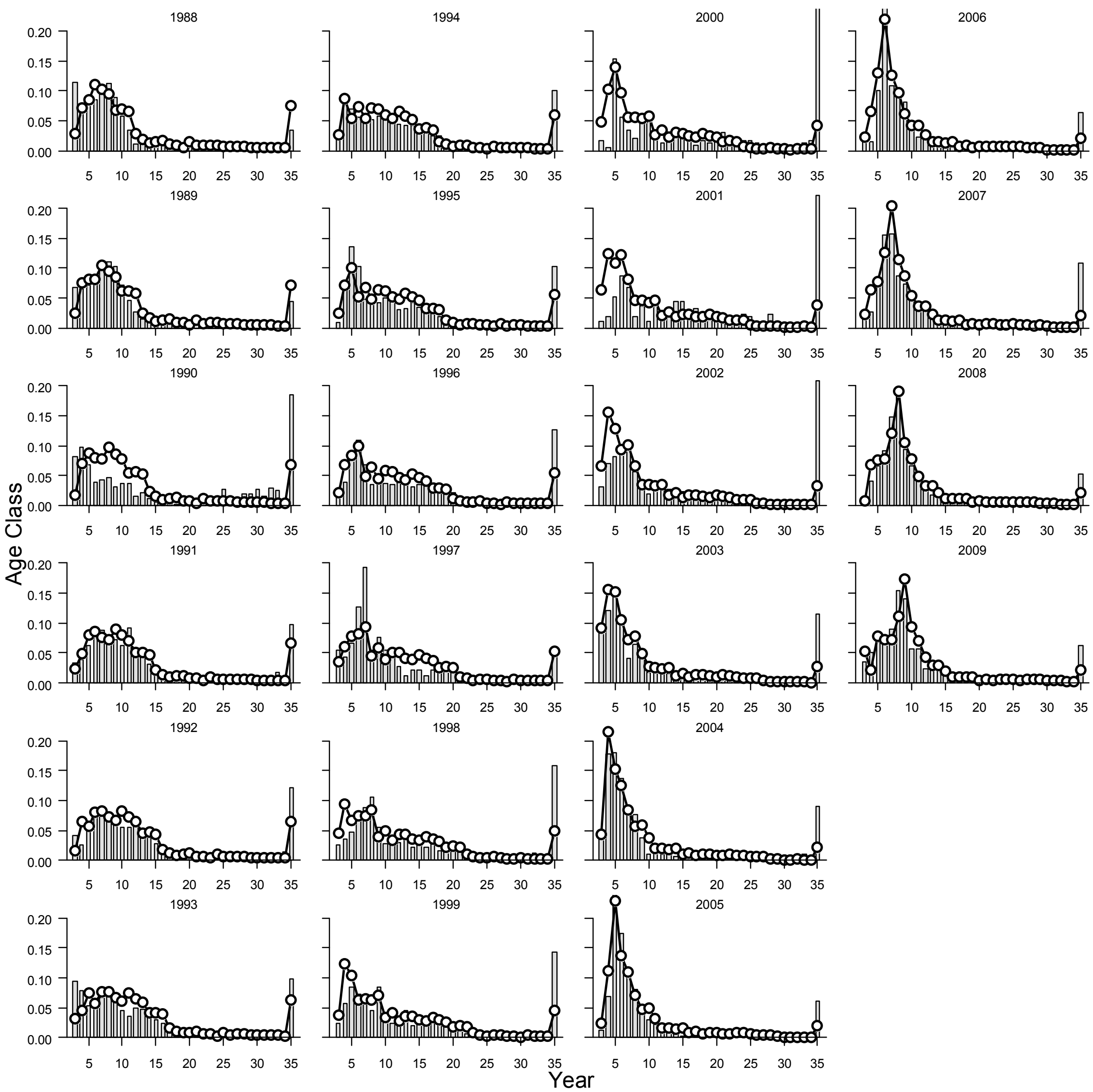

Figure D-9. Observed (bars) and predicted (lines and circles) proportion-at-age in the standardized survey.

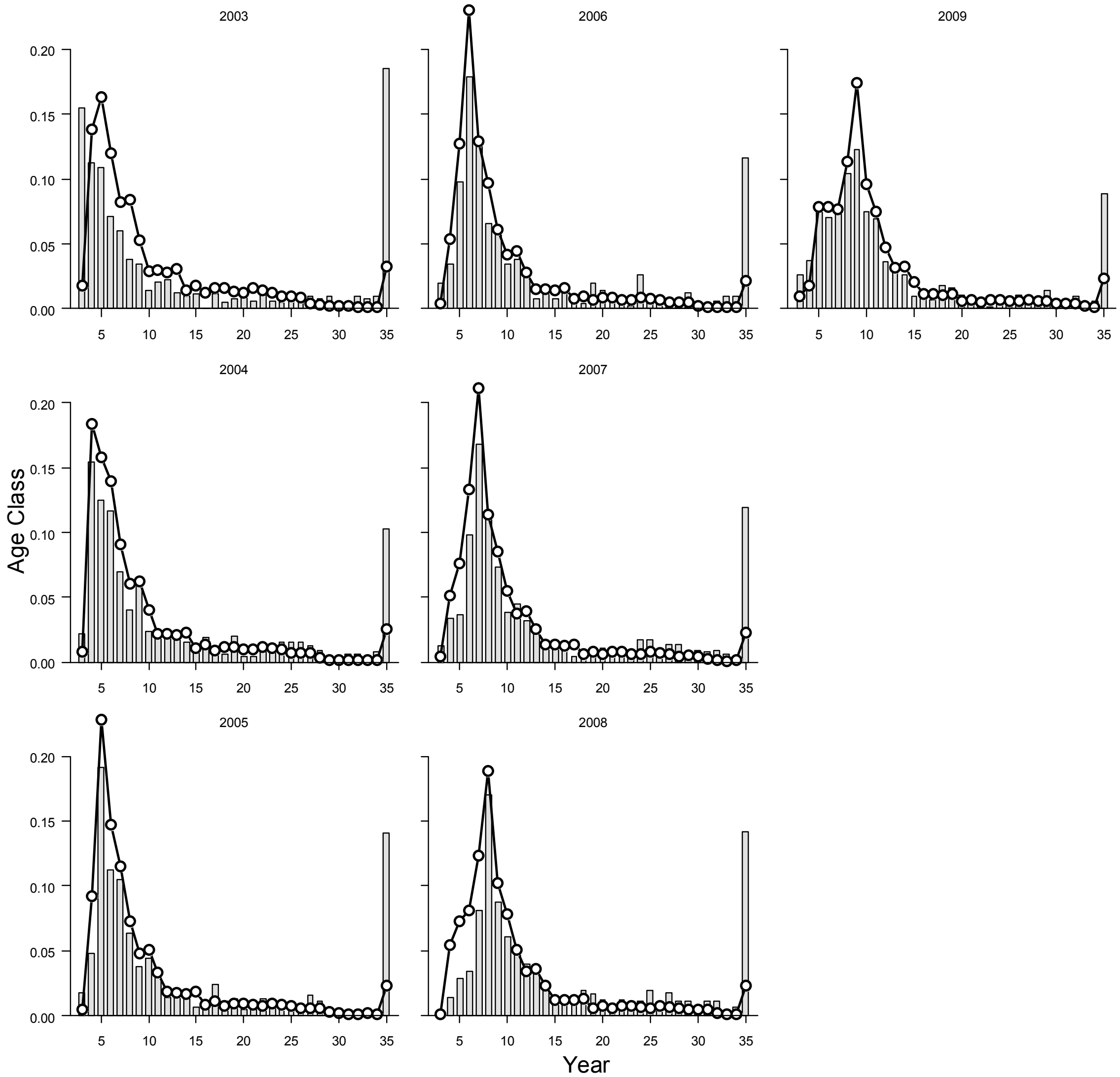

Figure D-10. Observed (bars) and predicted (lines and circles) proportion-at-age in the stratified random survey.

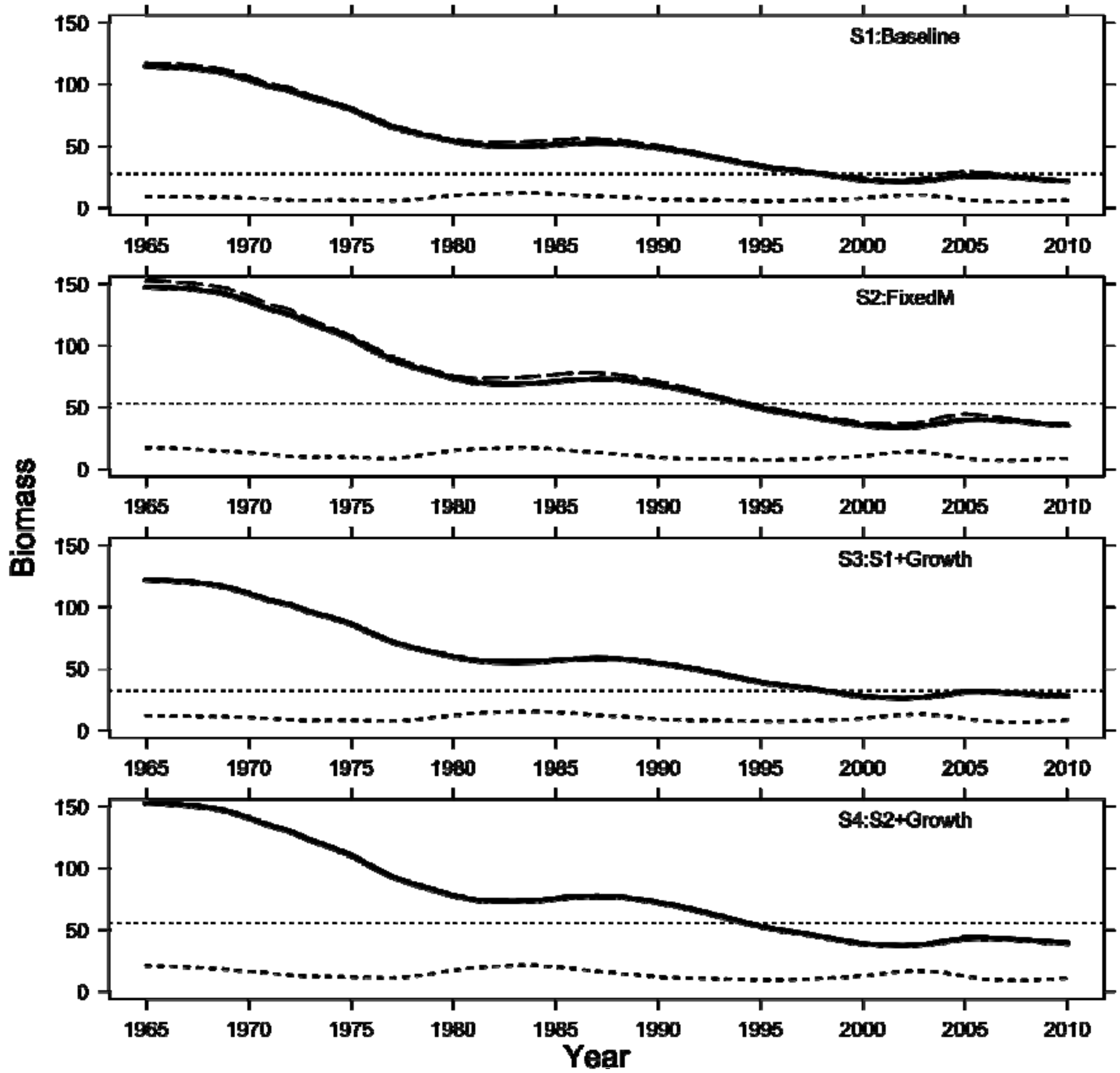

Figure D-11. Four operating model scenario estimates of sablefish spawning stock (solid lines), legal biomass (long-dashed lines), and sub-legal biomass (short-dashed lines) for 1965-2010. B^{MSY} for each scenario is indicated by a horizontal dotted line.

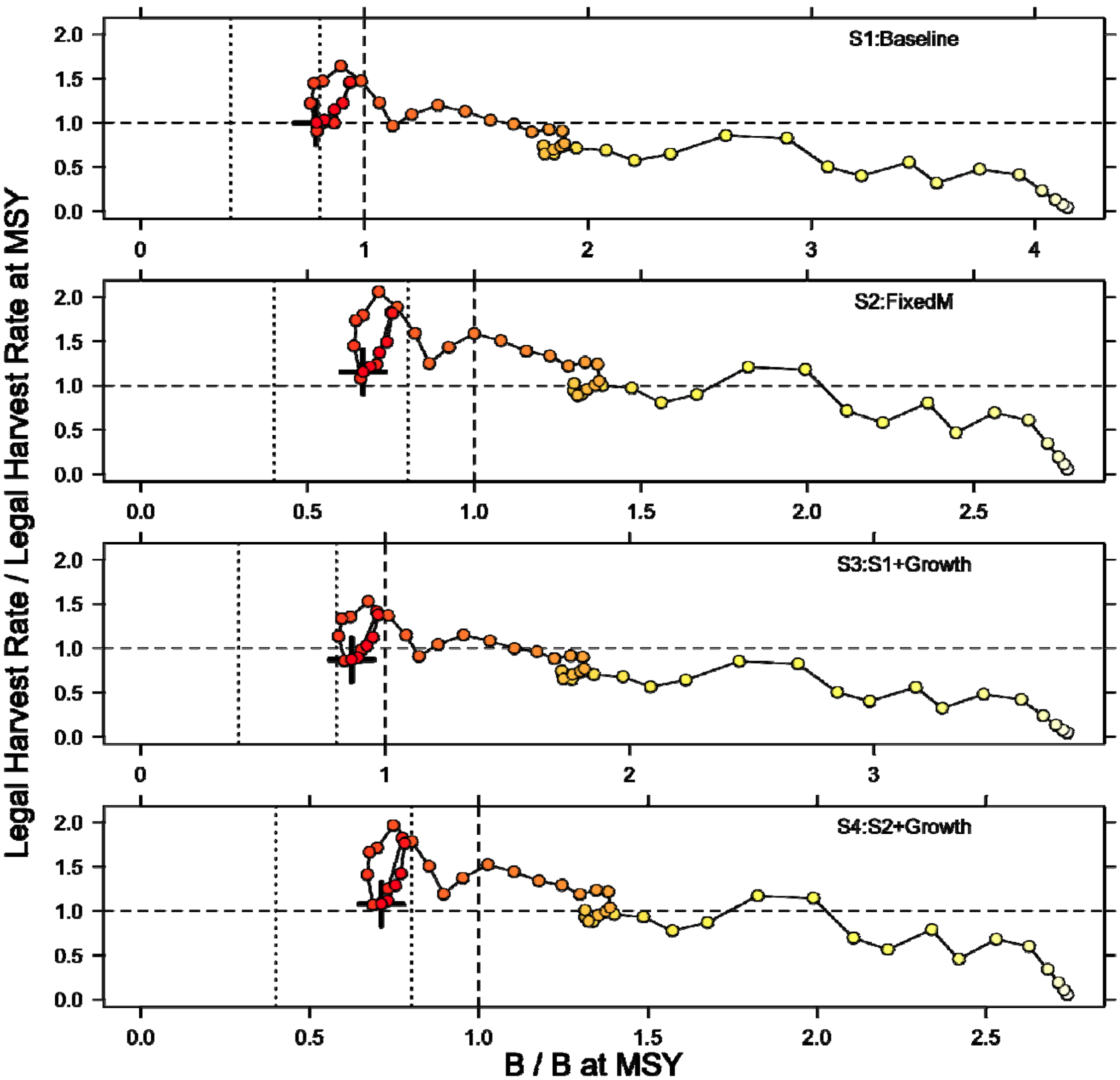

Figure D-12. Estimated phase trajectories of sablefish spawning biomass relative to B^{MSY} versus legal harvest rate relative to legal harvest rate at MSY *from 1965 (light shading) to 2010 (dark shading). The crosshair indicates the state estimate for 2010. The horizontal and vertical long-dashed lines separate the four state quadrants representing: Upper left - "over-fished and over-fishing"; Upper right – "not over-fished, but over-fishing"; Lower right – "not over-fished and not over-fishing"; and Lower left – "over-fished and not over-fishing".*

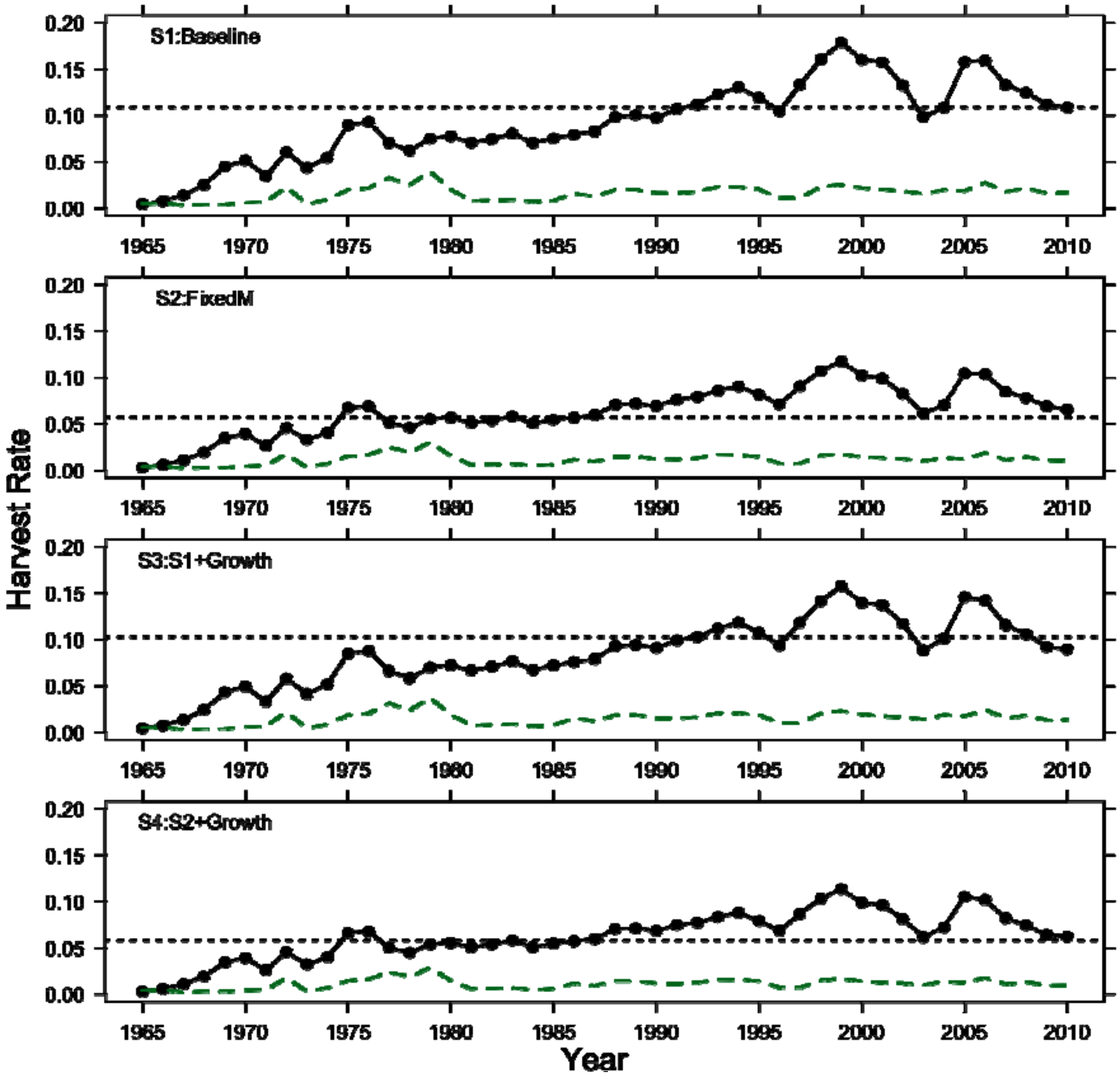

Figure D-13. Four operating model scenario estimates of the harvest rate on legal (solid lines and circles) and sub-legal (dashed lines) sablefish. The legal harvest rate at MSY for each scenario is shown by the horizontal dashed lines.

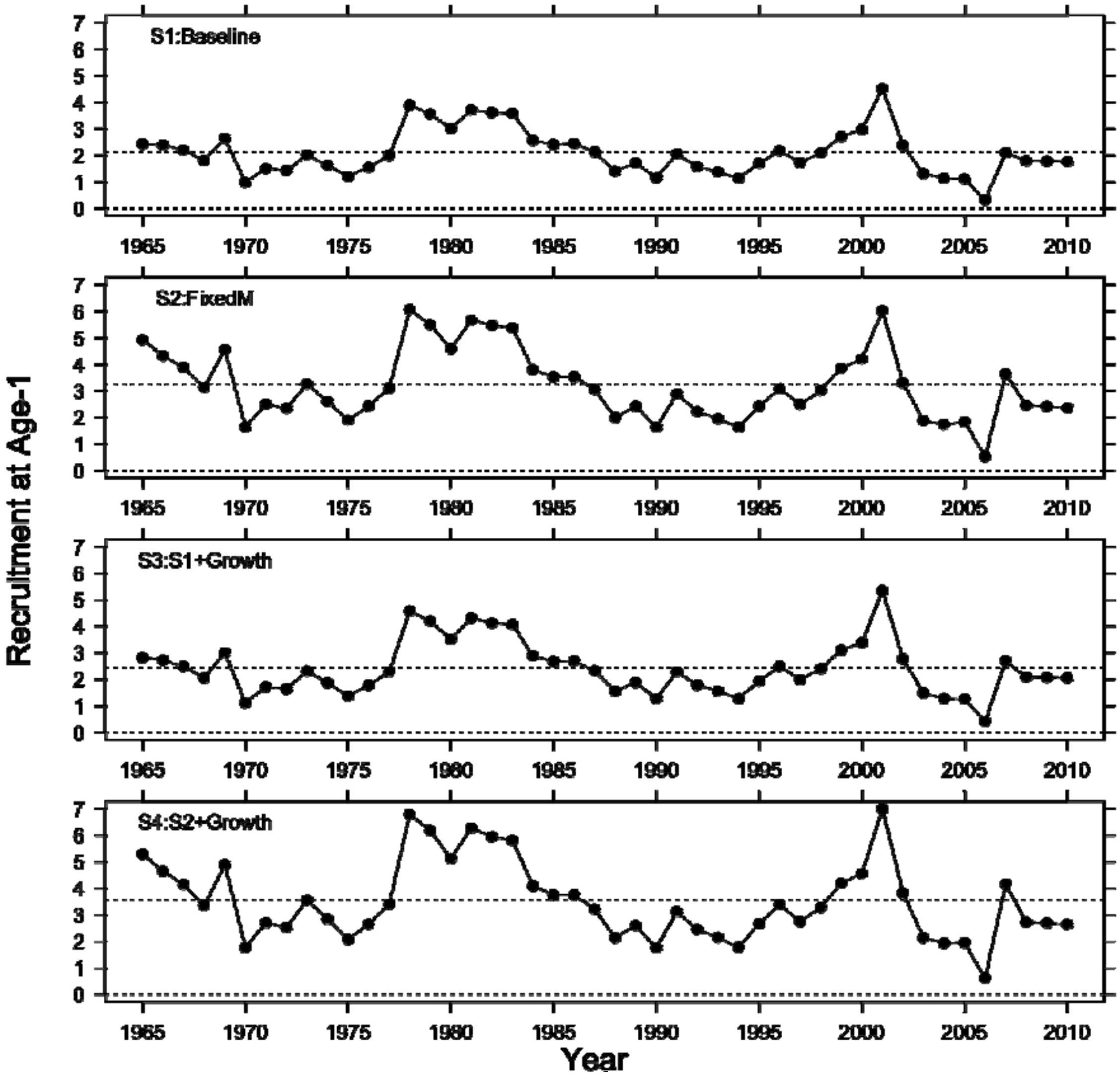

Figure D-14. Four operating model scenario estimates of sablefish age-1 recruitment. The average recruitment (excluding the last three years) is indicated by the horizontal dashed line.

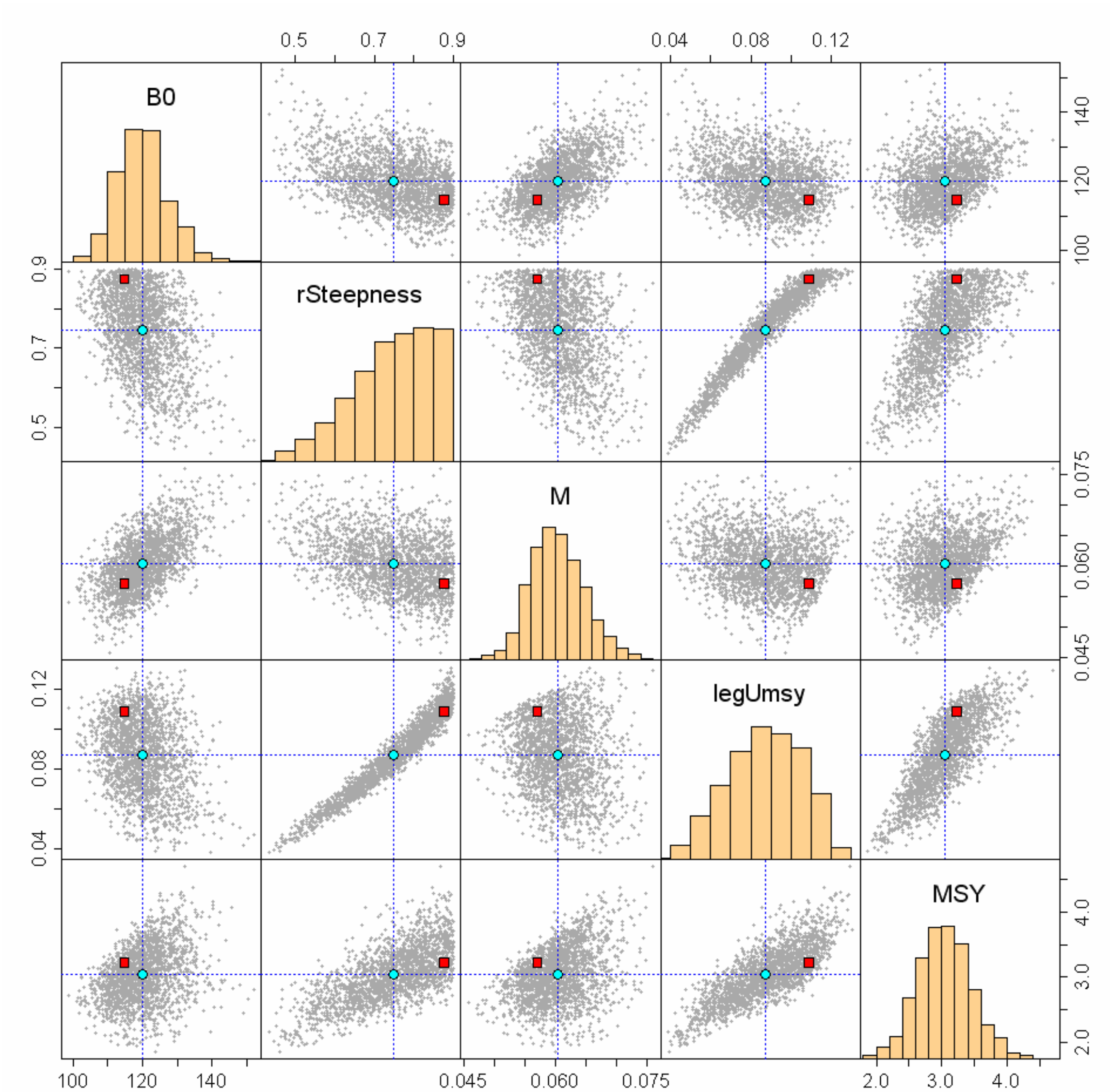

Figure D-15. Pair-wise and marginal (diagonal) distributions based on a sample of 2,000 points from the joint posterior for model S1. Parameters are: unfished spawning biomass (B0), stock-recruitment steepness (rSteepness), natural mortality (M), legal harvest rate at MSY (legUmsy), and MSY. Posterior means and maximum likelihood estimates are indicated by the blue circles and red square, respectively.

APPENDIX E PRODUCTION MODELS FOR MANAGEMENT PROCEDURE STOCK ASSESSMENTS.......

MODEL STRUCTURE

We use a Schaefer surplus production model for the annual stock assessment component of management procedures. Model notation and equations are listed in Table E-1 and Table E-2, respectively. The production model derives inferences about management parameters from time-series observations of total landed catch, and any combination of trap fishery CPUE, standardized trap survey CPUE, and stratified random trap survey CPUE. The assessment takes no account of legal and sub-legal discarding, even though both processes occur within the operating model.

Production models pool the effects of recruitment, growth, and natural mortality into a single production function to predict biomass in each year B_{t+1} based on four components: (*i*) the predicted stock present in the previous year B_t, (*ii*) an average production function $f(B_t)$ that depends on biomass, (*iii*) total landed catch C_t, and (*iv*) a random deviation ω_t from the average production relationship (Punt 2003). These components can be written into a production model of the form

(1) $$B_{t+1} = \left(B_t + rB_t\left(1 - B_t / K\right) - C_t\right)e^{\omega_t} ,$$

where B_t (tonnes) and C_t (tonnes) are the stock biomass at the start of year *t* $\left(t = 1, 2, \ldots, T+1\right)$ and catch biomass during year *t*, respectively and (*r,K*) are the usual logistic population dynamics growth rate and carrying capacity. The catch is assumed to be taken instantaneously and after production. The random production anomaly term ω_t is assumed independent of stock biomass and may represent, for example, the net result of (*i*) sablefish immigration into B.C. from Alaska or the lower west coast U.S., (*ii*) emigration out of the stock that is present in B.C. at any moment, and/or (*iii*) random deviations from the average production relationship within B.C. We assumed that production deviations, however they arise, are independent and identically distributed (Eq E2.1).

The Schaefer form assumes that fish production is a symmetric, dome-shaped function of existing stock biomass so that $U^{\text{MSY}} = r/2$ and $Y^{\text{MSY}} = rK/4$ define the optimum exploitation rate and maximum sustainable yield, respectively. The maximum sustained yield biomass level is $B^{\text{MSY}} = K / 2$. These quantities can be used by "passive adaptive" management strategies that attempt to steer fisheries exploitation toward theoretically optimal levels (c.f. Walters 1986 for full description of adaptive harvest policies). We re-parameterized equation (1) so that two management parameters, U^{MSY} and Y^{MSY}, are estimated directly. The resulting production model is given by equation E.2.6.

Indices of relative abundance for sources $g = 1, \ldots, G$ are used in estimating production model parameters via a linear observation model of the form

(2) $$I_{t,g} = q_g B_t e^{\xi_{t,g}} ,$$

where q_g is a constant catchability coefficient and $\xi_{t,g}$ is a normally distributed random observation error in year *t* for index *g*.

LIKELIHOOD FUNCTION

Different assumptions about how to allocate random deviations in the data to the stock dynamics (ω_t) or the observations ($\xi_{t,g}$) give different production model estimators. Assigning the total model error to the observations leads to an “observation error” estimator in which the stock dynamics are assumed to be non-random and exactly equal to that predicted by Equation 1 with $\omega_t = 0$ for all values of *t*. Thus, observation error models ignore inter-annual changes in stock biomass that may occur via unmodelled processes like natural mortality, immigration, emigration, or environmental influences on production. On the other hand, assigning all random error to the underlying stock dynamics by setting $\xi_{t,g} = 0$ in the observation model (Equation 2) for all values of *t* and *g* leads to a “process error” estimator in which the observations are assumed to be exact, i.e., $I_{t,g} = q_g B_t$, and thus inter-annual fluctuations in the data indicate changes in true stock biomass. For the process error estimator, the variance and individual terms ω_t must be estimated.

Inferences about the dynamics of fish stocks depend upon uncertainty in both the observations and the underlying population dynamics processes. Admitting both observation and process errors in the stock assessment model leads to errors-in-variables estimators in which some proportion ρ of the total error variance is assigned to the observations and the remainder 1- ρ is assigned to unmodelled changes in the underlying stock dynamics. Formally, errors-in-variables estimators define the total error variance, κ^2, as

(5) $$\kappa^2 = \tau^2 + \sigma^2 \quad .$$

If the observation error proportion $\rho = \tau^2 \big/ \left(\tau^2 + \sigma^2\right)$ is assumed known, the individual variance components can then be expressed as

(6) $$\tau^2 = \rho\kappa^2, \quad \sigma^2 = \left(1-\rho\right)\kappa^2 \quad ,$$

for observation and process errors, respectively. For our analysis, ρ is considered to act as a control or tuning parameter in the estimation procedure. As ρ approaches 0, the emphasis on process error will tend to allow for relatively large random changes in the estimated stock biomass from year to year, provided, of course, that possibly multiple abundance indices suggest the same direction and magnitude of change. Conversely, values of ρ near 1 will cause the model biomass to change deterministically in response to changes in fishery impacts; that is, the stock will only increase if catches are less than the deterministic surplus production. Experience gained through simulation of production model assessments (Cox et al. 2009) suggests that high values of ρ performed adequately for longer-lived species such as sablefish, so we set $\rho = 0.95$. The resulting negative log-likelihood function is given by E2.10.

PRIOR DISTRIBUTIONS

We used informative prior distributions on U^{MSY} and Y^{MSY} to tune the behaviour of the production model. Priors were both based on the normal distribution with means $\left(\mu^U, \mu^Y\right)$ and standard deviations $\left(\sigma^U, \sigma^Y\right)$, respectively. Specifying informative priors for the assessment model component of management procedures is similar to the approach taken in the International Whaling Commission’s Catch Limit Algorithm (Cooke 1999).

Table E-1. Notation for the surplus production stock assessment model.

Symbol	Description
	Indices and index ranges
T	Year in which stock assessment is performed
t	Year, where $t = 1, \ldots, T$
g	Stock index (fishery or survey), where $g = 1, \ldots, G$
n_g	Number of non-missing observations for the index g
i	Index for non-missing survey observations $i = 1, \ldots, n_g$
	Data
$C_{t,g}$	Catch biomass removed during year t by gear type g
$I_{t,g}$	Stock relative abundance observation for year t
	Leading model parameters
Y^{MSY}	Maximum sustainable yield
U^{MSY}	Optimal exploitation rate
	Nuisance parameters
q_g	Catchability coefficient for abundance index g
κ^2	Total error variance
ρ	Observation error proportion of total variance (assumed known)
	State variables
B_t	Biomass at the beginning of year t
	Derived reference points
B^{MSY}	Maximum sustainable yield biomass level
	Prior distributions
$N\left(\mu^Y, \sigma^Y\right)$	Normal prior on Y^{MSY}
$N\left(\mu^U, \sigma^U\right)$	Normal prior on U^{MSY}
	Statistical error distributions
$\xi_{t,g} \sim N\left(0, \rho\kappa^2\right)$	Observation error in year t for index g
$\omega_t \sim N\left(0, (1-\rho)\kappa^2\right)$	Process error in year t

Table E-2. Mixed-error surplus production model used for annual stock assessments within management procedure simulations.

Model parameters

E2.1 $$\Theta = \left(U', Y', \{\omega_t\}_{t=1}^{t=T-1}\right)$$

Parameter transformations

E2.2 $$U^{\text{MSY}} = \exp(U')$$

E2.3 $$Y^{\text{MSY}} = \exp(Y')$$

Biomass dynamics model

E2.4 $$B_1 = 2Y^{\text{MSY}} / U^{\text{MSY}}$$

E2.5 $$B^{\text{MSY}} = Y^{\text{MSY}} / U^{\text{MSY}}$$

E2.6 $$B_{t+1} = \begin{cases} \left(B_t + 2U^{\text{MSY}} B_t \left(1 - \frac{B_t}{2B^{\text{MSY}}}\right) - \sum_{g=1}^{G} C_{t,g}\right) e^{\omega_t} & 1 \le t \le T-1 \\ B_t + 2U^{\text{MSY}} \left(1 - \frac{B_t}{2B^{\text{MSY}}}\right) - \sum_{g=1}^{G} C_{t,g} & t = T \end{cases}$$

Residuals

E2.7 $$\xi_{t,g} = \log_e\left(I_{t,g} / B_t\right)$$

Conditional maximum likelihood estimates

E2.8 $$\widehat{\log q_g} = \frac{1}{n_g} \sum_{i=1}^{n_g} \xi_{i,g}$$

E2.9 $$\hat{\kappa}^2 = \frac{1}{n. + T - 1} \left(\frac{1}{\rho} \sum_{g=1}^{G} \sum_{i=1}^{n_g} \left(\xi_{i,g} - \widehat{\log q_g}\right)^2 + \frac{1}{1-\rho} \sum_{t=1}^{T-1} \omega_t^2 \right)$$

Negative log-likelihood and objective function

E2.10 $$\ell(\mathbf{I} \mid \Theta) = \frac{n. + T - 1}{2} \log_e \left(\frac{1}{\rho} \sum_{g=1}^{G} \sum_{i=1}^{n_g} \left(\xi_{i,g} - \widehat{\log q_g}\right)^2 + \frac{1}{1-\rho} \sum_{t=1}^{T-1} \omega_y^2 \right)$$

E2.11 $$G(\Theta \mid \mathbf{I}) \propto \ell(\mathbf{I} \mid \Theta) + \frac{1}{2\left(\sigma^Y\right)^2}\left(Y^{\text{MSY}} - \mu^Y\right)^2 + \frac{1}{2\left(\sigma^U\right)^2}\left(U^{\text{MSY}} - \mu^U\right)^2$$