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A Revised Operating Model for Sablefish in British Columbia, Canada in 2016

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Fisheries and Oceans Canada (DFO) and the British Columbia (BC) Sablefish (*Anoplopoma fimbria*) fishing industry have collaborated on a management strategy evaluation (MSE) process since 2009. This process is used to develop and implement a transparent and sustainable harvest strategy for the multi-gear Sablefish fishery. Variations of age-structured models have been used in simulation testing candidate management procedures and therefore represent the cornerstone of the MSE process. In this paper, we revise the Sablefish operating model to account for potential structural model misspecification and lack-of-fit to key observations recognized in previous models. Specific modifications include: (i) changing from an age-/growth-group operating model to a two-sex/age-structured model to account for differences in growth, mortality, and maturation of male and female Sablefish, (ii) adjusting model age-proportions via an ageing error matrix, (iii) testing time-varying selectivity models, and (iv) revising the multivariate-logistic age composition likelihood to reduce model sensitivity to small age proportions.

These structural revisions to the operating model improved fits to age-composition and at-sea release data that were not well-fit by the previous operating model. Accounting for ageing errors improved the time-series estimates of age-1 Sablefish recruitment by reducing the unrealistic auto-correlation present in the previous model results. The resulting estimates clearly indicate strong year classes of Sablefish that are similar in timing and magnitude to estimates for the Gulf of Alaska. Two unanticipated results were obtained. First, time-varying selectivity parameters were not estimable (or necessarily helpful) despite informative prior information from tagging. Second, improved recruitment estimates helped to explain the scale and temporal pattern of at-sea release in the trawl fishery. The latter finding represents a major improvement in our ability to assess regulations and incentives aimed at reducing at-sea releases in all fisheries. Estimates of Sablefish stock status, productivity, and trends over the past several years are consistent with previous harvest strategy simulations. Estimated exploitation rates for years 2011-2015 varied across seven data scenarios (~8-10%) but are consistent with exploitation rates projected for the current U60-40+Floor management procedure under the former operating model.

1. INTRODUCTION

Fisheries and Oceans Canada (DFO) and the British Columbia (BC) Sablefish (*Anoplopoma fimbria*) fishing industry collaborate on a management strategy evaluation (MSE) process intended to develop and implement a transparent and sustainable harvest strategy (Cox et al. 2013; Cox et al. 2011).

The existing Sablefish harvest strategy is defined by four components:

1. operational fishery objectives used to assess the acceptability of alternative management procedures;
2. a management procedure (MP) that involves:
   a. data - total landed catch and three abundance indices.
   b. an assessment method – a tuned Schaefer state-space production model, and
   c. a segmented harvest control rule defined using B_{MSY} and F_{MSY} values estimated from the production model along with the estimated exploitable biomass;
3. a simulation-based evaluation of management procedure performance against alternative operating models that represent selected hypotheses about Sablefish stock dynamics; and
4. application and monitoring of the MP in practice.

The MP selected as part of the MSE process conducted in 2010 (Cox et al. 2011) was applied as designed for 2011-2012, inclusive, but was modified to include a total allowable catch (TAC) Floor for 2013-2015 (DFO 2013). The TAC Floor adjustment was also simulation-tested in DFO (2014) to confirm that an acceptable trade-off of conservation and yield objectives could be expected.

Harvest strategy components 1-3 were developed at the same time (Cox et al. 2011; Cox et al. 2013) with the consequence that a detailed evaluation of the operating model (OM) quality and fit to historical data was not conducted. The issue of OM quality and fit to historical data was also recognized in 2010 and 2011 peer reviews (DFO 2011) that specifically identified three areas for improvement:

1. **Assessing Sablefish model structure and fit.** A combined-sex statistical catch-at-age operating model was used for the 2010 simulations. However, Sablefish growth is sexually dimorphic, with females growing to larger sizes at older ages, which could increase (or decrease) their selectivity in some fisheries. The 2010 operating model used a growth group formulation to account for effects of large variability in size-at-age on size-based discarding. However, fits to the relatively large accumulator age-class at age-35+, or “plus group”, in the catch-at-age matrix were generally poor. Reasons for the lack of fit were not fully investigated but were suspected to arise from a combination of constant selectivity assumptions, ageing errors, sensitivity of the age-composition likelihood to small proportions, and possibly immigration/emigration of adult fish from/to Sablefish populations outside BC.
2. **Fitting at-sea releases in the commercial trawl fishery.** The 2010 Sablefish operating model was used to evaluate whether MPs aimed at reducing at-sea releases of under-sized Sablefish (< 55 cm length) would improve overall fishery performance against objectives. Closed-loop simulations indicated only small benefits from MPs that included: maintaining the current 55 cm legal size limit, incentives for avoiding sub-legal Sablefish (assuming these would be 100% effective) and retaining all Sablefish regardless of size. The small effects of what seemed like substantial management measures were attributed primarily to

the assumption that trawl selectivity was constant over time. The 2010 operating model could not fit observations for at-sea releases in the trawl fishery that ranged from 200 t to 800 t in the 1990s and early 2000s. Residual patterns in the fits to at-sea releases suggested that trawl selectivity may have shifted in recent years compared to the 1996-2006 period. Uncertainty associated with the size-based at-sea release functions and post-release mortality rates were thought to be less important factors.

3. **Survey indices of abundance.** The International Pacific Halibut Commission longline hook survey was suggested as a potential source of abundance indexing data. Other potential sources include a Sablefish trap survey conducted in four mainland inlets, four fishery-independent bottom trawl surveys, as well as two shrimp bottom trawl surveys. These surveys were not included in the 2010 analyses – or in this assessment – because none are designed to survey the BC Sablefish population. Individual survey differences in spatio-temporal coverage and gear efficiency would lead to differences in Sablefish availability and selectivity that would further complicate the model. Furthermore, none of these alternative surveys have reliable age-composition data from which to estimate selectivity except the mainland inlets Sablefish survey. However, that survey is an *ad hoc* design, and most fish are unavailable to the fishery due to a directed Sablefish fishery closure. Therefore, alternative surveys are assessed qualitatively for relevance and trend in Appendix C and will not be discussed further in this main document.

This paper addresses these three issues by:

1. Developing a two-sex statistical catch-age model to replace the combined-sex growth-group model used in 2010. Although the model structure has changed, the likelihood formulations are largely the same except for a minor change in the age-composition likelihood that accumulates all age proportions less than 0.005 into a single accumulator bin. This change reduces model sensitivity to small proportions that inevitably arise for long-lived species.
2. Testing whether an ageing error matrix (Appendix F) applied to the model age proportions would improve model fit to observed age-composition, improve overall stability, and reduce auto-correlation in estimated recruitment. Ageing error is not well-understood or documented for the Canadian Sablefish ageing lab, so we based our ageing error matrix on one developed for Gulf of Alaska Sablefish (Hanselman et al. 2012).
3. Evaluating whether time-invariant and time-varying fishery selectivity estimated from the Sablefish tagging program would improve model fit to age composition and, especially, the model fit to at-sea releases by the trawl fishery (Appendix E). Tagging-based estimates of selectivity parameters are used as priors for fisheries, especially longline hook and trawl fisheries that lack age-composition data.
4. Updating fishery catch and at-sea releases (Appendix A, B) as well as the Sablefish stratified random survey series (Appendix C) and age-composition (Appendix D).

2. METHODS

2.1. TWO-SEX STATISTICAL CATCH-AT-AGE MODEL

The new Sablefish operating model is a two-sex/age-structured model fitted to fishery-specific landed catch (1965-2015), indices of total abundance and age-composition for the Trap fishery (1990-2009), Standardized Survey (1991-2009), and Stratified Random Survey (2003-2014), and at-sea releases (2006-2015) in each of commercial longline trap, longline hook, and trawl fisheries. Model notation and equations are given in Table 1 to Table 3, respectively.

The OM partitions the base model parameters into four subsets consisting of leading parameters (Θ^{est}), nuisance catchability and variance parameters estimated conditionally on the leading parameters (Θ^{cond}), fixed parameters for growth, maturity, discard mortality rates, and selectivity parameters that are not estimated (Θ^{fixed}), and parameters specifying the prior distributions (Θ^{priors}) for some of the leading parameters. Parameter membership in the fixed and estimated sets will differ from the base model for the alternative data scenarios considered in this analysis.

The OM is driven by a Beverton-Holt stock-recruitment function (Beverton and Holt 1957) parameterized via stock-recruitment steepness (h), unfished female spawning biomass (β_0), and uncorrelated process deviations (ω_t) from the average relationship. Fishing mortality rates by year and fishery ($F_{t,g}$) are either:

a. estimated directly as free parameters (in the base model) assuming that catch is known with error, or

b. obtained via a numerical solution to the Baranov catch equation assuming that gear-specific catches are known without error.

Natural mortality rates for males (M_m) and females (M_f) are either estimated independently (given identical prior distributions) or fixed *a priori*. Finally, selectivity is assumed to depend on length, which allows us to use only one selectivity function for both sexes. In addition, we use length because the tagging estimates of fishery selectivity are only available based on length.

2.2. GROWTH, SELECTIVITY, PROPORTION RETAINED AT AGE, AND MATURITY

Sablefish mean length (cm) for age-a is modeled using a von Bertalanffy growth function with parameters $(L_{\infty,x}, k_x)$ (Figure 1; OM.2) estimated from biological data collected on Sablefish surveys. We use the sex-specific base model growth rates $k_m = 0.29, k_f = 0.25$, which we obtained from review of the literature (Appendix D). Estimated growth rates from biological samples obtained in BC $k_m = 0.50, k_f = 0.39$ were considerably higher, so we save this issue for possible alternative operating models in management strategy simulations.

Selectivity-at-age (OM.4) is parameterized based on length-at-age because, as noted above, estimates from tagging data are only available based on length. The tagging-based estimates are needed because both longline hook and trawl fisheries provide no age-composition data for which age-based selectivity could be estimated. Selectivity parameters estimated from tagging based on the dome-shaped (Normal) models were used to parameterize log-normal prior distributions on selectivity parameters for trap (Appendix E, 2N.3 model), longline hook (Appendix E, 2N.3) (both time-invariant), and normal priors on the peak and spread (σ) selectivity parameters for trawl (Appendix E, 2N.2) fisheries. We attempted to allow time-varying selectivity for each fishery, but models with constant selectivity tended to be more stable and provided better fits, especially for at-sea releases.

At-sea release of sub-legal Sablefish (i.e., < 55 cm fork length) is a key process to be tested in future harvest strategy simulations. Therefore, we explicitly modeled the proportions of Sablefish retained ($P_{g,a,x}$) as well as released at-sea (conditional on being captured in the first place) ($1 - P_{g,a,x}$) given a fixed distribution of length at age-*a* (OM.5). We obtained $P_{g,a,x}$ by computing the proportion of the normal probability density function $N(L_{\infty,x}, \sigma_L^2)$ that lies above the size limit. The integration in OM.5 is performed numerically once for each model in AD Model Builder via the **adromb()** function since the growth parameters and legal size limit are all constants (Fournier et al. 2012).

Maturity-at-age of female Sablefish is estimated from biological samples obtained from fishery-independent trap surveys (Figure 1). It is likely that estimates of age-at-50% and age-at-95% maturity are biased downwards relative to the population because we do not account for size-selectivity in the sampling the population (Appendix D.4).

2.3. STATE DYNAMICS

We assume that the numbers-at-age in 1965 (OM.8) reflect an unfished equilibrium state. We chose this because there was little observed catch prior to 1965 and age-composition data were not available until 1988. This means that the initial abundances-at-age are not estimable, as we confirmed in preliminary model testing. The unfished spawning biomass-per-recruit (ϕ, OM.7) is computed based on natural mortality, weight-at-age, and maturity-at-age of female Sablefish (see Cox et al. 2011 for equilibrium calculations). Equations OM.9-OM.11 give the stochastic Beverton-Holt recruitment and age-structured model dynamics.

When year-/gear-specific fishing mortality rates are estimated as free parameters, they are parameterized based on

a. the log-F value (OM.12) in the first year (t_1) where catch is greater than zero; and

b. a random walk away from this value based on annual deviations ($\delta_{F,t}$).

Equation OM.13 gives the modified catch equation, which is adjusted for the proportion of fish retained as computed from OM.5. The predicted biomass released at-sea is given in OM.14. The effect of at-sea release on total mortality depends on gear-specific post-release mortality rates (d_g) that we obtained from review of the literature (Appendix D.7).

2.4. OBSERVATION MODELS

Biomass index observations consist of catch rate (CPUE) observations from the fishery, standardized survey, and stratified random survey. We use fishery CPUE (1988-2009), reluctantly, because it is the only time-series that extends into the 1980s when some of the largest and most influential cohorts entered the fishery and dominated the dynamics for many years. The fishery CPUE series extends back to 1979, but we removed the 1979-1987 observations because the trap fishery was just beginning at that time and catch rates appeared qualitatively different (and lower). In previous studies, we modeled time-varying catchability, as well as time-blocked fishery catchability, and neither had strong impacts on the model estimates probably because the model never fit those observations well in the first place; fits and estimated abundance trends with or without the 1979-1987 observation are similar. Finally, we truncated the fishery CPUE and standardized (Std) survey series as of 2009 based on simulation analyses (Cox et al. 2011). The stratified random survey (StRS) is now the main source of fishery-independent abundance trend information for BC Sablefish.

We modeled each of the biomass indices assuming constant catchability (q_g), constant selectivity, and that the index is obtained after some fraction f_S of the year has expired

(OM.18). For the fishery, we assumed that CPUE was taken halfway through the year f_S = 0.5, while f_S = 0.75 for the surveys that occur in October and November. Selectivity has time subscripts in OM.18 to allow for possible scenarios involving changes over time in fishery selectivity. Unlike catchability, tagging data exist to provide information about how fishery length-based selectivity might have changed since the 1990s (Appendix E).

Information about changes in population age-structure consists of proportions-at-age in trap fishery catches (1982-2014 with several missing years), standardized surveys (1990-2009), and the stratified random survey (2003-2014). Fishery age proportion samples are available back to 1979; however, we dropped 1979-1980 data because the samples appeared qualitatively different and would require year-effects parameters to obtain any reasonable model fits. In general, the fishery age composition data show weak coherence in tracking Sablefish cohorts over time (Appendix D.5, Figure D-4 and D-5). The observation model for these proportions is in OM.19 and OM.20, where the latter adjusts the true age proportions to account for ageing errors; that is, the ageing error matrix (see below) multiplied by the true proportions gives the predicted observed proportions that we use in the computing the likelihood function.

The survey age proportions (Figure D-6 through Figure D-9) generally show better coherence in cohort tracking over time with the stratified random survey being the most consistent. Also, it appears that female age composition data show clearer cohort patterns compared to males. This could arise from differences in ageing errors (see below) and/or differences in movement in/out of BC; however, recent strong cohorts in BC should be similar to those observed for Alaska and the lower US states, so we doubt that it arises from variation in movement. Age selectivity (i.e., via length-based selectivity) is assumed constant for surveys even though these have time subscripts in OM.19.

2.5. AGEING ERROR MATRIX

One of the main objectives of this paper is to determine whether accounting for ageing errors would improve assessment model behaviour; specifically, giving estimates of recruitment that were not strongly auto-correlated. Although the existing auto-correlated (AR) estimates are not particularly plausible, we have included AR recruitment scenarios in harvest strategy simulations (Cox et al. 2011) until we obtain recruitment series that indicate otherwise.

An ageing error matrix describes how the true proportions-at-age are spread among adjacent age classes as a result of under-/over-estimation of fish ages. We develop an ageing error matrix $\mathbf{Q}$ based on Hanselman et al. (2012) who used known-aged fish from tagging studies to develop an ageing error relationship for fish aged 3-18 years. Their results indicated that Sablefish ages tend to be under-estimated more as fish get older. Figure 2 includes our interpretation of their model via R code (R Core Development Team 2015) to compute $\mathbf{Q}$.

Hanselman et al. (2012) did not mention how their ageing error could be applied to a stock assessment model with a potentially large accumulator age class (i.e., the plus group). Here, we assumed that their geometric model parameter values for ages 10-18 extended to all fish aged 18+. Their model also assumed that ageing errors greater than |10| years do not occur; therefore, ageing errors are only relevant here to +45 in since our plus group age class was 35; that is, all fish > 45 years of age in the data will always be correctly assigned to the 35+ age class. Details of the ageing error calculations and resulting matrix are given in Appendix F.

2.6. OBJECTIVE FUNCTION

The objective function for this model consists of likelihood functions for observations, prior distributions for some leading parameters, and priors on the annual deviations for time-varying parameters where appropriate (Table 3).

Biomass index observations are assumed to be log-normally distributed with mean given by OM.18 and variance $\tau_{g,I}^2$ where I indicates a biomass index variance and g indexes the source. The residual function in L.1 is used in computing the conditional MLE for log-catchability in L.2 and sum-of-squares in L.3. The conditional MLE for $\tau_{g,I}^2$ is given in L.4 and the concentrated likelihood in L.5 (Bard 1978). Note that the concentrated likelihoods are multiplied by weight factors ($\lambda_{g,I}$) to assess the implications of alternative data combinations and weighting schemes. Similar weight factors are included for age composition likelihoods as well. Otherwise, data sources influence the estimation procedure via their estimated variances; no other arbitrary weighting factors are used to adjust the influence of alternative data sources.

The age-composition data are modelled using a multivariate-logistic (MVL) distribution on the proportions-at-age (Schnute and Richards 1995; Schnute and Haigh 2007). We chose the MVL likelihood mainly for its self-weighting likelihood property in which variances are computed directly from the model fits rather than being implied by assumptions about effective sample sizes. Equation L.6 gives the residual function, L.7 the sum-of-squares, and L.8 the conditional MLE for the variance $\tau_{g,A}^2$ where the subscript A indicates an age-composition variance. The MVL distribution has at least two advantages over the more traditional multinomial distribution for age composition. First, it is more realistic to treat an age-composition sample as *A* (number of age classes, e.g., 35), potentially noisy, observations rather than *N* (number of samples, e.g., 600) independent samples. Second, the variance is determined by the fit rather than the sample size, *A*, so re-weighting the age composition data via some complicated iterative scheme is unnecessary. In addition, the biomass index and age composition variances are comparable. In preliminary analyses, we found it odd that the model could not fit age-proportions in the young/middle-aged groups. In other models, we have included a restriction p > X on the magnitude of age-proportion observations allowed into the likelihood. Here, we used X = 0.005 as a threshold such that any observed age proportion below this value was added to an accumulator bin. By keeping track of the age/year combinations that contribute to this bin, we can easily generate a prediction for it from the model proportions. The sample size for variance calculations is then reduced by $n - 1$, where n is the number of age classes contributing to the accumulator bin. This change improved model performance considerably, although we have not tested alternative values for the threshold, X. Finally, fitting to trap fishery ages less than age-25 only improved model stability, mainly because it eliminated the large plus-group residual that is mostly inconsistent with other, better, age-composition data.

The total biomass of Sablefish 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. At-sea releases (L.10-13) are assumed to be log-normally distributed with mean OM.16 and variance $\tau_{g,D}^2$. For the landed catch, we use a small, fixed standard error to ensure that the model catch closely matches the observed catch (L.14-15).

We use Beta and Normal prior distributions on stock-recruitment steepness and natural mortality (L.16-17), respectively because these parameters are usually difficult to estimate from one-way trip data and relatively high variance, short time-series. The baseline steepness prior parameters $\beta_1 = 40, \beta_2 = 20$ imply a mean and coefficient of variation of $h = 0.67, \sigma_h = 0.01$, respectively. For natural mortality, we used the same $\mu_M^x = 0.10, \sigma_{M_x} = 0.01$ prior mean and standard deviation for both males and females. As noted above, noisy trap fishery age-composition along with missing longline hook and trawl fishery age compositions require prior information about selectivity. Baseline priors for the length-at-50% and length-at-95% selectivity were estimated from the long-term Sablefish tagging program conducted as part of annual surveys and at-sea biological sampling in longline trap, longline hook, and trawl fisheries (Appendix E). Annual deviations in recruitment (L.19-20) and random walk deviations in fishing mortality (L.21-22) are constrained by Normal prior distributions. Finally, L.23 gives the total negative log-posterior, which we refer to as the total objective function.

2.7. SENSITIVITY ANALYSES

Although we present a large number and variety of data for this assessment, the information about absolute stock size and recruitment are weak for a number of reasons. For example, the time-series are relatively short for a long-lived fish, much of the age-composition data lacks coherence in Sablefish cohort prevalence over time, ageing errors are unknown and could be substantial, the 20-year time-series of standardized survey catch rates have high variance, and the stock has only shown a one-way decline in all of the biomass index series. Therefore, we expect the model biomass estimates to be sensitive to what appear as minor changes in the data and prior assumptions. We demonstrate this sensitivity by running the model under select combinations of data weighting (Data Scenarios) to establish a suite of seven scenarios (D1-D7; Table 4) to be considered in future harvest strategy simulations.

The D1-Base-L model contains all the biomass, age-composition, and at-sea release data sets without applying external weighting factors. The "L" is used to indicate that a "Long" 1980-2015 time-series of recruitment deviations is used. As data sources are removed, the model cannot estimate historical recruitments prior to the 1990s, so the reduced models estimate "Short" time-series of recruitment deviations 1990-2015. The D1-Base-L model is not meant to represent our "best available information" because subsets of data might actually provide better model fits, more stable parameter estimates, and more reliable assessments of stock and productivity. Instead, the D1 model represents the sex-structured alternative to the previous age-structured model used for BC Sablefish (Cox et al. 2011).

The D2-Base-AE-L model is the same as D1-Base-L except the ageing error (hence “AE”) function is applied to the model ages (OM.20, Figure 2). This is the first BC Sablefish assessment model to account for ageing error, although this particular ageing error matrix is not specific to the Canadian ageing lab and could therefore add erroneous signals to the age data. The original work by Hanselman et al. (2012) only modeled ageing errors to age 20 and did not mention how to handle age samples in the accumulator class (ages 35+ in this model). Preliminary models showed that ageing errors near the plus group, even when accounted for correctly, smeared age assignments into ages < 35 years, reducing the size of the plus group to levels much lower than the observed values in the data. Therefore, we assumed that over-/under-ageing errors cancel out for the plus group age class. This assumption is consistent with the Hanselman et al. (2012) analysis for true ages > 45 since ageing errors larger than -10 years are unlikely.

Scenario D3-Base-AE-S is the same as D2-Base-AE-L but with the short recruitment time-series estimated (“S” indicating the 1990-2015 series of recruitment deviations are estimated). Scenarios D4-D7 sequentially remove or down-weight data until only the StRS survey remains in D7. Scenario D4-Survey-AE-S is meant to examine the implications of using fishery CPUE as a biomass index by excluding it, D5-Survey-F-AE-S excludes the trap fishery index and reduces the influence of the male age-composition (hence “F”, females only) from the Std Survey which seems to show very large proportions in the age-35+ class, and D6-StRS-F-AE-S uses only the StRS survey biomass index and also reduces the influence of male age-composition. Note that for scenarios D4-D6 only the index data are removed from a particular source but the age-composition data for each source remain in the model. Scenario D7-StRS-AE is the most reduced StRS survey-only model that remains feasible to implement. For this scenario the age composition for the trap fishery and Std Survey are removed but there is no reduction in the influence of male age-composition from the StRS survey.

For all Data Scenarios, estimated parameters included steepness (h), unfished female spawning biomass (B_0) male and female natural mortality (M_x with priors given above), selectivity parameters for all included surveys and fisheries except trawl, which we fixed at the means of the tagging estimates, fishing mortality rates for all years in which fisheries had catch, and recruitment deviations for the short or long time period. Recruitment and fishing mortality rate deviation parameters were always initialized at zero, while selectivity, natural mortality, and steepness parameters were initialized at their prior means.

3. RESULTS

Summaries of residual error variances for biomass surveys, age-composition, and at-sea releases are given in Table 5 and parameter estimates with standard errors in Table 6. Example model fits to each data set are given in Figure 4 to Figure 24, mainly for the D2-Base-AE-L scenario except where figures include D1-Base-AE for comparisons. Note that none of these models fully converged, so the solutions may not be unique even though we were able to get estimated standard errors from the Hessian matrix. In general, models showed strong convergence until later phases when selectivity parameters became active in the minimization and performance declined.

3.1. FULL DATA MODELS WITH AND WITHOUT AGEING ERRORS: D1-BASE-L VS D2-BASE-AE-L

In general, model residual errors increased after accounting for ageing errors in the age-composition data (Table 5; Figure 9 to Figure 12). Increased parameter uncertainty results from these slightly worse model fits when ageing errors are included (Table 5). Exceptions where the model fit slightly better were male fishery and Std Survey female age-composition, and at-sea releases from the trap fishery. Including ageing errors reduced what were severe correlations among model parameters when ageing errors were ignored (Figure 3).

Unfished biomass was approximately 17% higher, while steepness was lower for the D2-Base-AE-L scenario suggesting the stock is slightly larger but less productive (Table 6). Current spawning and legal biomass were both higher, while current spawning biomass relative to unfished was lower at 15.9%. Current exploitation for both legal and sub-legal Sablefish was also lower for the ageing error scenario at 8.8% and 6.9%, respectively. Note that our estimates of sub-legal exploitation rates based on the 2011 operating model were < 2%; this difference likely results from adopting a two-sex model instead of the growth group formulation, and differences in estimating selectivity. Natural mortality rate estimates were not noticeably affected by accounting for ageing errors.

Accounting for ageing error results in substantially different, and more realistic estimates of annual Sablefish recruitment (Figure 19). Most notably, recruitment estimates show greater inter-annual variability and clearer separation of year-classes, particularly the influential ones that occurred in the late 1970s, 2000, and 2008. It appears that this model still has difficulty resolving the size of the 1977 year-class and seems to attribute that recruitment to several possible years. These differences between recruitment series estimated with, and without, ageing errors are similar to the results obtained for the Gulf of Alaska Sablefish assessment (Hanselman et al. 2012).

3.2. LONG VS SHORT RECRUITMENT TIME-SERIES: D2 VS D3

Reducing the length of the recruitment series estimated in the model from 1980-2015 to 1990-2015 had little effect on the time-series of estimated recruitment (Figure 20) or parameter estimates (Table 6). For the short model, average recruitment increased slightly for the 1965-1979 period, mainly because unfished biomass increased relative to the long model.

3.3. DATA SCENARIOS: D4 – D7

Data scenarios D1-D7 produced qualitatively similar patterns in spawning biomass and depletion over time (Figure 21, Table 6). As more data were removed, spawning biomass depletion in 2015 decreased from 16% for D1-Base-AE-L to 11% for the D7-StRS-AE-L model. Exploitation for 2015 also increased from 9.8% for D1 to 12.7% for D7. The sub-legal harvest rate doubled between these two scenarios from 7.1% (D1) to 14.1% (D7).

Removing trap fishery CPUE from the biomass index series had only minor effects on parameter estimates and fits to other data. The most noticeable effects were on legal biomass and exploitation. Estimated legal-sized biomass in 2015 decreased 5,000 t from approximately 25,000 t (when CPUE was included) to 19,380 t (when CPUE was excluded), while exploitation rates increased from 7.9% to 10.1% (Table 6).

Down-weighting male age-composition from the trap fishery had little effect on model parameter estimates (Table 6), although combining the down-weighting and dropping the standardized survey biomass index resulted in a rather massive drop in legal biomass down to 14,570 t and the exploitation up to 14.6%. The StRS survey alone resulted in slightly less severe changes (Table 6). It appears that stock-recruitment steepness (for D7, StRS-AE-S $h \sim 0.39$) is probably not estimable from a time-series as short as the StRS alone because there is little contrast in spawning biomass since 2003.

3.4. MODEL FITS TO AT-SEA RELEASES

Residual standard errors for at-sea releases were not noticeably affected by including/excluding other data sources in the model, despite some visual differences in the fits and model values (Figure 5). The longline hook data fit best followed by trap and trawl. Unlike our 2011 operating model, this one does a much better job accounting for higher at-sea releases in the trawl fishery during the early 2000s. Including ageing errors led to higher, more concentrated at-sea releases around 2001/2002 (Figure 5, Trawl panels). This concentration results from the combination of two factors: the ageing error model creating a more distinct and larger 2000 (partly assigned also to 2001) year-class and strongly dome-shaped trawl selectivity (Figure 6). The model also suggests that longline trap and longline hook fisheries had large at-sea releases as the 2000 year-class entered the offshore fishing areas.

3.5. MODEL FITS TO AGE COMPOSITION

Although the average residual standard errors taken across all data scenarios were nearly identical for males (0.51) and females (0.50), the residual patterns over age and year were sometimes different depending on the source and whether ageing errors were included (Figure 7 to Figure 12). For instance, in the D2-Base-AE-L model, residuals in the Std Survey for female Sablefish appeared smaller at older ages and highest for younger ages. In contrast, the opposite occurred for males which fit most ages reasonably except the plus group age-35+, which is consistently over-estimated in both survey data sets (except for 1997-2004 in the Std survey). High predicted proportions of males in the age-35+ class arise from the low natural mortality rate estimate $M_m \sim 0.05$ yr^{-1}. Residuals for the plus group age were high for both sexes in the StRS survey.

In most cases, age composition residuals included large, patterned groups of residuals and/or runs of positive or negative values, suggesting that the model is likely mis-judging the magnitude and possibly timing of some recruitment events (such as 2000 year class). Persistent random effects in the observations are also likely to be missed by the model (e.g., time-varying selectivity, availability), or short-term dynamics involving immigration and emigration as some fish may migrate through BC waters temporarily.

Both survey age composition data sets show large plus group age proportions ranging from 6%-30% for the Std Survey (sometimes between adjacent years) and 6-20% for the StRS survey. In general, age-composition for males showed much larger plus group abundances than females (Figure 18 to Figure 19for Std and Figure 20 to Figure 21for StRS). The structure and dynamics of this operating model clearly indicates that changes of the magnitude suggested by the Std survey data are probably not caused by fluctuations in recruitment, mortality, and growth of a long-lived species like Sablefish since the model rarely generates more than 8-10% of the population in the age-35+ class. The variation is probably due to a combination of ageing errors and sampling variability with the latter potentially arising from the small number of fixed sampling locations for the Std Survey that were located in areas thought to be productive fishing localities. In contrast, the statistically designed StRS survey age-35+ proportions are consistently less than 12-15%.

It appears that we may be mis-specifying the ageing error matrix based on the pattern of observed and predicted proportions-at-age for "known" large Sablefish year-classes. In particular, for female Sablefish the 2000 year-class appears prominently each year at the correct age until 2011 and beyond where the age assignments become error-prone and also inconsistent (Figure 17). The model predicted values in that figure are adjusted for ageing errors and so they should closely match the bias and smearing effects. A similar pattern appears for males, but perhaps not as pronounced (Figure 18). Given that we are fitting multiple age-composition data sets, it might be possible to estimate a common ageing error matrix, or at least the small adjustments that might be needed to improve these fits. The ultimate effect will be in better resolution of particular recruitment events and, thus variability in recruitment, both of which are important for harvest strategy simulations.

3.6. RETROSPECTIVE PATTERNS

Retrospective patterns in spawning biomass and recruitment estimates suggest that the D1-Base-L model (Figure 25), i.e., without ageing errors, is somewhat insensitive to new data and may be overly constrained by the priors and recruitment estimates. The latter exhibit little difference across a 10-year span of retrospective estimates. When ageing errors are included for the D2-Base-AE-L scenario, the estimated recruitment pattern becomes more sensitive to new data (Figure 26) as expected. The outlier series of estimates for 2008 is probably a result of sensitivity to the starting conditions.

4. DISCUSSION

The harvest strategy for BC Sablefish is designed around a management procedure that needs to be simulation-tested against operating models that capture quantifiable uncertainties in Sablefish dynamics and fisheries. Review of our previous operating model pointed out some shortcomings that we attempted to address here. In particular, our previous model did not account for Sablefish ageing errors, did not fit the age-35+ groups very well, ignored male/female Sablefish differences in growth and mortality, and was not able to replicate the temporal pattern of at-sea releases in the trawl fishery. In this paper, we developed a new operating model that addresses these specific issues given what we have learned over the past several years from experience, new data, and new scientific understanding about Sablefish dynamics, fisheries, and data.

The additional complexity by splitting male and female Sablefish in the data and operating model appears to provide similar results to our previous sexes-aggregated model. One benefit seems to be improved model fits to the age-35+ class in the data. We also obtained preliminary estimates of male (M_m ~ 0.06) and female (M_f ~ 0.09) natural mortality rates. Lower estimates of M_m for males mainly arise from the larger proportion of males in the 35+ age-class. However, at this time we have not investigated the degree to which these differences are due to confounding between natural and fishing mortality. Male Sablefish grow to smaller asymptotic sizes, which may reduce their overall vulnerability to fishing. Other explanations might be that male and female Sablefish move at different rates and that differences in M_x might be reflecting unmodelled immigration/emigration rates. Movement is a key future issue given the prevalence of tagged BC Sablefish returned from other jurisdictions, as well as U.S. tagged fish recovered in BC (DFO 2013).

Including ageing error in the Sablefish operating model produces recruitment estimates that are clearly more realistic than those estimated in our previous model. Even though we used an ageing error function parameterized from a U.S. ageing lab, the results are remarkably consistent with reasonably well-known recruitment events that occurred in the 1970s, 2000, and 2008. The improved recruitment estimates have only marginal effects on key population dynamics parameters; however, the most beneficial effect will be better representation of recruitment in harvest strategy simulations. Our previous operating model showed highly auto-correlated recruitment, which is expected when ageing error is present, but ignored (Bradford 1992). The auto-correlation presents a problem because these scenarios generate the most pessimistic simulation outcomes, yet they are difficult to assign plausibility; that is, we don't believe that recruitment is as strongly correlated as indicated in the original assessment estimates (Cox et al. 2009, 2011). Recruitment estimates from the new model show little auto-correlation (estimated lag-1 correlation < 0.1 for AE models).

Size-selectivity for Sablefish captured in longline trap, longline hook, and trawl fisheries all appear to vary over time based on our analysis of long-term tagging data. However, most of our model fits could not support time-varying selectivity models, because only one fishery had age-composition data and the noise in that data meant that the model could not discern changes in selectivity from measurement noise. In any case, the constant selectivity models, constrained by priors developed from tagging estimates, produced reasonably good results, especially for fitting the at-sea releases. We originally expected that time-varying selectivity was the main cause of our inability to fit the strong temporal pattern in trawl at-sea releases in our previous model. However, the new model, with better resolution of annual recruitment, largely explains the pattern via constant trawl selectivity combined with a more distinct estimate for the magnitude of the 2000 Sablefish year-class. High at-sea releases in trawl fisheries in the 1996-1999 years remain unexplained since recruitment appeared to be low during that time.

4.1. CONSIDERATIONS FOR FURTHER MODEL DEVELOPMENT

The biomass trend data present a classic one-way trip for BC Sablefish and the assessment model behaves in the typical fashion given these data. In particular, estimates of biomass and productivity are highly correlated and can be sensitive to data choices and model assumptions (i.e., fishery CPUE is proportional to biomass). Improving operating model consistency with historical data, and therefore, quality and reliability of projections, first and foremost requires improving the biological data collected for the commercial trap, longline hook, and trawl fisheries. Problems with small sample sizes, non-representative sampling, and logistical difficulties sampling at-sea are documented in previous assessments and discussion papers for this fishery. It also remains a key issue for industry. Nevertheless, a new look at ways to improve biological sampling is critical to include in the Sablefish long-term research strategy.

Utilizing more of the BC Sablefish tagging program data is probably the best option to provide short-term improvements in the operating models. Tagging analyses formed the core of Sablefish assessments prior to 2005 but were put into hiatus because the models were complex and non-transparent to both science and industry (Cox and Kronlund 2008). Interestingly, some of the model scenarios in this paper produce similar magnitude estimates of biomass and harvest rates compared to those tagging models. Future model development could attempt to integrate the tagging data more explicitly into the sex/age-structured Sablefish operating model. For example, Cadigan (2015) presents such a model for Canada's 2J3KL Northern Cod stock in which tagging data are useful to estimating both fishing and natural mortality rates, as well as changes in fish availability to surveys resulting from large-scale shifts in distribution. Tagging information about F and M could break up some of the correlation among the parameters, B_0, h, and length-based selectivity (age and sex of tagged Sablefish can only be determined for the recapture sample). As with any tagging model, this integrated approach is sensitive to estimates of tag reporting rates and therefore will require operating models to represent different biases in reporting.

4.2. IMPLICATIONS FOR RENEWING THE SABLEFISH HARVEST STRATEGY

Inferences about Sablefish stock status, dynamics, and the impacts of future management procedures are dependent on operating model structure and assumptions about the types and quality of data used in conditioning the models. Here we present a potential suite of operating models to be used in future harvest strategy simulations.

Previous operating models for BC Sablefish focused on hypotheses about stock size, productivity, and the degree of recruitment auto-correlation. Based on our results, stock size and productivity remain key uncertainties, while we could potentially move our attention away from recruitment auto-correlation and on to more specific data issues underlying the operating models themselves. For instance, depending on the data choices, recent exploitation rates for legal-sized BC Sablefish range from 8-13% and 7-14% for sub-legal fish. These alternative models are directly relevant to evaluating the impacts of alternative at-sea release regulations or incentives for rebuilding this fishery. The sub-legal exploitation rates (i.e., non-landed mortality), in particular, suggest that a considerable proportion of the stock production is lost prior to full recruitment to fisheries. Eliminating wastage incurred by release mortality would provide a direct benefit to the stock rebuilding effort, while perhaps reducing the economic impact on the fishery of further reducing TACs.

Female age-at-maturity and estimated growth rates for both male and female Sablefish vary considerably coastwide depending on where/how the biological samples were collected. Our previous set of operating models included scenarios for these biological parameters, which we assume are known within the assessment. Although the absolute value of management procedure performance metrics such as the probability of spawning biomass exceeding spawning biomass at maximum sustained yield, Pr($B > B_{\mathrm{MSY}}$), were somewhat sensitive to alternative growth parameters, the rank order of MPs was not affected. Therefore, growth parameter scenarios seem like candidates that we could drop in future operating models. One of the key issues arising from this new model is that we do not have actual sex-ratios for the landed or released catch – the model only fits to total landed and released catch by fishery.

Most of the stock status and productivity estimates we present are not necessarily surprising or new to our harvest strategy simulation research for BC Sablefish. For instance, Cox and Kronlund (2009) examined data-based and model-based management procedures for Sablefish against operating model scenarios that exhibited similar patterns to those presented here. In particular, our estimates of the stock trend over the past 8 years based on the sex/age-structured model with ageing errors looks very similar to the biomass pattern projected using conservative target exploitation rates (6-8%) on the low productivity/low initial depletion scenario in that 2008 paper. Biomass depletion in Year 51 (e.g., 2015) was projected to be approximately 15% of the unfished level and increasing very slowly, which is consistent with our current assessment. This contrasts with the high depletion/high productivity scenarios in which biomass depletion is projected to be > 20% by Year 51. In 2008, we included fishery CPUE with a hyper-depletion parameter to generate the low productivity/low depletion scenarios. Of the data scenarios we examined here, scenario D4-Survey-AE-S would be the most comparable since it ignores fishery CPUE and could be combined with alternative scenarios for stock-recruitment steepness to provide a new set of productivity/depletion scenarios.

The closed-population assumption for BC Sablefish continues to be necessary despite considerable evidence of widespread Sablefish movement throughout the Northeast Pacific. Although tagging data clearly demonstrate this movement, the data also show that up to 80% or more of tagged fish are recaptured in BC within 5-10 years of release. It is likely that the closed-population assumption is good enough to manage short-term harvests for Sablefish. Nevertheless, as mentioned above, Sablefish have declined coastwide since the 1980s and show little sign of the productive recovery indicated by assessment model projections for the Gulf of Alaska, BC, or the lower US states. A coastwide model for Sablefish, developed in collaboration with US National Marine Fishery Service labs, could help to provide more realistic operating models and projections.

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7. TABLES

Table 1. Notation and parameter values for the Sablefish operating model.

Symbol	Value	Description
T	51	Total number of years between 1965 and 2015
A	35	Plus group age-class
t	$1,2,...,T$	Time step. Corresponding year range is 1965-2015
a	$1,2,...,A$	Age-class index
G	$1,2,...,G$	Fishery/gear index: 1=Trap, 2=Hook, 3=Trawl, 4=Std survey, 5=StRS survey
$n_{g,\cdot,\cdot}$	-	Sample size for non-missing indices (I), ages (A), or at-sea releases (D). Other dimensions may include time (t) or sex (x)
B_0	-	Unfished female spawning biomass (tonnes)
h	-	Stock-recruitment function steepness
β_1, β_2	40, 20	Steepness prior parameters corresponding to a mean = 0.67 and CV = 0.01
q_g	-	Catchability coefficient for gear *g*
σ_R	1.0	Standard error of log-recruitment
M_x	0.1, 0.1	Natural mortality rate prior means (/yr) for males (x=m) and females (x=f)
σ_M	0.01	Natural mortality prior standard deviation for both males and females
$L_{\infty,x}$	68, 72	Asymptotic length (cm) for males (x=m) and females (x=f)
σ_{L_∞}	0.12, 0.12	Coefficient of variation in length-at-age
k_x	0.29,0.25	von Bertalanffy growth constant for males and females
$L_{1,x}$	32.5, 32.5	Length-at-age 1 for males and females

Symbol	Value	Description
c_1, c_2	1.04e-5, 3.08	length-weight coefficients (i.e., a, b)
$\tilde{A}_{50}, \tilde{A}_{95}$	5, 12	Age-at-50% and -95% maturity
L_{lim}	55	Minimum size limit (cm)
$\tilde{L}_{50,g,t}, \tilde{L}_{95,g,t}$	-	Length-at-50% and -95% selectivity
$\tilde{L}_{\max,g,t}, \sigma_{S,g,t}$	-	Normal selectivity mode and std deviation
d_g	0.16, 0.35, 1.6	Discard mortality rate (yr^{-1}) for Trap (g=1), Hook (g=2), and Trawl (g=3)
$L_{a,x}$	-	Length-at-age (cm) for males (x=m) and females (x=f)
$w_{a,x}$	-	Weight-at-age for males (x=m) and females (x=f)
m_a	-	Proportion of females mature-at-age
$p_{a,x}$	-	Proportion of age class a males (x=m) or females (x=f) larger than the size limit
$P_{g,t,a,x}$	-	Proportion of age-a males (x=m) and females (x=f) retained by fishery g in year t
$S_{g,t,a,x}$	-	Selectivity for age-a, males (x=m) and females (x=f)
R_0	-	Unfished equilibrium recruitment
ϕ	-	Unfished spawning biomass per recruit
$N_{t,a,x}$	-	Number of age a males (x=m) and females (x=f) in year t
ω_t	-	Log-normal recruitment process deviation
B_t	-	Female spawning biomass in year t
$C_{t,g,a,x}$	-	Predicted catch-at-age in fishery g of males (x=m) and females (x=f)
$D_{t,g}$	-	Observed total at-sea releases for year t and fishery g

Symbol	Value	Description
$\hat{D}_{t,g}$	-	Predicted total at-sea releases for year t and fishery g
$F_{t,g}$	-	Fully-selected fishing mortality rate for gear g in year t
$Z_{t,a,x}$	-	Total mortality rate in year *t* for age-*a* males (x=m) and females (x=f)
$I_{g,t}$	-	Observed biomass index for gear g = *1, 4, 5*
$\hat{I}_{g,t}$	-	Predicted biomass index for gear g = *1, 4, 5*
$u_{g,t,a,x}$	-	Proportion of age class *a* fish in the sampled catch for male (x=m) and female (x=f) Sablefish
$\hat{\mathbf{u}}_{g,t,x}$	-	Vector of predicted values for the observed age proportions after accounting for ageing error. If ageing error is being ignored, these values will be the same as $u_{g,t,a,x}$
$\mathbf{Q}$	-	Ageing error probability matrix (A x A)

Table 2. Age-/sex-structured model equations defining the population dynamics and observations for BC Sablefish. Parameter subsets in OM.1 are as follows: Θ^{est} *estimated as free parameters,* Θ^{cond} *estimated conditional on free parameters,* Θ^{fixed} *fixed input parameters not estimated, and* Θ^{priors} *Bayes prior distribution parameters. The subscript* x *is used where parameters have specific male and female values.*

Operating model

Parameters

OM.1 $$\Theta^{est} = \left(h, B_0, \{\omega_t\}_{t=2:T}, \{\log F_{t,g}\}_{g=1:3}^{t=1:T}, M_m, M_f, \{\tilde{L}_{50,g,t}\}_{g=1:5}^{t=1:n_{S,g}}, \{\tilde{L}_{95,g,t}\}_{g=1:5}^{t=1:n_{S,g}}\right)$$

$$\Theta^{cond} = \left(\{q_g\}_{g=5,6}, \{\tau_{g,I}^2\}_{g=1,4,5}, \{\tau_{g,A,x}^2\}_{g=1,4,5}^{x=m,f}, \{\tau_{g,R}^2\}_{g=1:3}\right)$$

$$\Theta^{fixed} = \left(L_{\infty.f}, L_{\infty.m}, k_f, k_m, \sigma_{L.f}, \sigma_{L.m}, \tilde{A}_{50}, \tilde{A}_{95}, \{d_g\}_{g=1:3}\right)$$

$$\Theta^{priors} = \left(\mu_M^m, \mu_M^f, \sigma_M^m, \sigma_M^f, \mu_h, \sigma_h, \sigma_R, \{\sigma_F\}_{g=1:3}, \{\tau_C\}_{g=1:3}\right)$$

Growth, selectivity, proportion retained at age, and maturity

OM.2 $$L_{a,x} = L_{1,x} + \left(L_{1,x} - L_{\infty,x}\right) e^{-k_x(a-1)}$$

OM.3 $$w_{a,x} = c_1 {L_{a,x}}^{c_2}$$

OM.4 $$S_{g,t,a,x} \propto \begin{cases} \left(1 + \exp\left[-\log(19)\left(L_{a,x} - \tilde{L}_{50,g,t}\right) \big/ \left(\tilde{L}_{95,g,t} - \tilde{L}_{50,g,t}\right)\right]\right)^{-1} & \text{asymptotic} \\ \exp\left(-\dfrac{\left(L_{a,x} - L_{\max,g,t}\right)^2}{\sigma_{S,g,t}^2}\right) & \text{normal} \end{cases}$$

OM.5 $$P_{g,a,x} = p\left(l_{a,x} > L_{\text{Lim}} \mid L_{\infty,x}, k_x, \sigma_{L,x}\right) = \frac{\int_{l=L_{\text{Lim}}}^{l=L_{\infty,x}(1+4\sigma_x)} \exp\left(-\dfrac{\left(l - L_{a,x}\right)^2}{2\sigma_{L,x}^2 l^2}\right)}{\int_{l=0}^{l=L_{\infty,x}(1+4\sigma_x)} \exp\left(-\dfrac{\left(l - L_{a,x}\right)^2}{2\sigma_{L,x}^2 l^2}\right)}$$

Operating model

OM.6 $$m_a = \left(1 + \exp\left[-\log(19)\left(a - \tilde{A}_{50}\right)\Big/\left(\tilde{A}_{95} - \tilde{A}_{50}\right)\right]\right)^{-1}$$

State dynamics

OM.7 $$R_0 = B_0 / \phi$$

OM.8 $$N_{1,a,x} = \begin{cases} R_0 e^{-(a-1)M_x} & 1 \le a \le A-1 \\ \dfrac{N_{1,a-1,x}}{\left(1 - e^{-M_x}\right)} & a = A \end{cases}$$

OM.9 $$N_{t,1,x} = \frac{4 R_0 B_{t-1}}{B_0(1-h) + (5h-1)B_{t-1}} e^{\omega_t - 0.5\sigma_R^2}$$

OM.10 $$N_{t,a,x} = \begin{cases} N_{t-1,a-1,x} e^{-Z_{t-1,a-1,x}} & 2 \le a \le A-1 \quad t > 1 \\ N_{t-1,a-1,x} e^{-Z_{t-1,a-1,x}} + N_{t-1,a,x} e^{-Z_{t-1,a,x}} & a = A \quad t > 1 \end{cases}$$

OM.11 $$B_t = \sum_{a=1}^{A} m_a w_{a,x=f} N_{t,a,f}$$

OM.12 $$\log F_{t,g} = \begin{cases} \log F_{t_1,g} & t = t_1 \\ \log F_{t-1,g} + \delta_{g,t} & t > 1 \end{cases}$$

OM.13 $$C_{t,g,a,x} = w_{a,x} N_{t,a,x} \frac{S_{g,t,a,x} F_{t,g} P_{g,t,a,x}}{Z_{t,a,x}} \left[1 - e^{-Z_{t,a,x}}\right]$$

OM.14 $$D_{t,g,a,x} = w_{a,x} N_{t,a,x} \frac{S_{g,t,a,x} F_{t,g} \left(1 - P_{g,t,a,x}\right)}{Z_{t,a,x}} \left[1 - e^{-Z_{t,a,x}}\right]$$

OM.15 $$\hat{C}_{t,g} = \sum\nolimits_a C_{t,g,a,x=m} + \sum\nolimits_a C_{t,g,a,x=f}$$

Operating model

OM.16 $$\hat{D}_{t,g} = \sum_a D_{t,g,a,x=m} + \sum_a D_{t,g,a,x=f}$$

OM.17 $$Z_{t,a,x} = M_x + \sum_{g=1}^{g=3} S_{g,t,a,x} F_{t,g} \left(P_{g,a,x} + \left(1 - P_{g,a,x}\right) d_g \right)$$

Observation models

OM.18 $$\hat{I}_{t,g} = q_g \left(\sum_{a=1}^{A} S_{g,t,a,m} w_{a,m} N_{a,t,m} e^{-f_S Z_{t,a,m}} + \sum_{a=1}^{A} S_{g,t,a,f} w_{a,f} N_{a,t,f} e^{-f_S Z_{t,a,f}} \right)$$

OM.19 $$u_{g,t,a,x} = \frac{N_{t,a,x} S_{g,t,a,x} e^{-f_g Z_{t,a,x}}}{\sum_j N_{t,j,x} S_{g,t,j,x} e^{-f_g Z_{t,j,x}}}$$

OM.20 $$\hat{\mathbf{u}}_{g,t,x} = \mathbf{Q}\mathbf{u}_{g,t,x}$$

Table 3. Negative log-posterior (G) computation based on negative log-likelihood functions for biomass indices (ℓ_I), age composition data (ℓ_A),catch-by-gear (ℓ_C), at-sea releases (ℓ_D), and negative log-prior distributions for recruitment (ℓ_R), fishing mortality deviations (ℓ_F), stock-recruitment steepness (ℓ_h) and natural mortality (ℓ_M).

Likelihoods and Priors

Observations: Biomass indices

L.1 $$z_{g,t} = \log\left(\frac{I_{g,t}}{\hat{I}_{g,t}}\right)$$

L.2 $$\widehat{\log q_g} = \frac{1}{n_{g,I}}\sum\nolimits_{t=1:n_{g,I}} z_{g,t}$$

L.3 $$Z_{g,I} = \sum\nolimits_{i=1:n_{g,I}}\left(z_{g,t} - \widehat{\log q_g}\right)^2$$

L.4 $$\hat{\tau}^2_{g,I} = \frac{1}{n_{g,I}-1} Z_{g,I}$$

L.5 $$\ell_I = \sum\nolimits_{g=1,4,5} \lambda_{g,I} n_{g,I} \log \hat{\tau}^2_{g,I}$$

Observations: Age-composition

L.6 $$\eta_{g,a,t,x} = \log p_{g,a,t,x} - \log \hat{u}_{g,a,t,x} - \frac{1}{n_{g,A,t,x}}\sum\nolimits_{a=1:n_{g,A,t,x}}\left[\log p_{g,a,t,x} - \log \hat{u}_{g,a,t,x}\right]$$

L.7 $$Z_{g,A,x} = \sum\nolimits_{t=1:T}\sum\nolimits_{a=1:n_{g,A,t,x}} \eta^2_{g,a,t,x}$$

L.8 $$\hat{\tau}^2_{g,A,x} = \frac{1}{n_{g,A,x}} Z_{g,A,x}$$

L.9 $$\ell_A = \sum\nolimits_{x=m,f}\sum\nolimits_{g=1,4,5} \lambda_{g,A} n_{g,A,x} \log \hat{\tau}^2_{g,A,x}$$

Observations: At-sea releases

L.10 $$z^D_{g,t} = \log\left(\frac{D_{g,t}}{\hat{D}_{g,t}}\right)$$

L.11 $$Z_{g,D} = \sum\nolimits_{i=1:n_{g,D}}\left(z^D_{g,t}\right)^2$$

Likelihoods and Priors

L.12 $\hat{\tau}^2_{g,D} = \dfrac{1}{n_{g,D} - 1} Z_{g,D}$

L.13 $\ell_D = \sum_{g=1,2,3} n_{g,D} \log \hat{\tau}^2_{g,D}$

Observations: catch-by-fishery

L.14 $Z_C = \sum_g \sum_{t=1}^{t=T} \left(\log C_{t,g} - \log \hat{C}_{t,g} \right)^2$

L.15 $\ell_C = \dfrac{1}{2\tau^2_{g,C}} Z_C$

Prior distributions: steepness, natural mortality, and selectivity

L.16 $\ell_h = -\left[\left(\beta_1 - 1 \right) \log h + \left(\beta_2 - 1 \right) \log \left(1 - h \right) \right]$

L.17 $\ell_M = \dfrac{\left(M_m - \mu_M^m \right)^2}{2\sigma^2_{M_m}} + \dfrac{\left(M_f - \mu_M^f \right)^2}{2\sigma^2_{M_f}}$

L.18 $\ell_S = \dfrac{\left(L_{50,g} - \mu_{L50,g} \right)^2}{2\sigma^2_{L50,g}} + \dfrac{\left(L_{95,g} - \mu_{L95,g} \right)^2}{2\sigma^2_{L95,g}}$

Prior distributions: annual deviations in recruitment

L.19 $Z_R = \sum_{t=2:T} \omega_t^2$

L.20 $\ell_R = \dfrac{1}{2\sigma^2_R} Z_R$

Prior distributions: fishing mortality rate deviations

L.21 $Z_F = \sum_{g=1,2,3} \sum_{t=t_1:T} \delta^2_{g,t}$

L.22 $\ell_F = \dfrac{1}{2\sigma^2_F} Z_F$

L.23 $G = \ell_I + \ell_A + \ell_D + \ell_F + \ell_C + \ell_h + \ell_M + \ell_S + \ell_R + \ell_F$

Table 4. Data scenarios created by excluding particular data series and ageing error corrections. The weights listed are in order of the trap fishery, standardized survey, and stratified random survey. Weights are multipliers of the data likelihoods, so for example, a weighting of 50% on all age likelihood components for males is indicated by (0.5, 0.5, 0.5). Long and Short labels indicate recruitment series 1980-2015 (Long) and 1990-2015 (Short).

	Description	**Label**	**Index Weight**	**Male Age Weight**	**Female Age Weight**	**Ageing Error correction**
D1	Base-Long	Base-L	(1,1,1)	(1,1,1)	(1,1,1)	No
D2	Base with ageing error correction - Long	Base-AE-L	(1,1,1)	(1,1,1)	(1,1,1)	Yes
D3	Base with ageing error correction - Short	Base-AE-S	(1,1,1)	(1,1,1)	(1,1,1)	Yes
D4	Exclude trap fishery index, with ageing error correction – Short	Survey-AE-S	(0,1,1)	(1,1,1)	(1,1,1)	Yes
D5	Exclude trap fishery index, male age data weights reduced, with ageing error correction - Short	Survey-F-AE-S	(0,1,1)	(0.5,0.5,0.5)	(1,1,1)	Yes
D6	Exclude trap fishery and Std Survey indices, male age data weights reduced, with ageing error correction - Short	StRS-F-AE-S	(0,0,1)	(0.5,0.5,0.5)	(1,1,1)	Yes
D7	StRS survey index with ageing error correction - Short	StRS-AE-S	(0,0,1)	(0,0,1)	(0,0,1)	Yes

Table 5. Estimated residual standard errors by data source: second subscript 1= trap fishery, 2= standardized survey, 3 = trawl fishery, 4 = standardized survey, and 5 = stratified random survey. The term $\ell_{I,A,D}$ is the total data likelihood over biomass indices (I), age-composition (A), and at-sea releases (D). Standard errors are estimated regardless of whether data sets were excluded from the overall objective function. Gray shaded values, marked with an asterisk, not involved or down-weighted in the fit.

			Indices			**Ages males**			**Ages females**			**Releases**		
	Label	$\ell_{I,A,D}$	$\tau^2_{1,I}$	$\tau^2_{4,I}$	$\tau^2_{5,I}$	$\tau^2_{1,A,m}$	$\tau^2_{4,A,m}$	$\tau^2_{5,A,m}$	$\tau^2_{1,A,f}$	$\tau^2_{4,A,f}$	**-**	$\tau^2_{1,D}$	$\tau^2_{2,D}$	$\tau^2_{3,D}$
D1	Base-L	-2934.540	0.518	0.532	0.400	0.543	0.606	0.437	0.162	0.522	0.146	0.486	0.315	0.585
D2	Base-AE-L	-2609.480	0.518	0.582	0.461	0.531	0.640	0.457	0.169	0.502	0.147	0.418	0.352	0.618
D3	Base-AE-S	-2576.140	0.520*	0.584	0.466	0.533	0.645	0.457	0.164	0.502	0.149	0.414	0.372	0.624
D4	Survey-AE-S	-2516.930	0.521*	0.582	0.459	0.534*	0.641*	0.462*	0.178	0.509	0.156	0.421	0.421	0.612
D5	Survey-F-AE-S	-1695.580	0.529*	0.584*	0.462	0.533*	0.638*	0.458*	0.181	0.509	0.158	0.417	0.399	0.620
D6	StRS-F-AE-S	-1562.940	0.534*	0.582*	0.483	0.561*	0.647*	0.481	0.193*	0.528*	0.187	0.414	0.322	0.640
D7	StRS-AE-S	-519.844	1.330*	0.642*	0.449	2.093*	0.699*	0.463	0.314*	0.516*	0.172	1.479	0.308	0.413

Table 6. Key parameters, estimated states (first row), and their standard errors (second row) for operating model data scenarios D1-D7: stock-recruitment steepness (h), natural mortality rates for males and females (M_m, M_f), unfished female spawning biomass (B_0), female spawning stock biomass in 2015 (B_{2015}), spawning stock depletion ($D_{2015}=B_{2015}/B_0$), total male and female legal biomass in 2015 ($LB_{2015,L}$), harvest rate on legal-sized (LHR_{2015}) and sub-legal-sized ($SLHR_{2015}$) fish. Biomass units are thousands of metric tonnes and natural mortality is yr^{-1}.

Scenario	**Label**	h	M_m	M_f	B_0	B_{2015}	D_{2015}	$LB_{2015,L}$	LHR_{2015}	$SLHR_{2015}$
D1	Base-L	0.589	0.041	0.084	48.90	7.94	0.162	19.88	0.098	0.071
		0.069	0.000	0.001	0.97	0.78	0.014	1.96	0.010	0.011
D2	Base-AE-L	0.537	0.043	0.086	55.10	8.74	0.159	22.20	0.088	0.069
		0.072	0.002	0.002	2.33	0.91	0.014	2.34	0.009	0.011
D3	Base-AE-S	0.567	0.046	0.087	60.74	9.87	0.162	24.74	0.079	0.065
		0.077	0.002	0.002	2.43	1.06	0.014	2.65	0.008	0.011
D4	Survey-AE	0.559	0.045	0.089	55.65	7.70	0.138	19.38	0.101	0.081
		0.069	0.002	0.002	2.24	1.00	0.016	2.58	0.013	0.015
D5	Survey-F-AE	0.573	0.043	0.089	54.13	7.39	0.137	18.85	0.104	0.081
		0.064	0.002	0.002	2.33	0.98	0.016	2.57	0.014	0.015
D6	StRS-F-AE	0.255	0.042	0.087	54.45	5.72	0.105	14.57	0.134	0.108
		0.001	0.002	0.002	2.78	1.09	0.018	2.83	0.026	0.024
D7	StRS-AE	0.386	0.058	0.104	54.10	6.08	0.112	15.41	0.127	0.141
		0.069	0.003	0.003	3.10	0.90	0.014	2.23	0.018	0.028

8. FIGURES

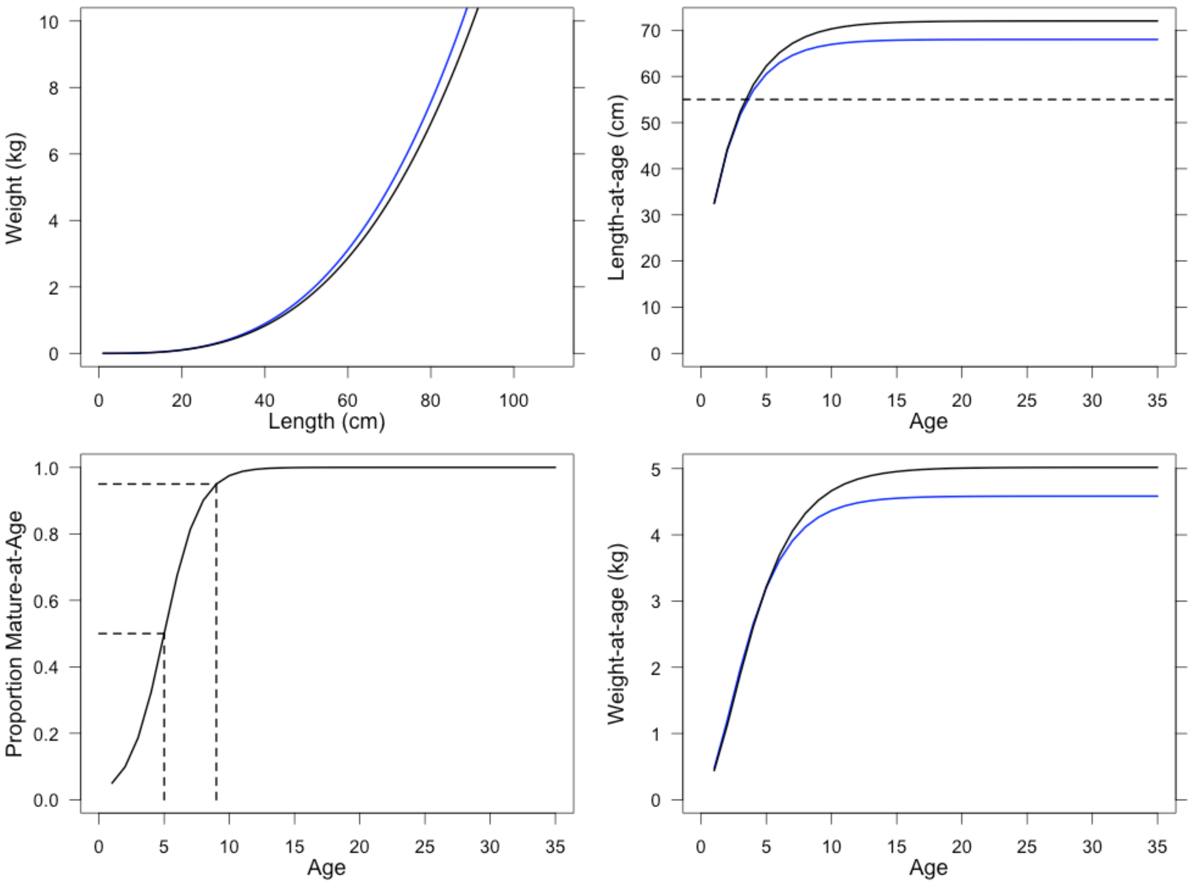


Figure 1. Sablefish life history relationships used as fixed inputs to the operating model. Weight-length (upper left panel), proportion mature-at-age (lower left panel), length-at-age (upper right panel) and weight-at-age (lower right panel) are shown for female (black solid lines) and male (blue solid lines) Sablefish. Dashed lines on the proportion mature-at-age panel indicate the ages at 50% and 95% maturity. The horizontal dashed line on the length-at-age panel is located at the 55 cm size limit.

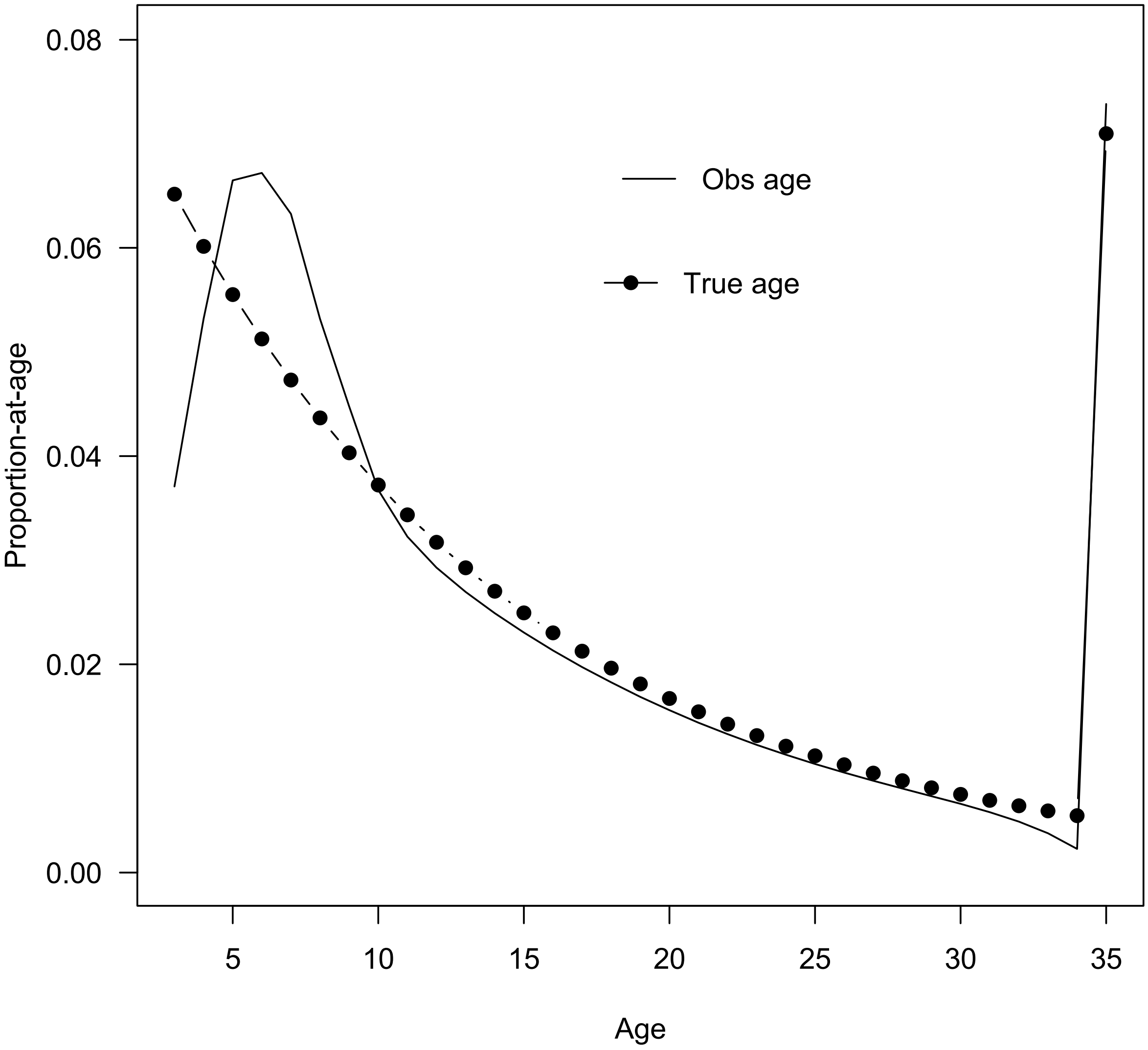
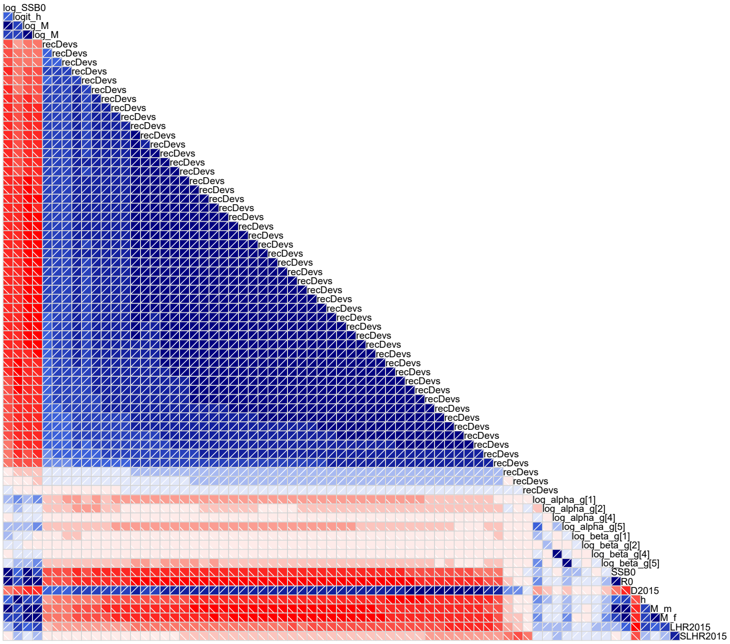


Figure 2. Ageing error function used to predict Sablefish age composition for ages 3-35+. This example is for a hypothetical unfished Sablefish population with M = 0.08 yr^{-1}*.*



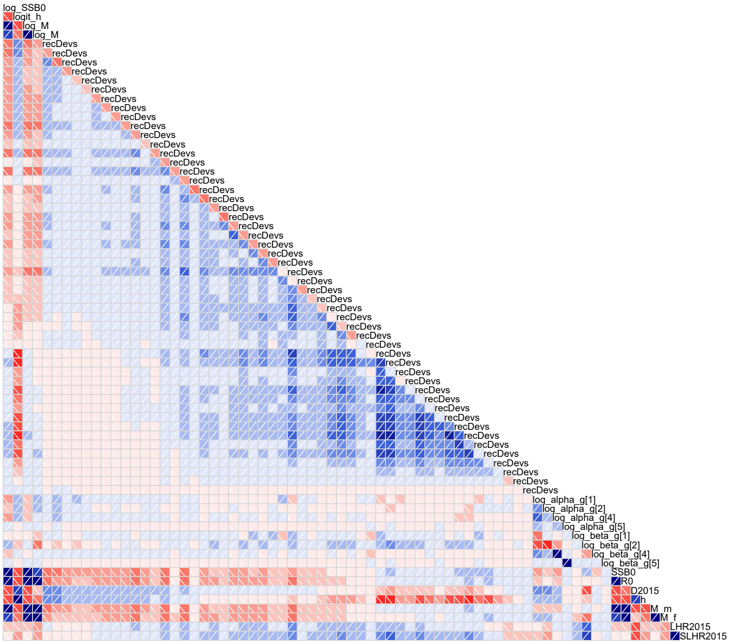


Figure 3. Parameter correlations for the D1-Base-L (top) and D2-Base-AE-L (bottom) models. Parameter names are on the diagonal from SSB0, h, Mm, Mf, recruitment deviations, and selectivity parameters. Correlations for the last several rows beginning with SSB0 are outputs from the ADMB ***sdreport****, so they can be ignored. Blue squares are positive, and red are negative. Darker shading indicates higher correlations – correlations in the upper left most corner for D1-Base-L are in the range 0.6-0.7 for both blue and red.*

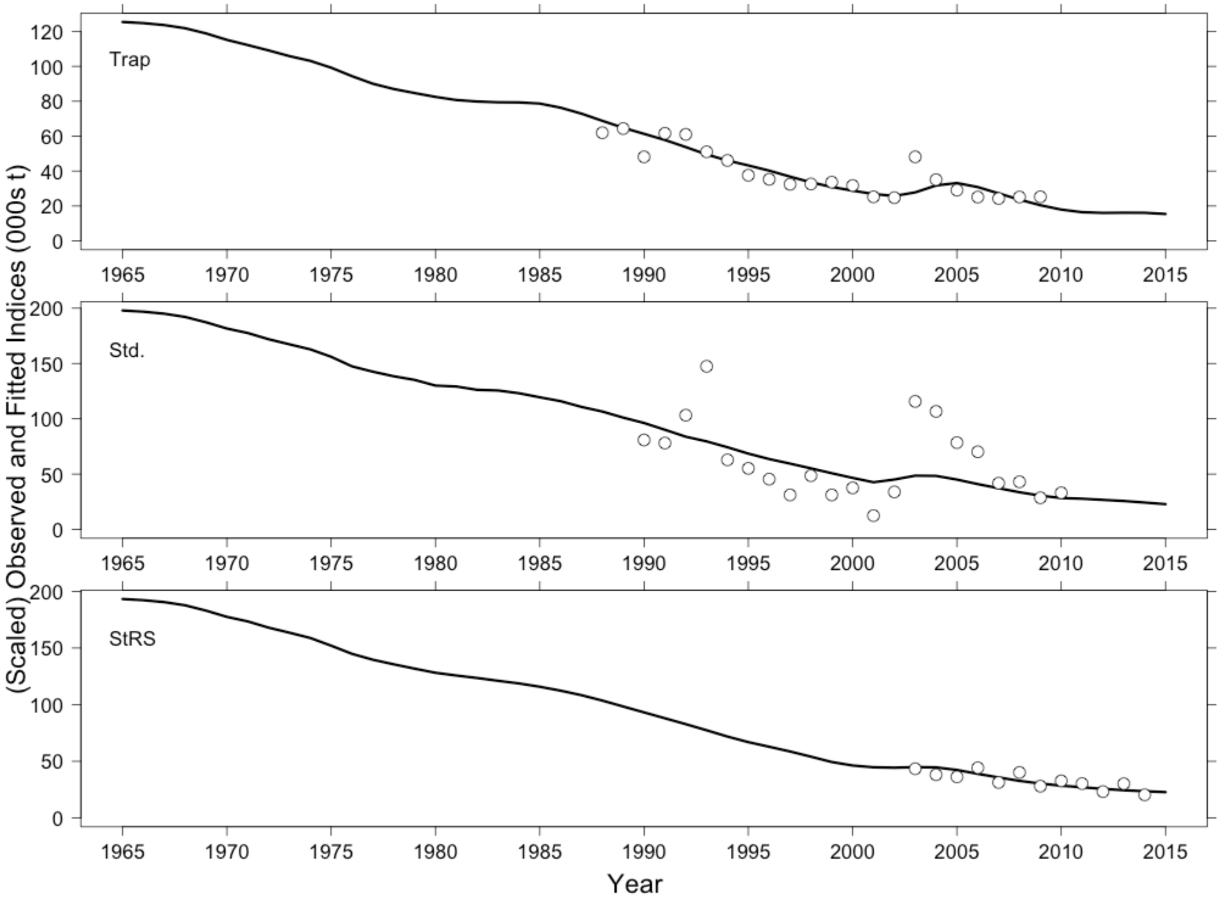


Figure 4. Fit to annual Sablefish stock indices scaled to biomass units by catchability estimates for commercial trap gear index (upper panel), standardized survey index (centre panel), and stratified random survey index (lower panel) for scenario D2-Base-AE-L. Scaled observations are indicated by open circles, the solid line in each figure panel shows the model estimates.

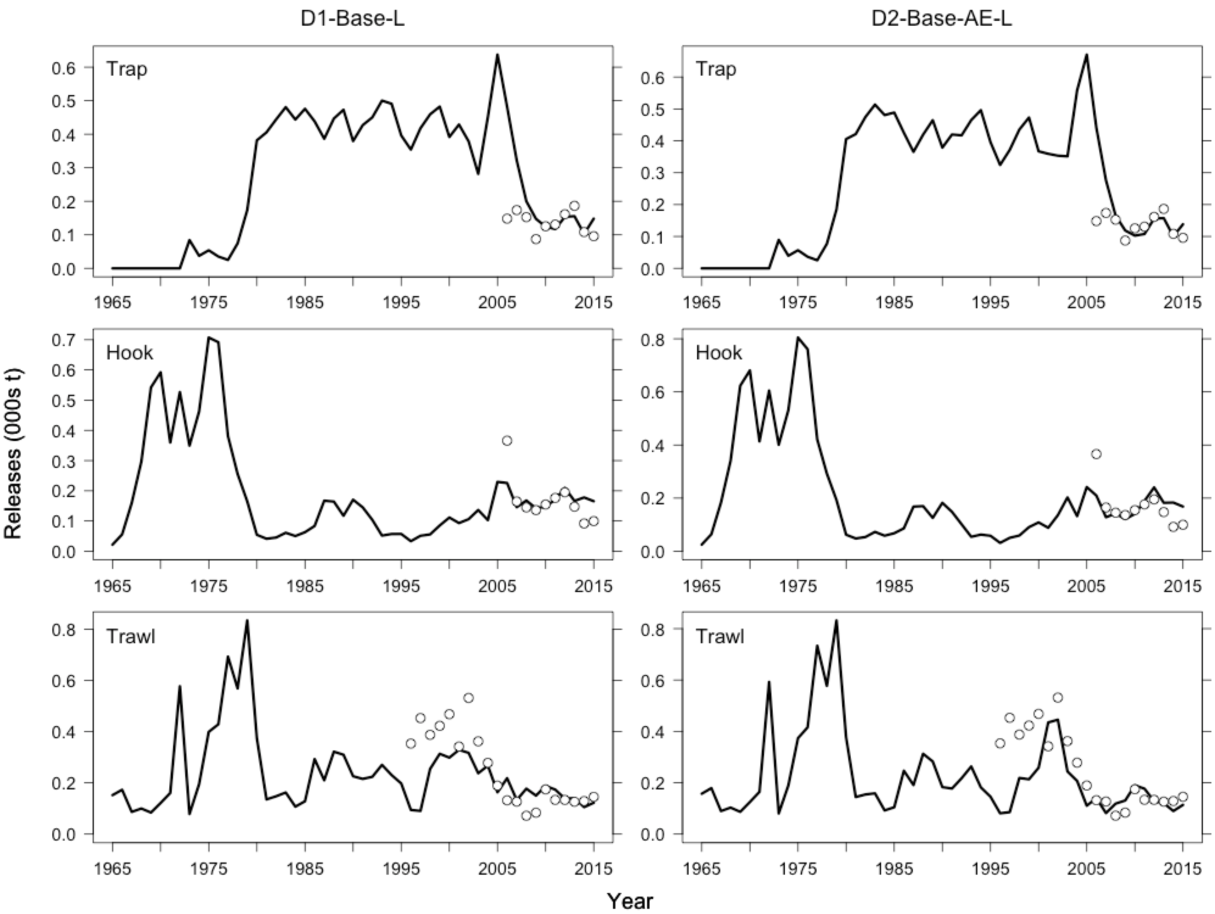


Figure 5. Fit to annual Sablefish releases for commercial trap gear index (upper panel), longline hook gear (centre panel), and trawl gear (lower panel) for data scenarios D1 and D2. Observed releases are shown as open circles, the solid line in each figure panel shows the model estimates.

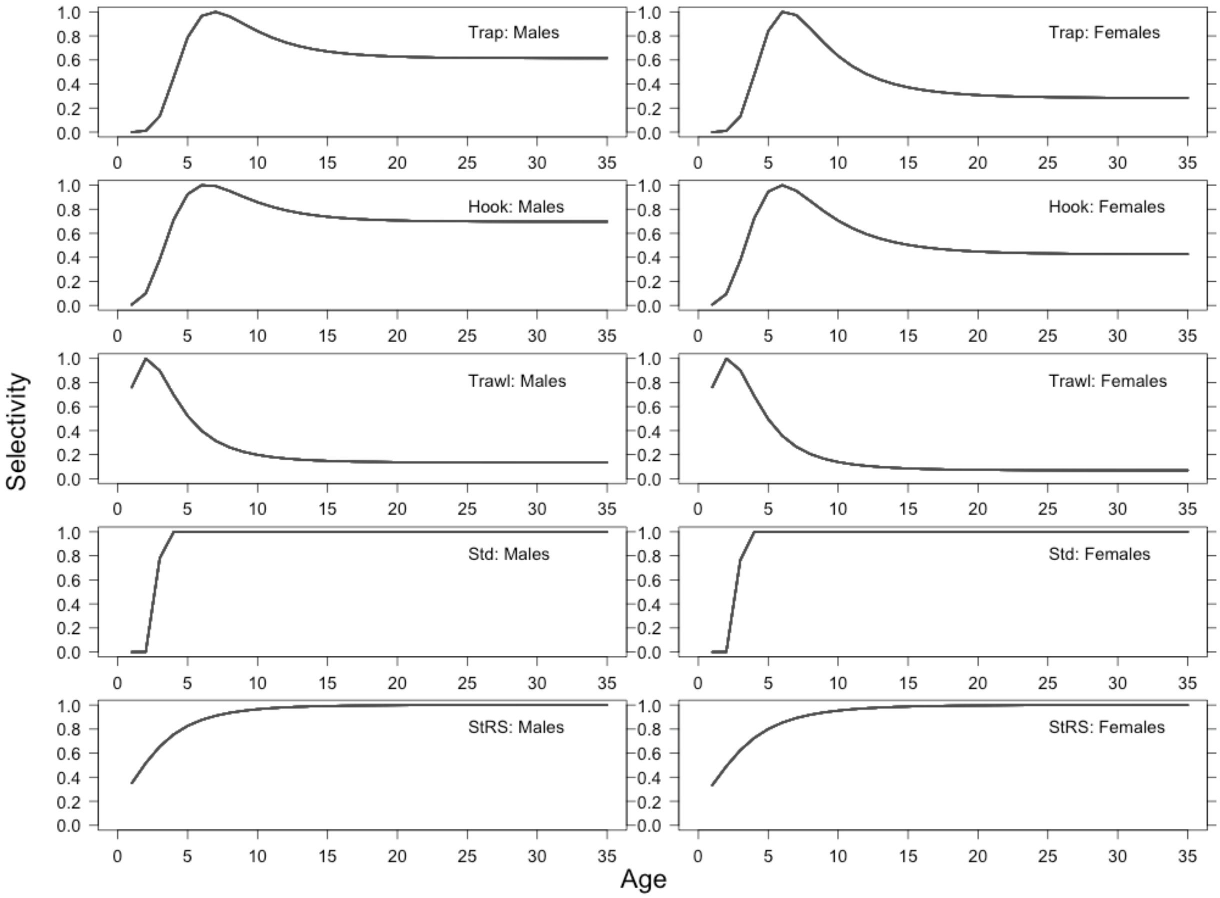


Figure 6. Estimated age-based selectivity by each gear type for male and female Sablefish for the D2-Base-AE-L data scenario.

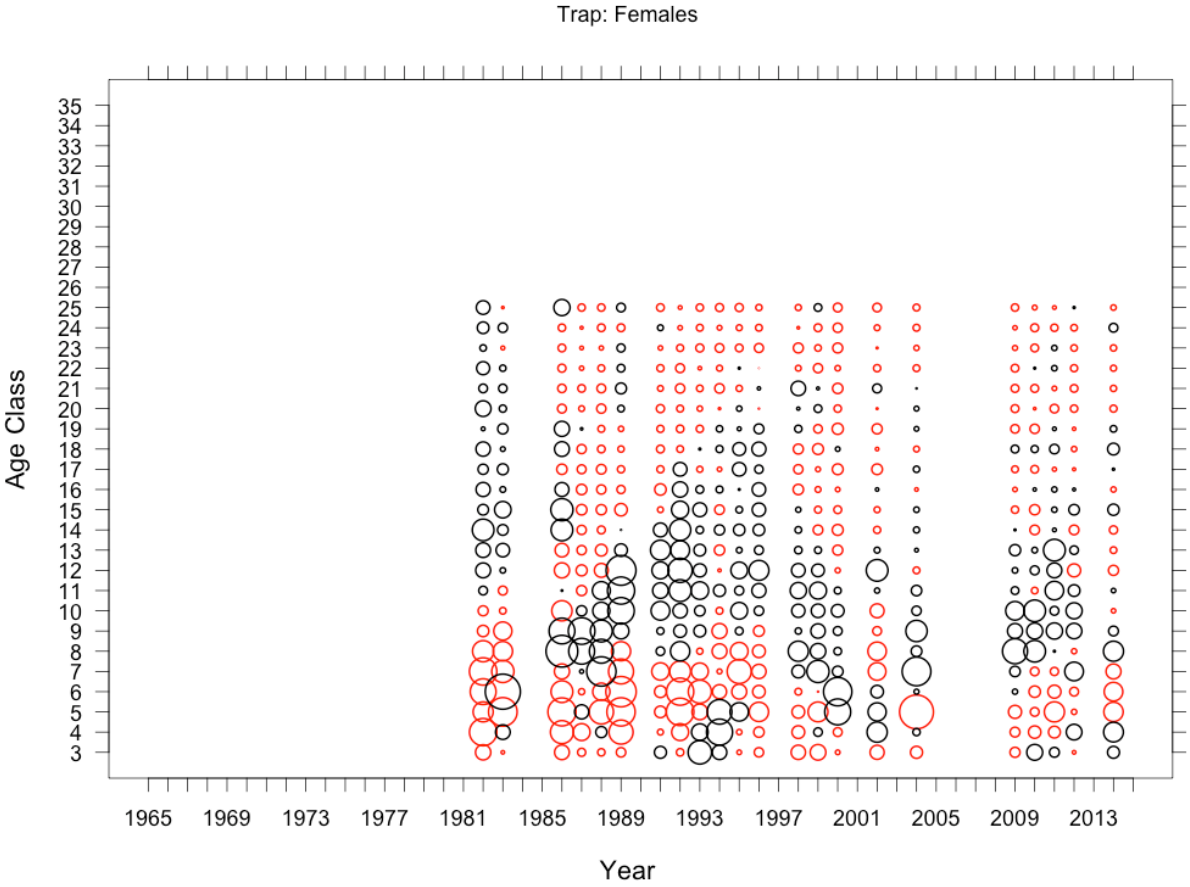


Figure 7. Age proportion residuals (observed minus predicted) of female Sablefish for the commercial trap gear fishery for the D2-Base-AE-L data scenario. Circles are sized in proportion to the magnitude of the residual value; black and red circles represent positive and negative residuals, respectively. Residuals with values of zero and missing observations are not shown. Age proportions 3 to 25 were fitted; observed proportions age 26 and greater did not enter the likelihood calculations.

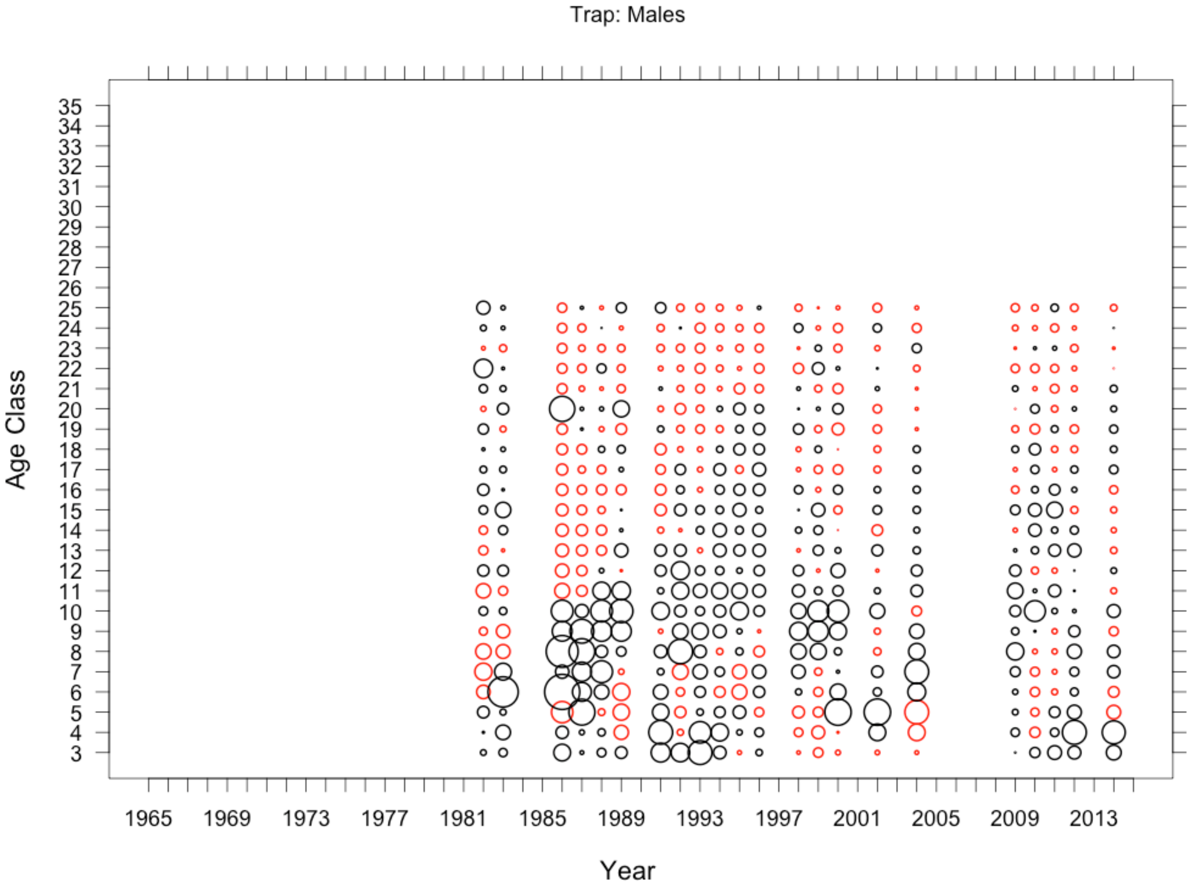
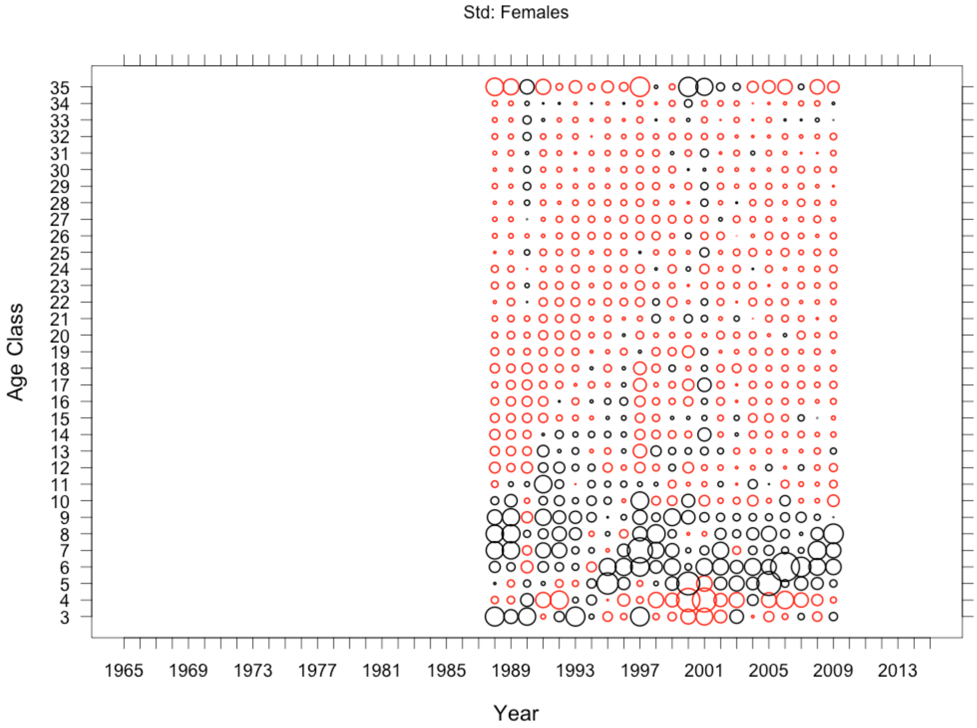


Figure 8. Age proportion residuals (observed minus predicted) of male Sablefish for the commercial trap gear fishery for the D2-Base-AE-L data scenario. Circles are sized in proportion to the magnitude of the residual value; black and red circles represent positive and negative residuals, respectively. Residuals with values of zero and missing observations are not shown. Age proportions 3 to 25 were fitted; observed proportions age 26 and greater did not enter the likelihood calculations.



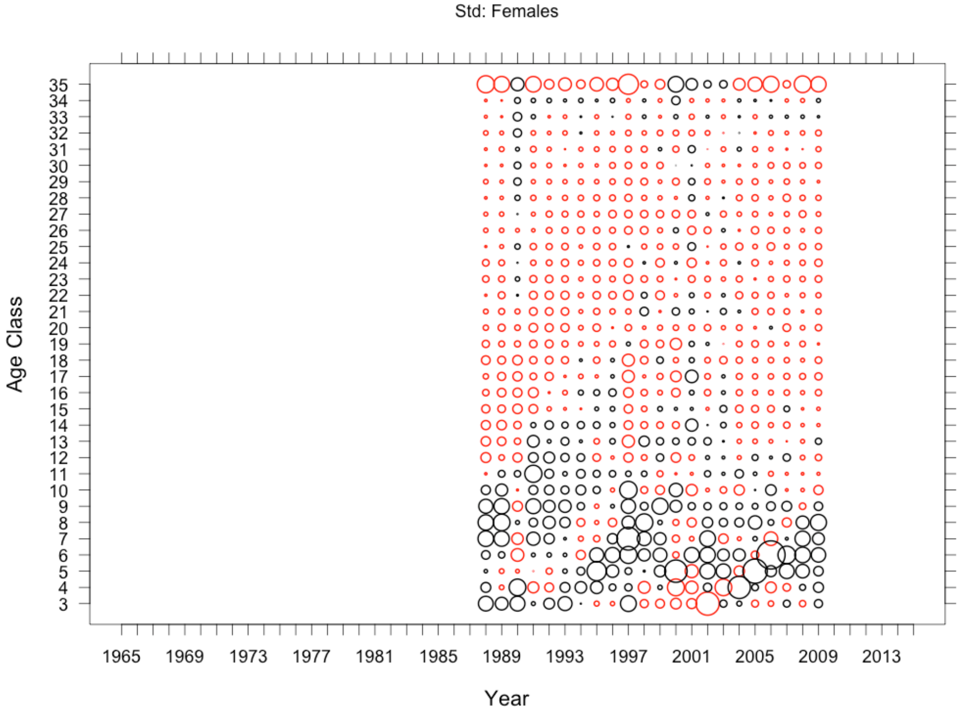
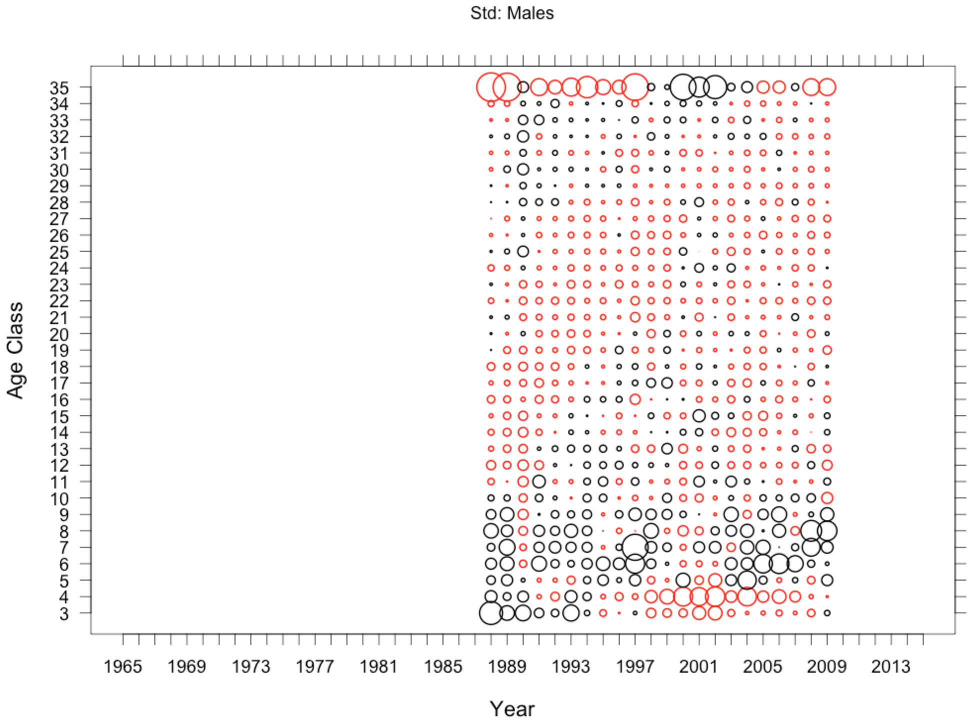


Figure 9. Age proportion residuals (observed minus predicted) of female Sablefish for the standardized trap gear survey for D1-Base-L (upper) and D2-Base-AE-L (lower). Circles are sized in proportion to the magnitude of the residual value; black and red circles represent positive and negative residuals, respectively. Residuals with values of zero and missing observations are not shown.



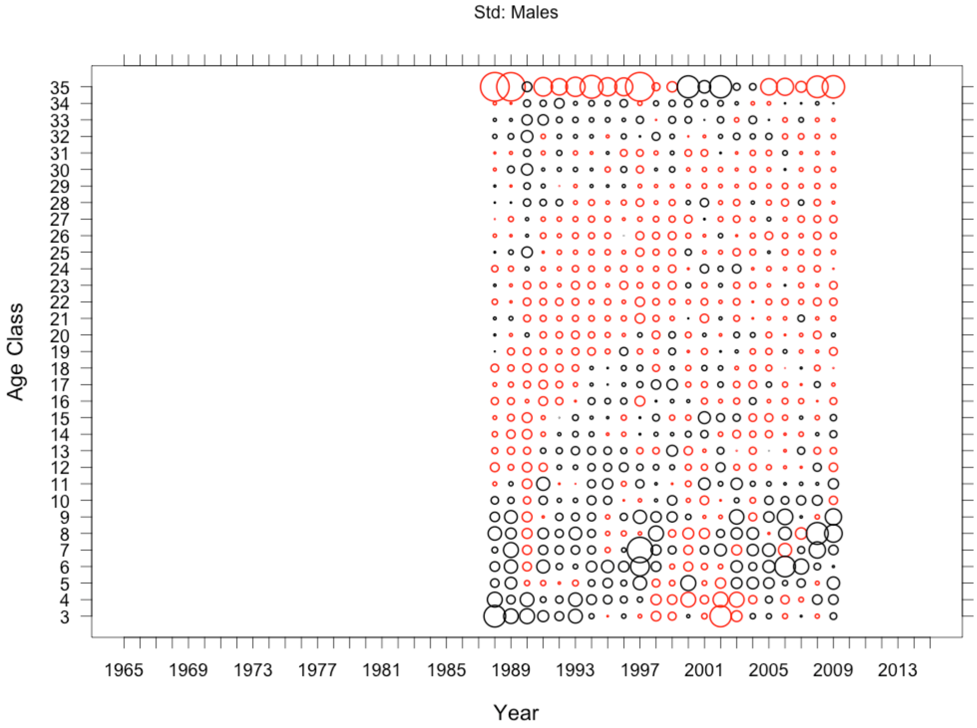
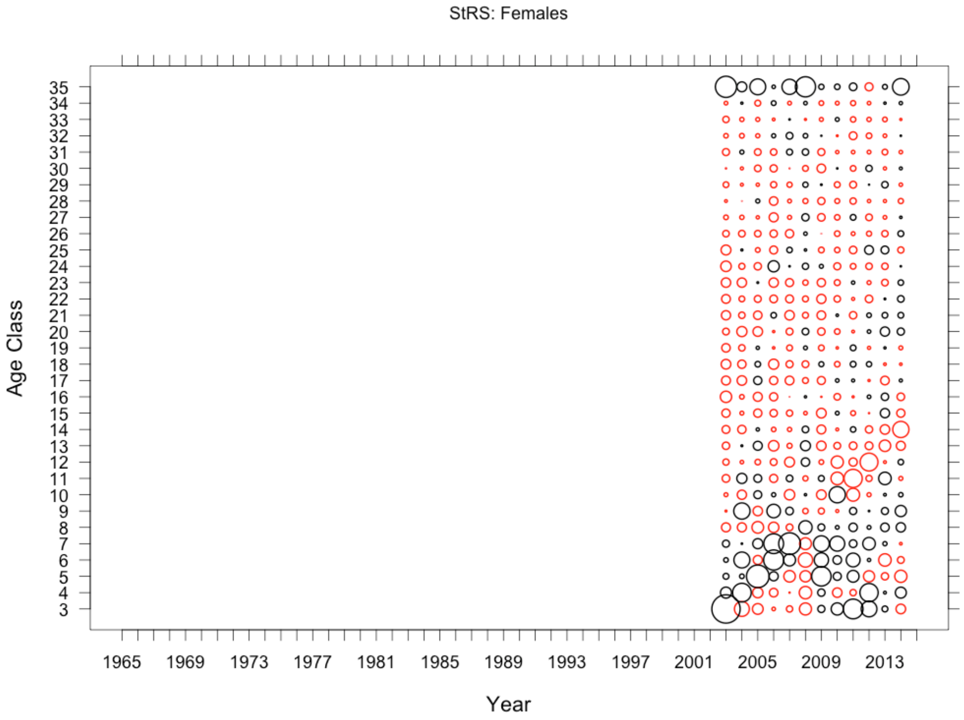


Figure 10. Age proportion residuals (observed minus predicted) of male Sablefish for the standardized trap gear survey for D1-Base-L (upper) and D1-Base-AE-L (lower). Circles are sized in proportion to the magnitude of the residual value; black and red circles represent positive and negative residuals, respectively. Residuals with values of zero and missing observations are not shown.



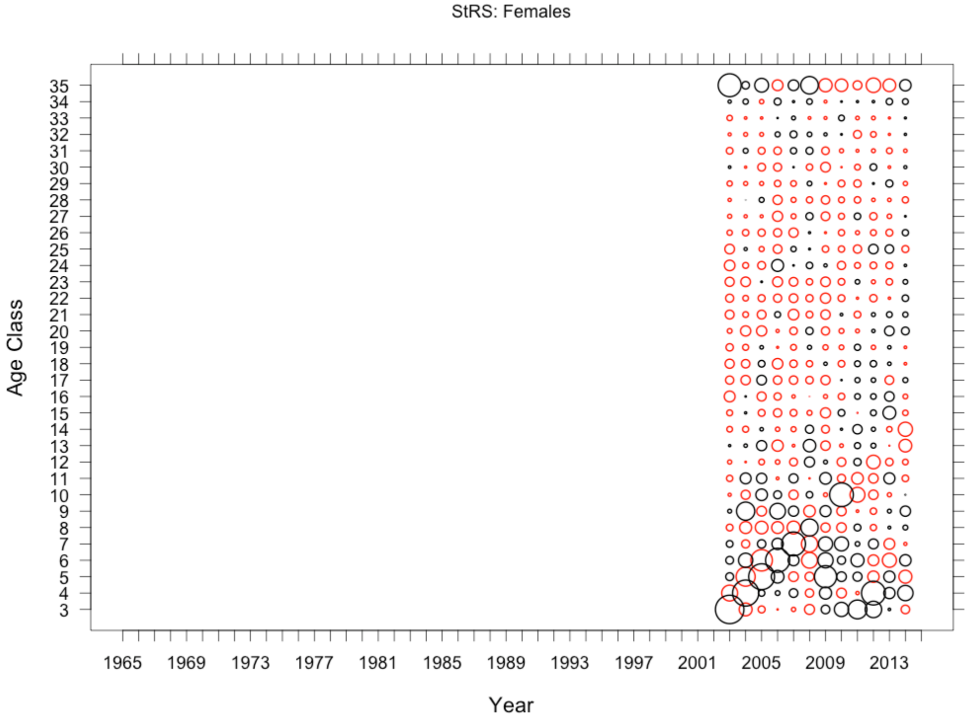
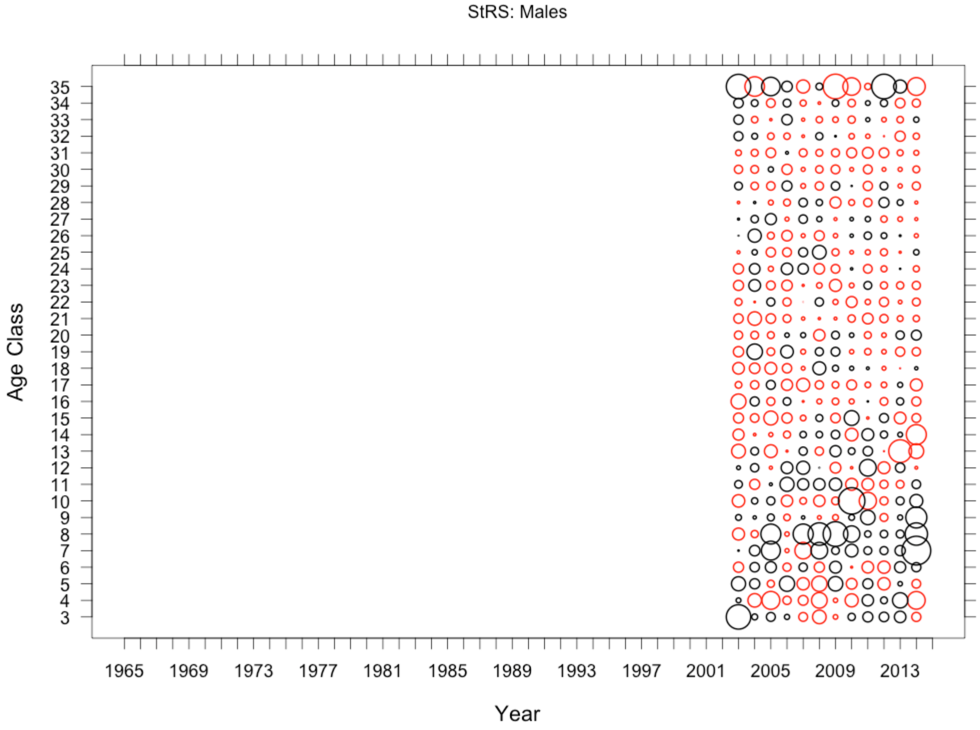


Figure 11. Age proportion residuals (observed minus predicted) of female Sablefish for the stratified random trap gear survey for D1-Base-L (upper) and D1-Base-AE-L (lower). Circles are sized in proportion to the magnitude of the residual value; black and red circles represent positive and negative residuals, respectively. Residuals with values of zero and missing observations are not shown.



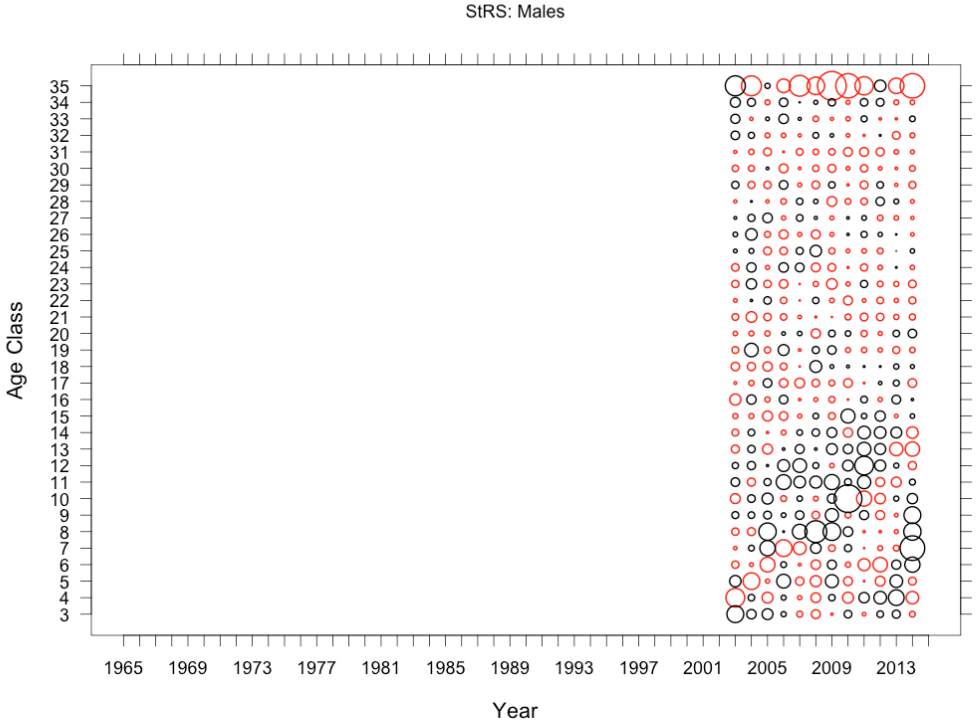


Figure 12. Age proportion residuals (observed minus predicted) of male Sablefish for the stratified random trap gear survey for D1-Base-L (upper) and D1-Base-AE-L (lower). Circles are sized in proportion to the magnitude of the residual value; black and red circles represent positive and negative residuals, respectively. Residuals with values of zero and missing observations are not shown.

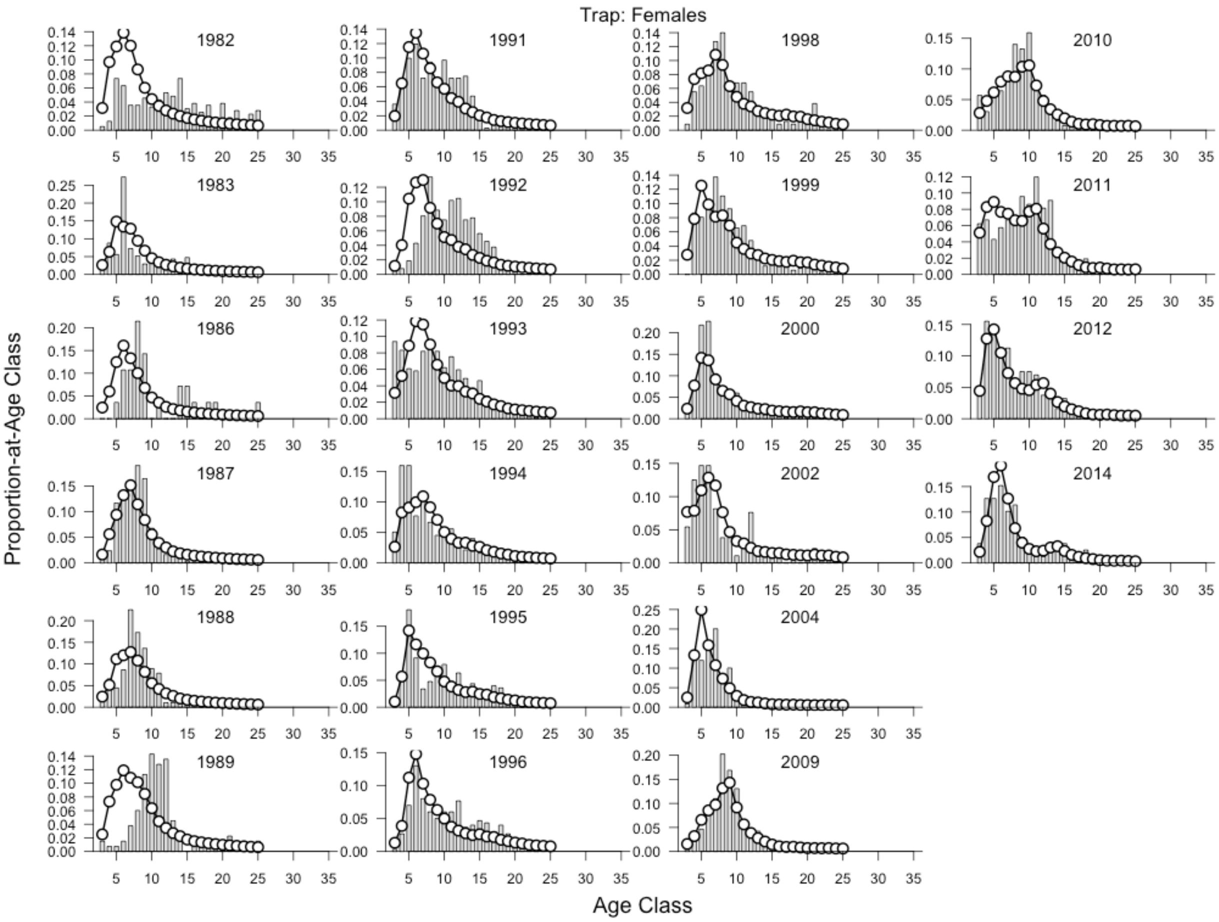


Figure 13. Annual observed (bars) and predicted (lines and circles) proportions-at-age of female Sablefish for the commercial trap gear fishery for the D2-Base-AE-L data scenario. Age proportions 3 to 25 were fitted; observed proportions age 26 and greater did not enter the likelihood calculations or age composition samples prior to 1990.

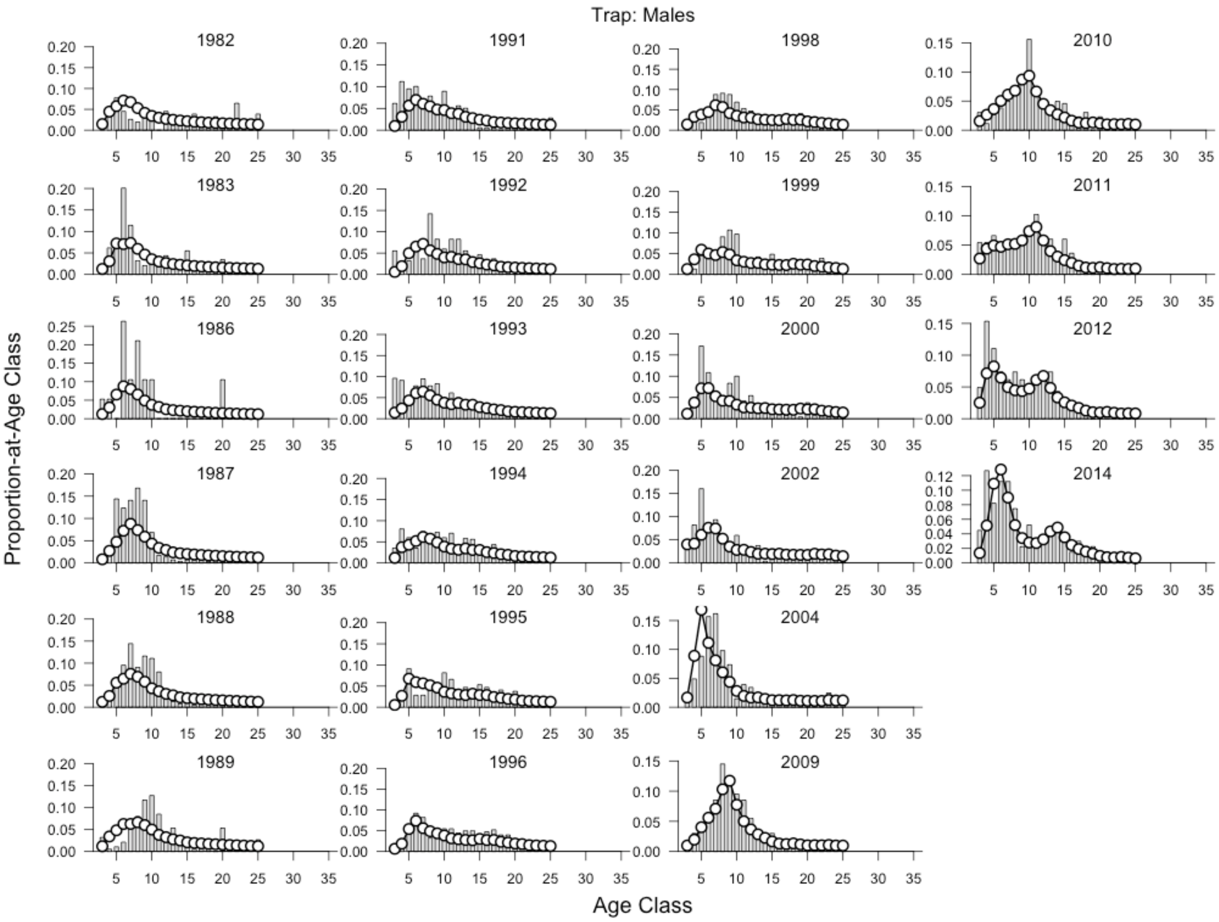


Figure 14. Annual observed (bars) and predicted (lines and circles) proportions-at-age of male Sablefish for the commercial trap gear fishery for the D2-Base-AE-L data scenario. Age proportions 3 to 25 were fitted; observed proportions age 26 and greater did not enter the likelihood calculations or age composition samples prior to 1990.

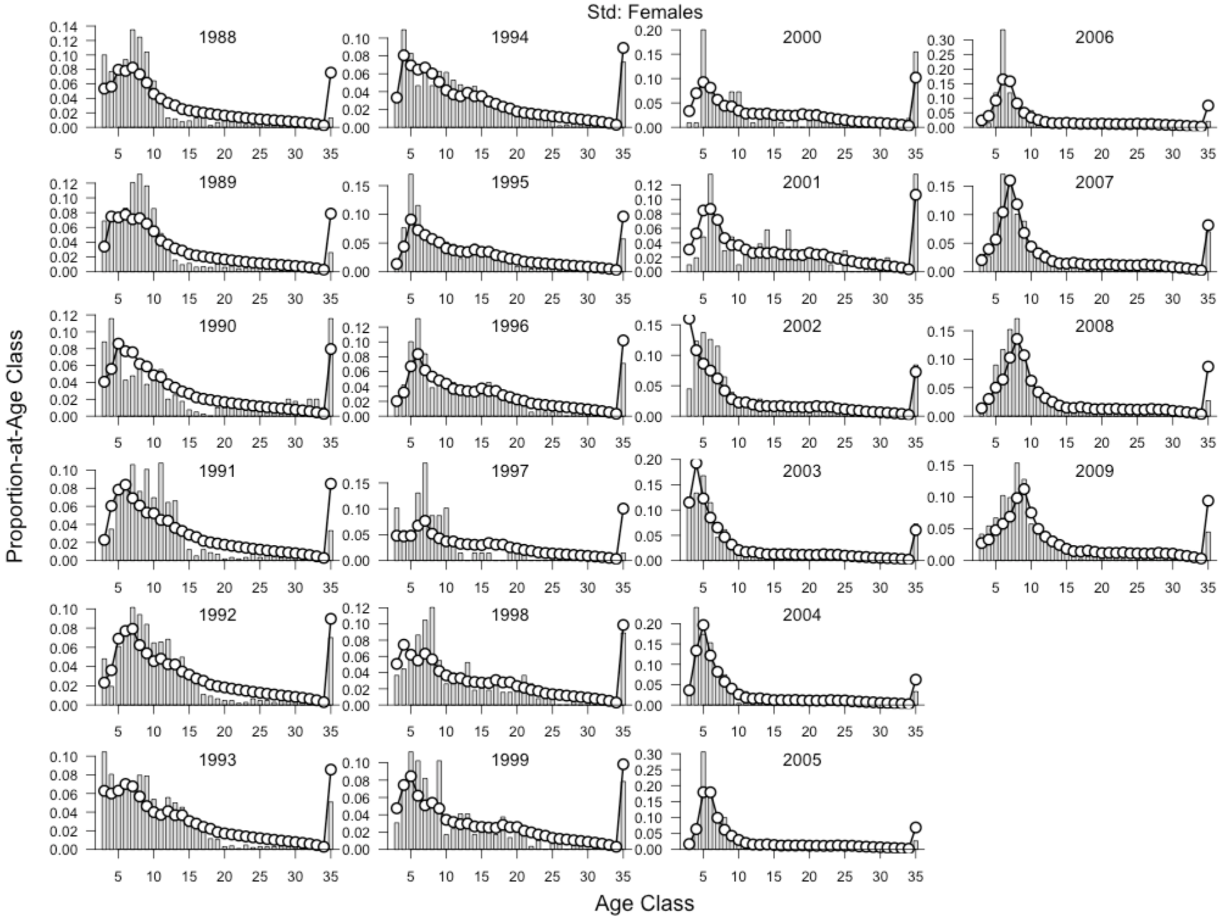


Figure 15. Annual observed (bars) and predicted (lines and circles) proportions-at-age of female Sablefish for the standardized trap gear survey year for the D2-Base-AE-L data scenario. Age proportions 3 to the plus group at age 35 were fitted.

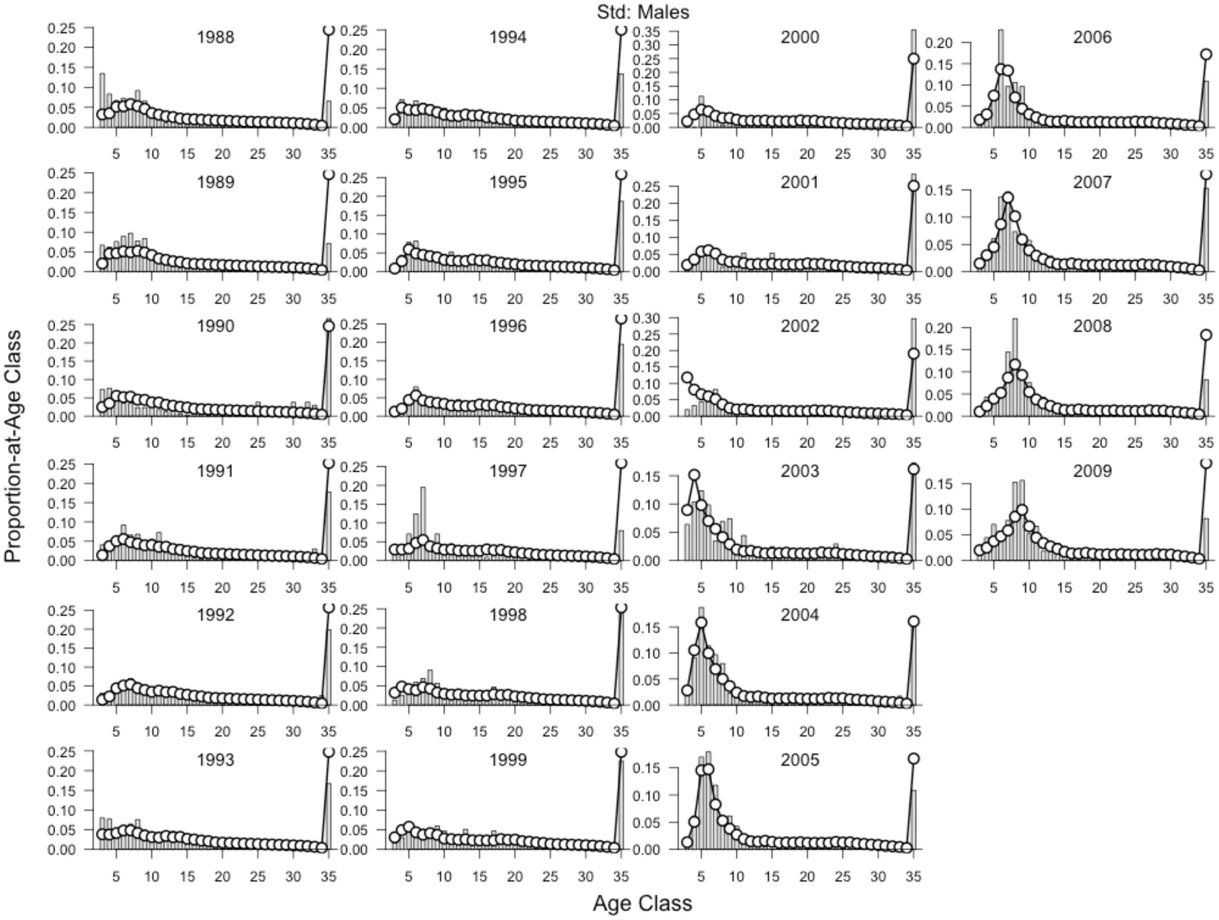


Figure 16. Annual observed (bars) and predicted (lines and circles) proportions-at-age of male Sablefish for the standardized trap gear survey by year for the D2-Base-AE-L data scenario. Age proportions 3 to the plus group at age 35 were fitted.

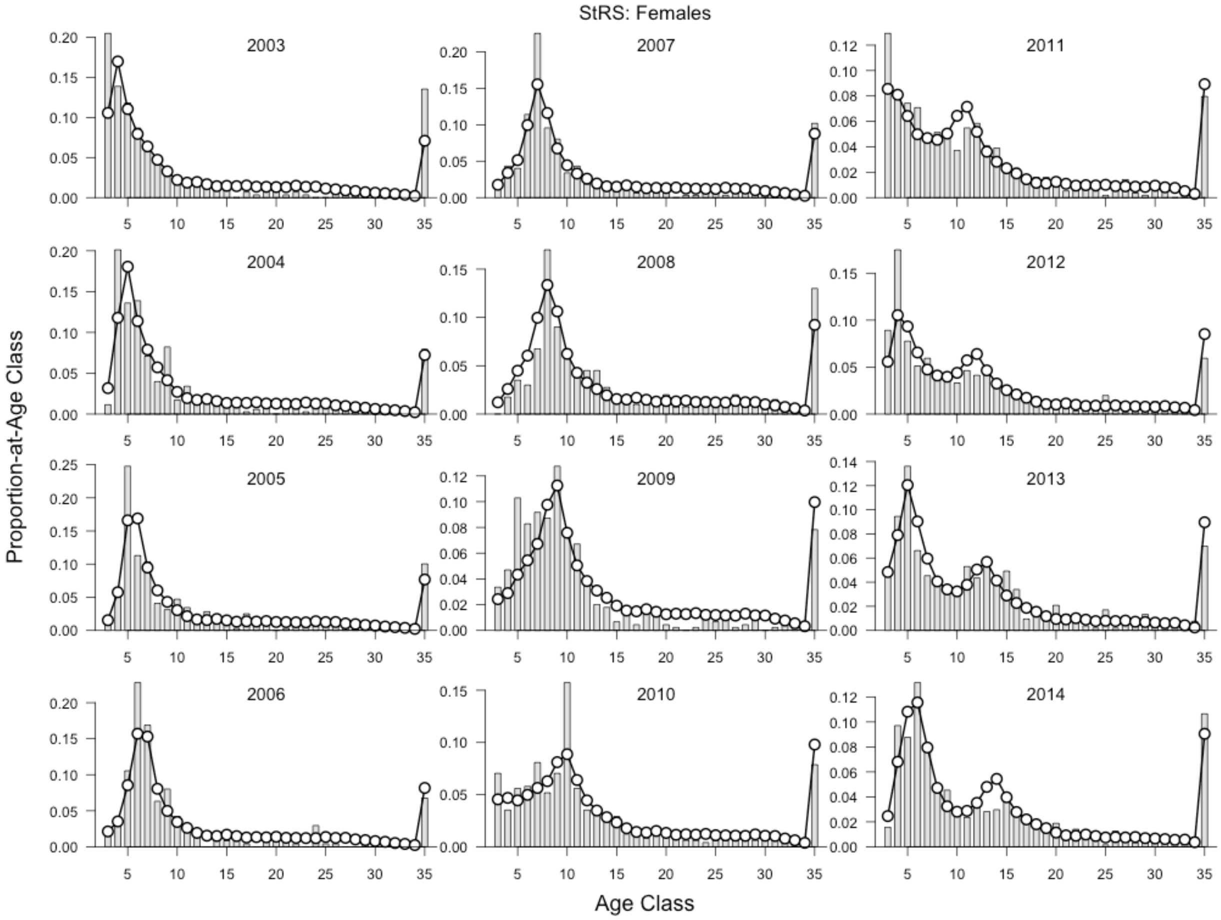


Figure 17. Annual observed (bars) and predicted (lines and circles) proportions-at-age of female Sablefish for the stratified random trap gear survey for the D2-Base-AE-L data scenario. Age proportions 3 to the plus group at age 35 were fitted.

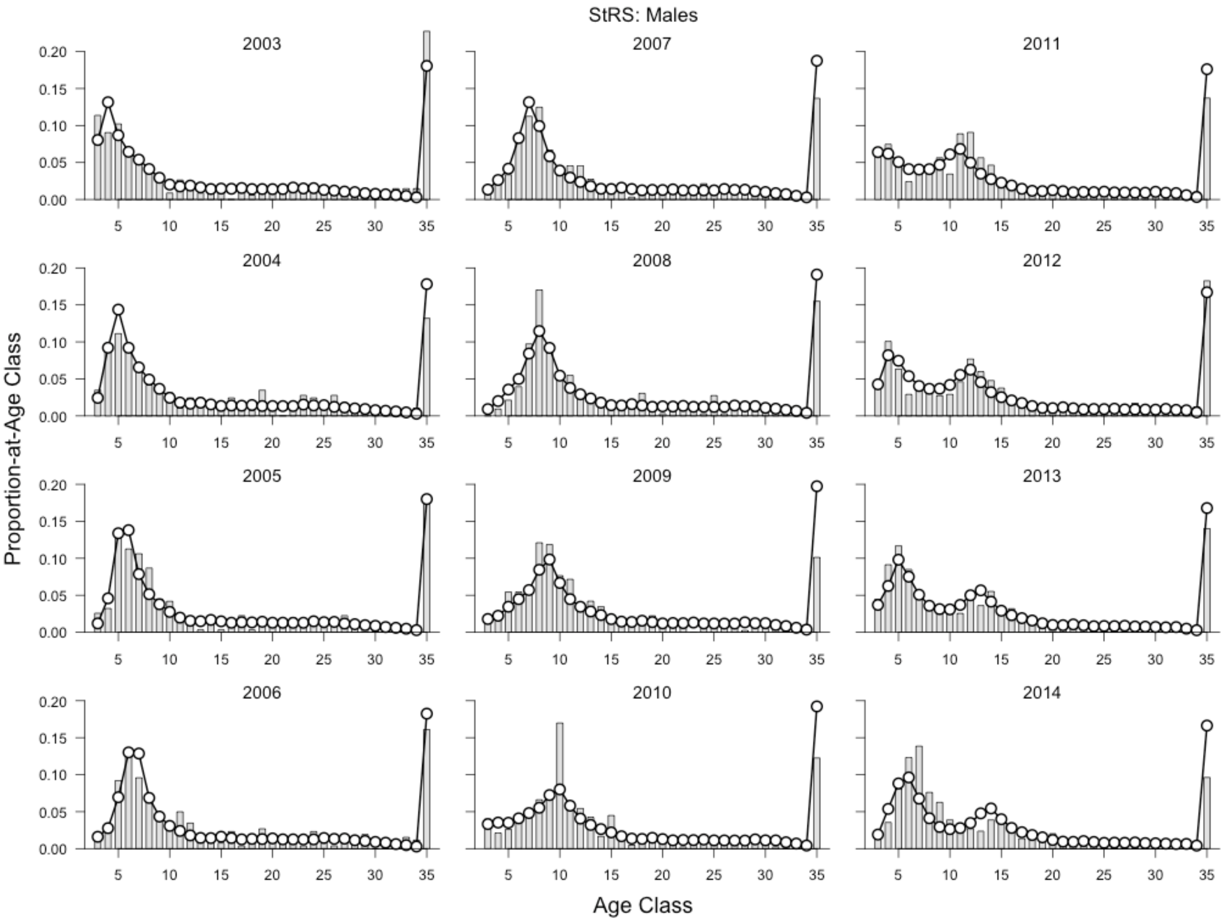


Figure 18. Annual observed (bars) and predicted (lines and circles) proportions-at-age of male Sablefish for the stratified random trap gear survey for the D2-Base-AE-L data scenario. Age proportions 3 to the plus group at age 35 were fitted.

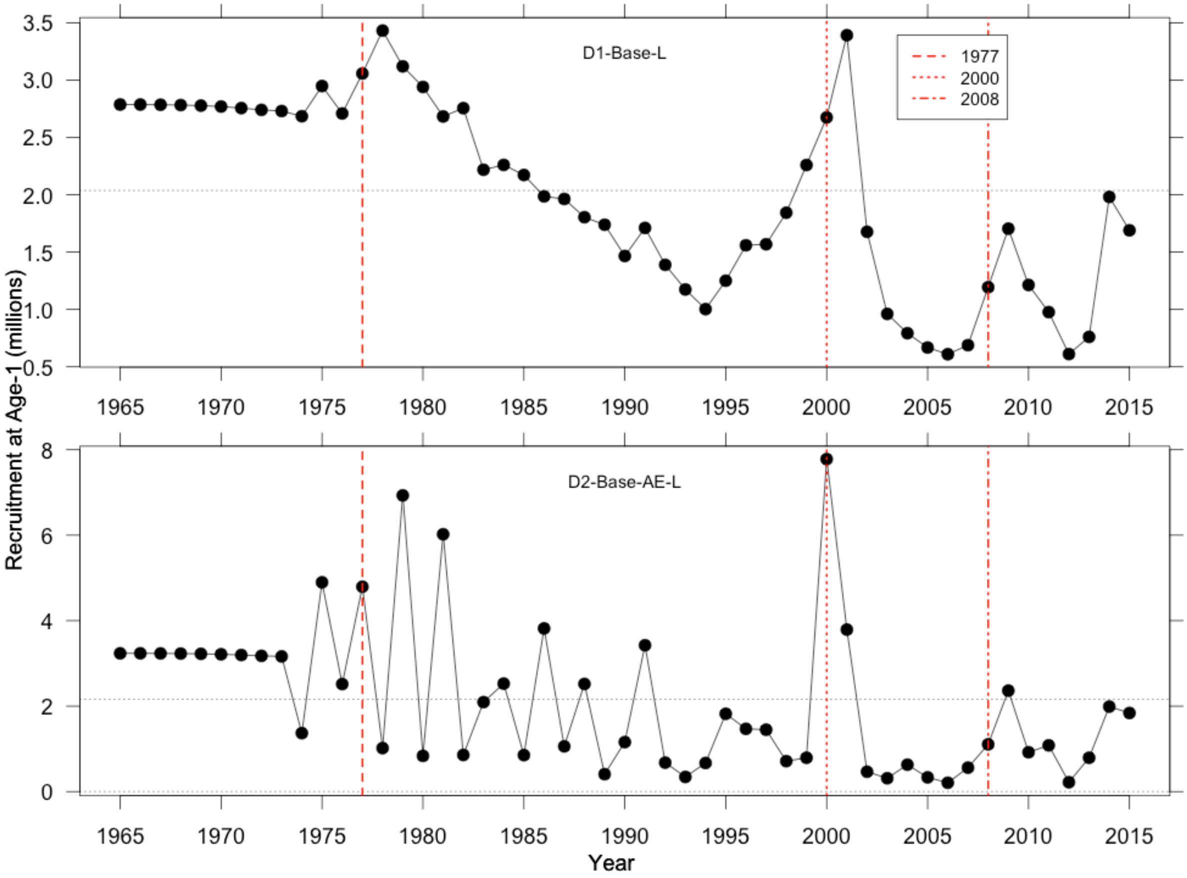


Figure 19. Annual estimates of Sablefish age-1 recruitment for the D1-Base-L and D2-Base-AE-L data scenarios. The average recruitment is indicated by the horizontal dashed line, excluding 2013-2015. Reference lines are provided for 1977, 2000, and 2008 brood years when influential recruitments are presumed to have occurred in the Gulf of Alaska, BC, and the US west coast.

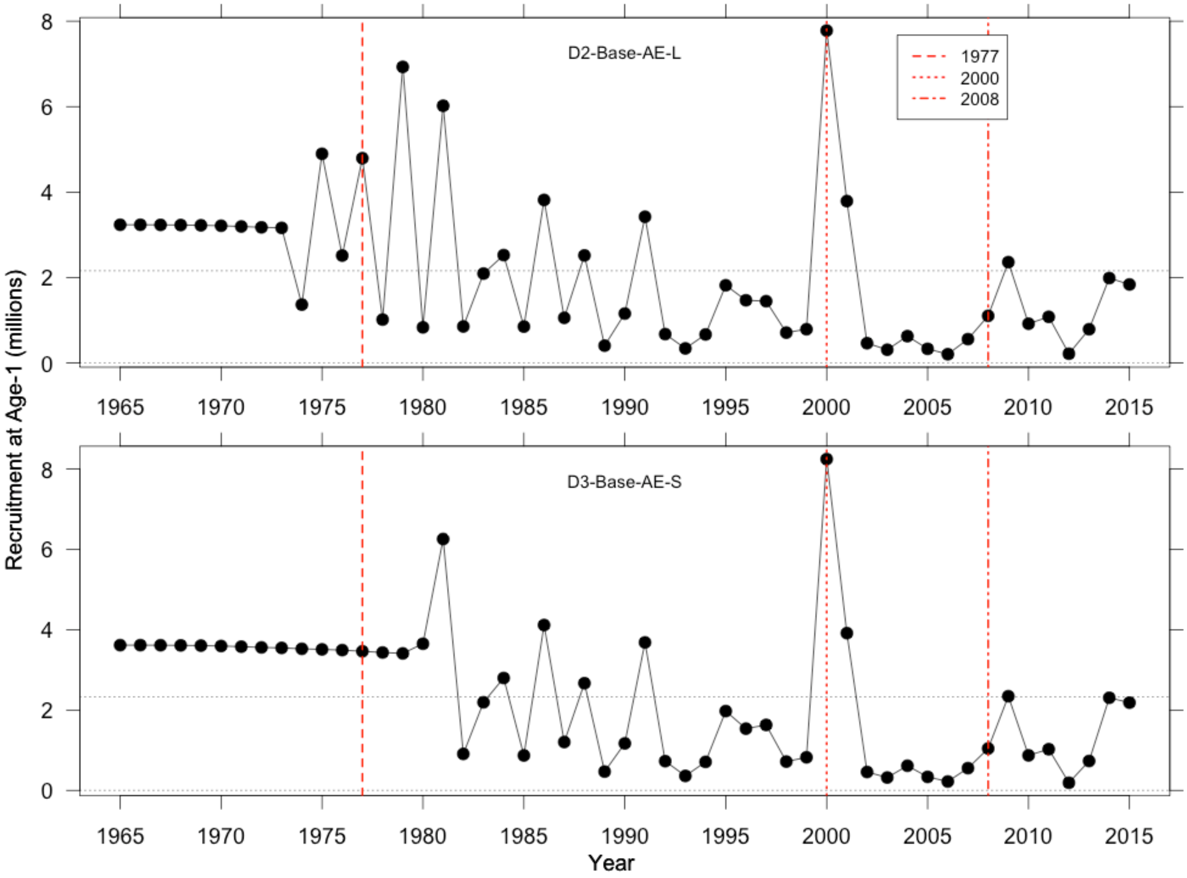


Figure 20. Annual estimates of Sablefish age-1 recruitment for the D2-Base-AE-L and D3-Base-AE-S data scenarios. The average recruitment is indicated by the horizontal dashed line, excluding 2013-2015. Reference lines are provided for 1977, 2000, and 2008 brood years when influential recruitments are presumed to have occurred in the Gulf of Alaska, BC, and the US west coast.

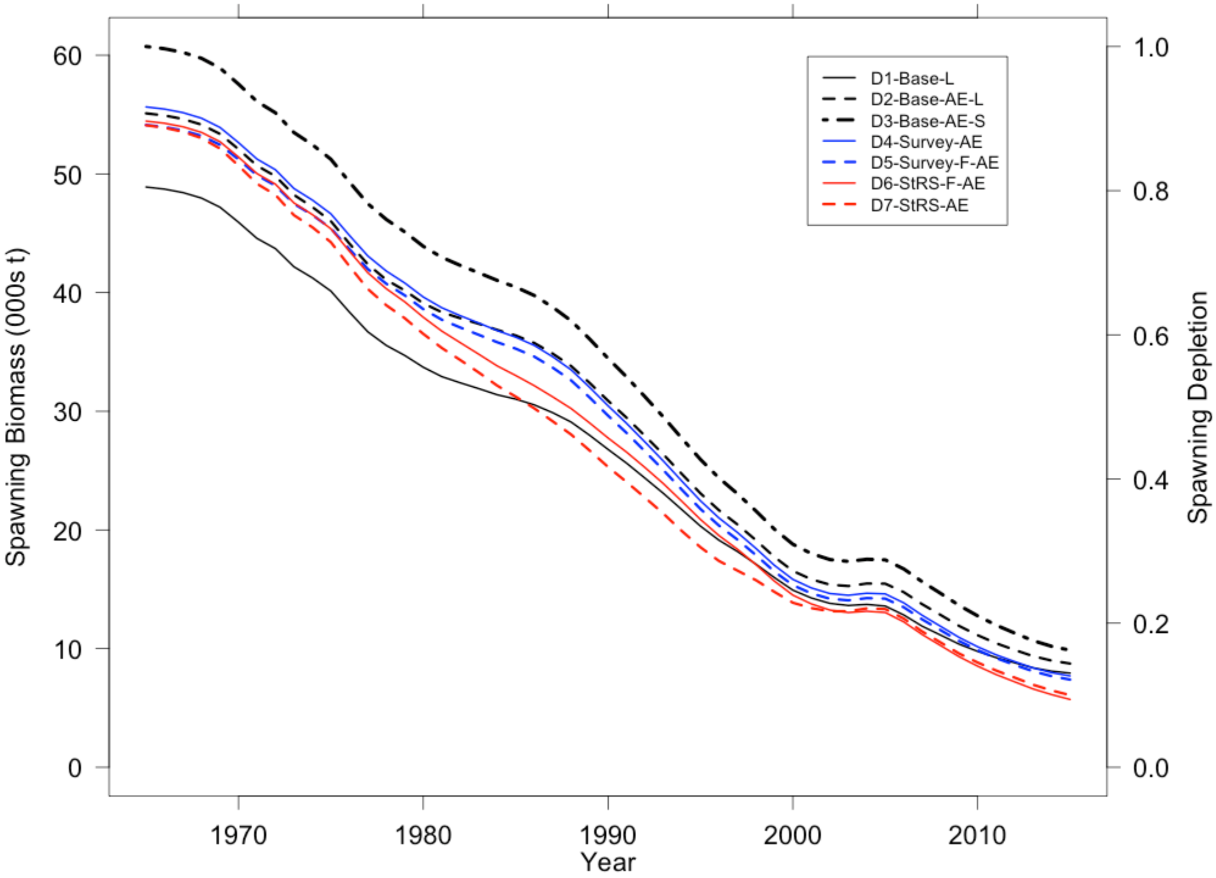


Figure 21. Annual female spawning biomass and depletion for seven data scenarios D1-D7 described in Tables 4-5.

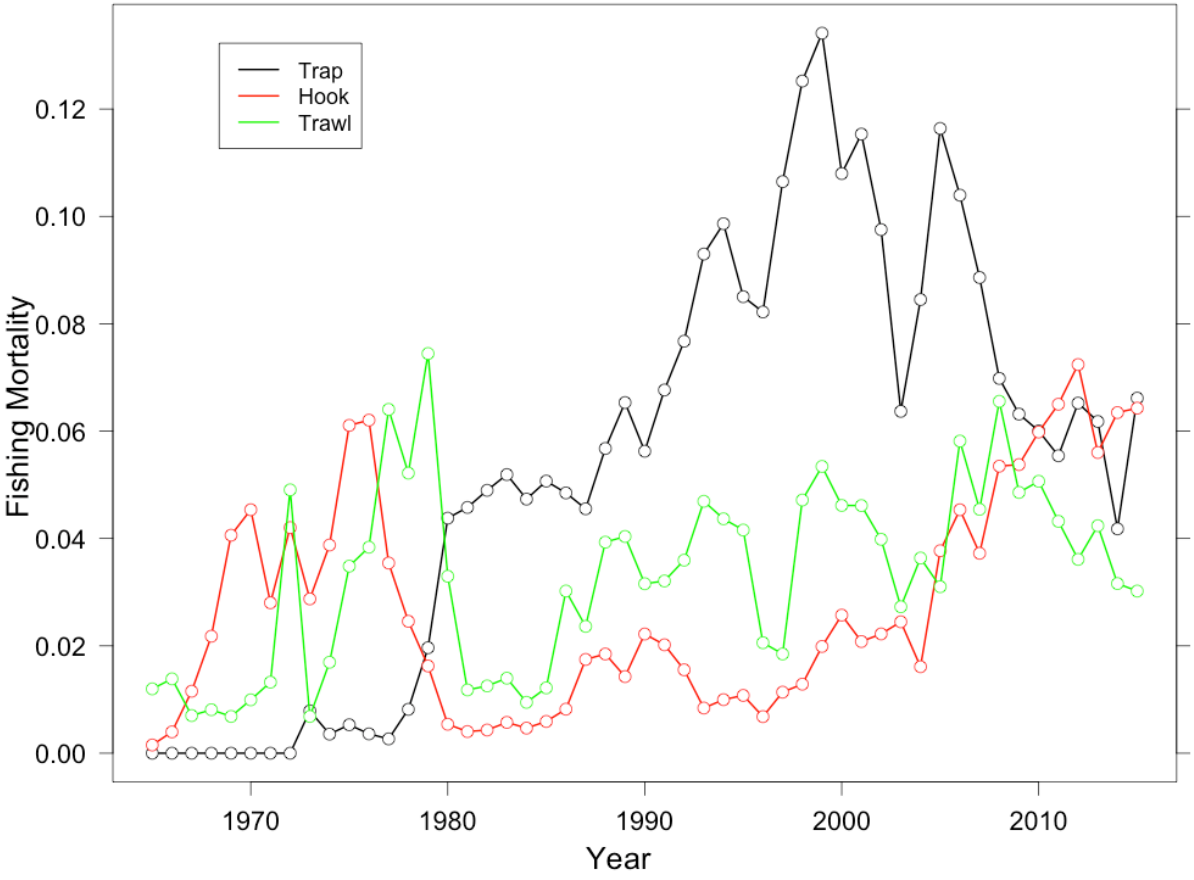


Figure 22. Annual instantaneous fishing mortality for longline trap, longline hook and trawl gears for the D2-Base-AE-L scenario.

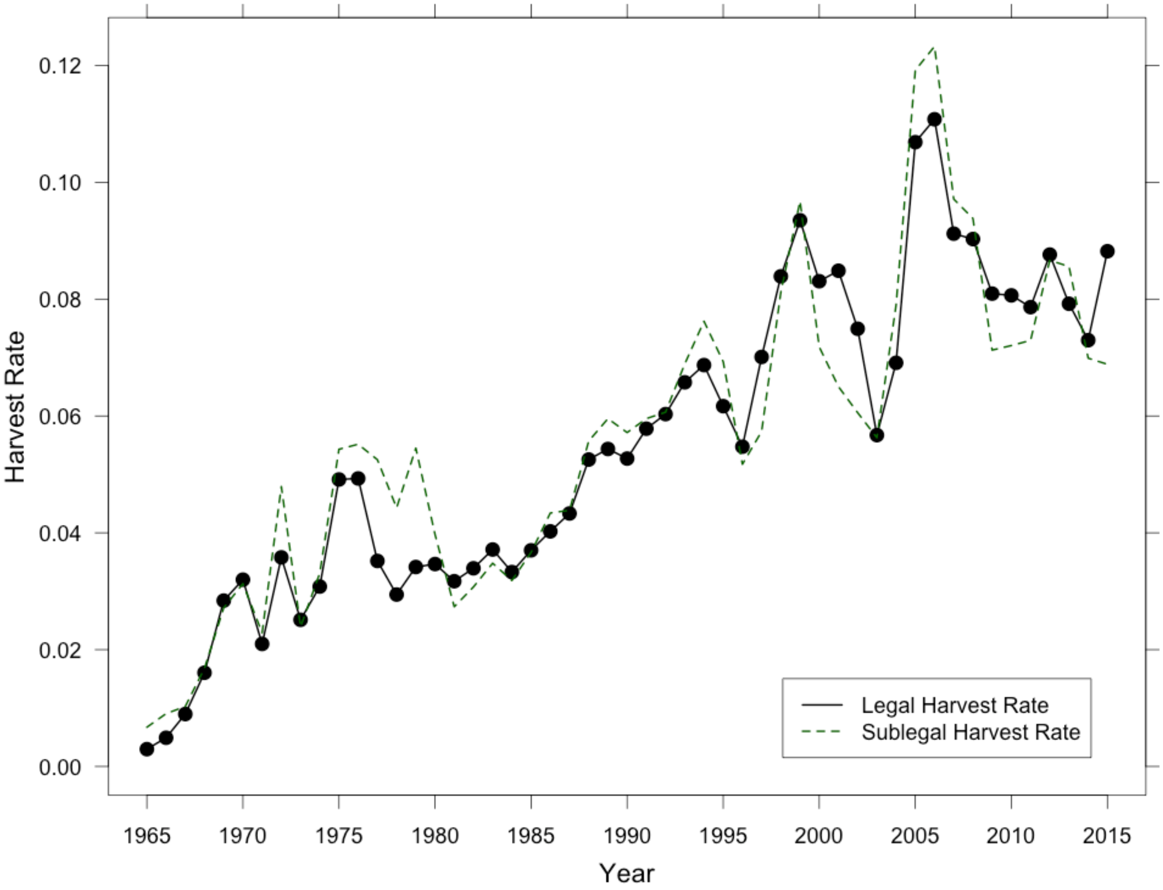


Figure 23. Estimated annual harvest rates for legal size and sublegal Sablefish for the D2-Base-AE-L data scenario.

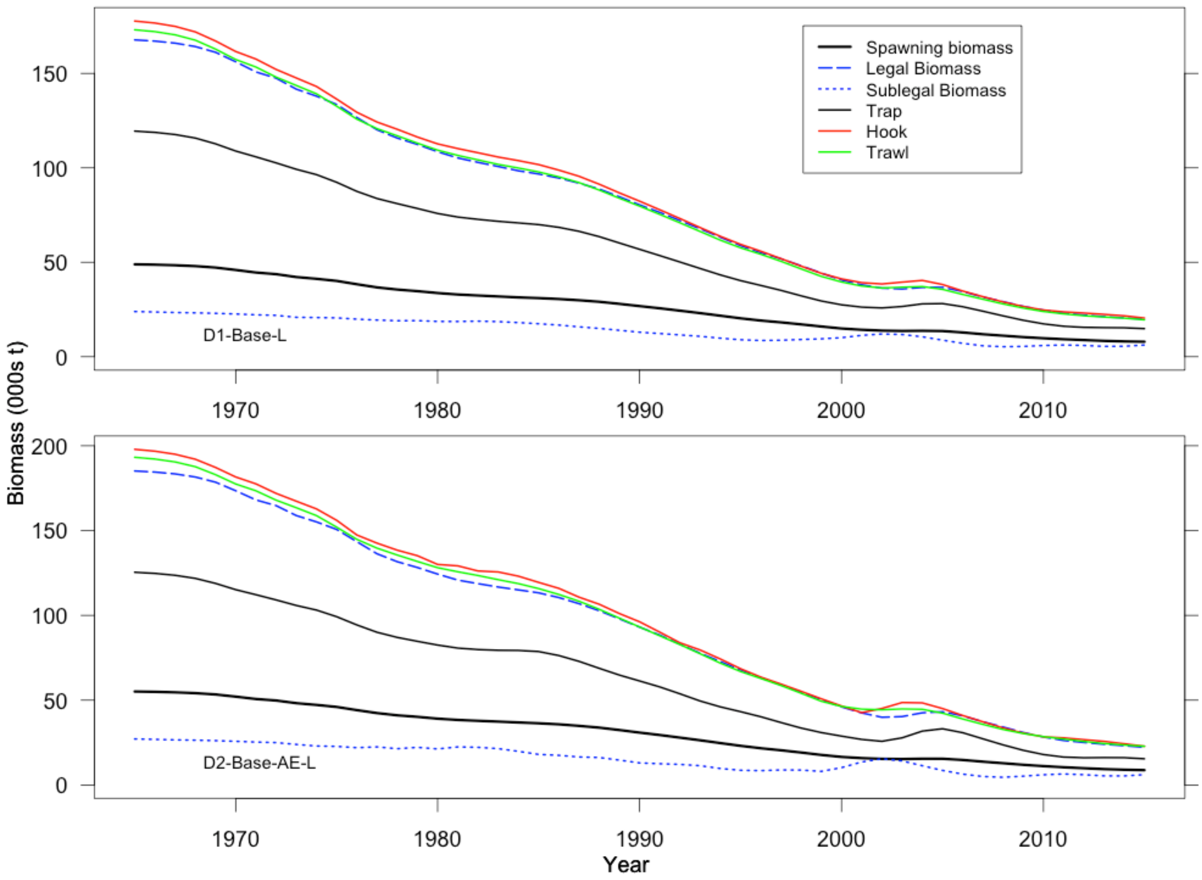
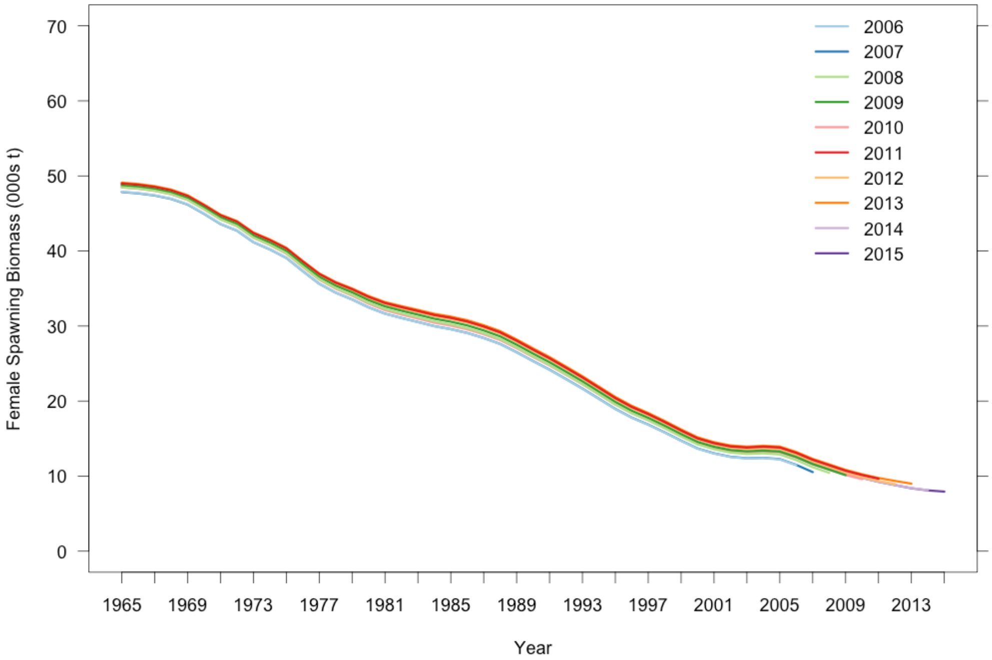


Figure 24. Estimated annual Sablefish biomass (000s t) trajectories for the D1-Base-L and D2-Base-AE-L data scenarios. Female spawning biomass is shown by the thick solid black line. Exploitable biomass is shown for longline trap, longline hook, and trawl gears. Sublegal biomass refers to the biomass of fish less than 55 cm fork length.



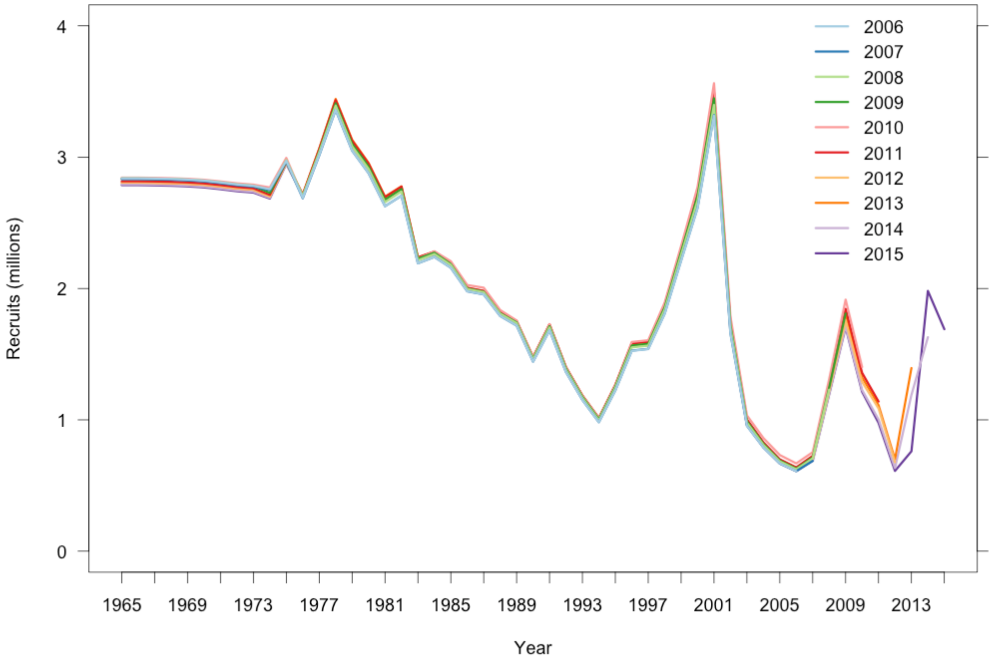
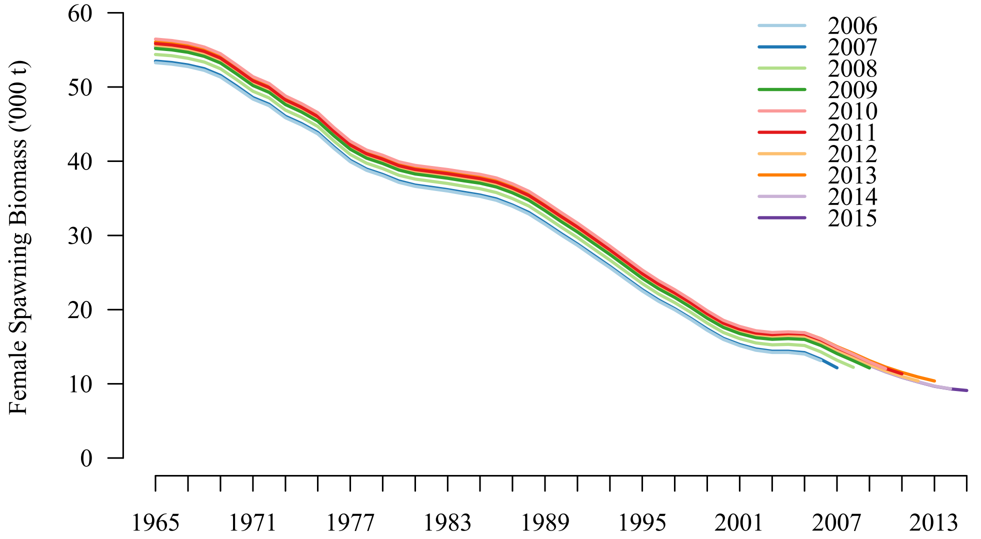


Figure 25. Retrospective pattern in female spawning biomass (000s t, upper panel) and recruitment (millions, lower panel) estimates for scenario D1-Base-L. Each lines represents the time-series of estimates given observed data up to the year indicated in the legend.



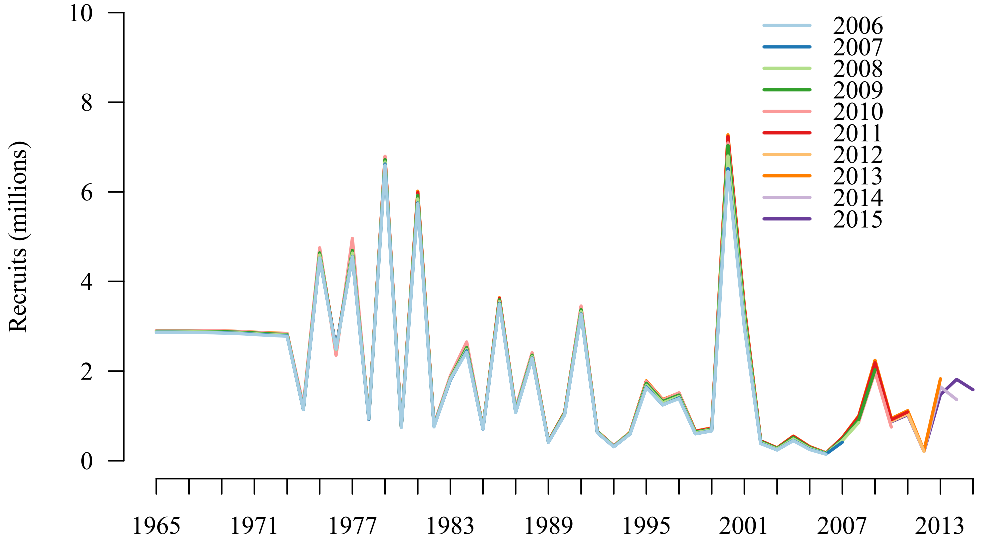


Figure 26. Retrospective pattern in female spawning biomass (000s t, upper panel) and recruitment (millions, lower panel) estimates for scenario D2-Base-AE-L. Each lines represents the time-series of estimates given observed data up to the year indicated in the legend.

APPENDIX A. MANAGEMENT AND CATCHES

A.1. MANAGEMENT

The history of Sablefish (*Anoplopoma fimbria*) fishery management from 1981 to 2015 is summarized in Table A-1. Current management regulations are specified in the Groundfish Integrated Fisheries Management Plan (DFO 2014a). Table A-1 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 the research allocation by Sablefish fishing year. Substantive management measures that affected fishing for Sablefish included:

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). By regulation, sub-legal Sablefish must be released at-sea by all commercial license categories.
2. Establishment of the Canadian 200-mile Economic Exclusion Zone in 1977 that resulted in departure of foreign fleets fishing Sablefish in Canadian waters by 1981.
3. Establishment of TAC 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). Currently 48 licenses are available.
5. The fixed allocation of 8.75% of the Sablefish TAC to trawl in 1981, which was based on historical average trawl landings.
6. The introduction of Individual Transferable Quota (ITQ) management to the Sablefish license sector in 1990.
7. Voluntary cessation of directed fishing for Sablefish by K licensed vessels in mainland inlets in 1994. Inlets are thought to be important rearing areas for juvenile Sablefish.
8. Several changes to the definition of a fishing “year”, including adjustments to start and end dates and to the length of the fishing year (see Table A-1). 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 licenses.
9. Various changes to “carry-over” rules that allow a percentage of uncaught ITQ (“an underage”) to be taken in the following fishing year, or an overrun of ITQ (“an overage”) to be applied against the following year’s ITQ.
10. The introduction of fishery-independent at-sea observers to the Option A trawl fleet in 1996 which resulted in improved accounting for retained and released catches, including catches of Sablefish.
11. The introduction of at-sea electronic monitoring (EM) to the non-trawl groundfish fleets, including the Sablefish licensed fleet, beginning in 2006 (see text below for details).
12. Changes in quota transferability beginning in 2006 with the introduction of the Integrated Groundfish Pilot Project that allowed non-K license holders to access a portion of Sablefish K quota on a temporary basis; the 2010/2011 fishing year was the first year of permanency for the Commercial Groundfish Integration Program (DFO 2010).

McFarlane and Beamish (1983) reported that total allowable catch management was introduced with the implementation 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 for each fishing year were set between 4,000 t and 4670 t until 1990 (Table A-1). Subsequently quotas were set based on harvest advice contained in stock assessments that attempted to provide low- and high-risk options, or by using decision tables based on fixed catch options.

In 2006 Fisheries and Oceans Canada (DFO) and the British Columbia (BC) Sablefish fishing industry began collaboration on the development of a management strategy evaluation (MSE) process intended to implement a transparent and sustainable harvest strategy (Cox and Kronlund 2008; Cox and Kronlund 2009; Cox et al. 2009). Although a management procedure was not applied immediately following this work, results were considered by fishery managers and in recommendations to DFO from the Sablefish Advisory Committee (SAC). Further development of the MSE process (Cox et al. 2011; DFO 2011) resulted a management procedure being selected and applied beginning with the 2011/2012 fishing year. A modified management procedure was implemented in 2014/2015 fishing year (DFO 2014b).

Table A-1 lists both directed Sablefish “K” and non-directed trawl “T” quotas. For the 1999/2000 to 2008/2009 Sablefish fishing years the two quota values cannot be added to obtain the overall yearly quota by Sablefish fishing year because of the difference in fishing year definitions between the two license types. 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 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 2008/09 fishing year for Sablefish was shortened to 204 days to achieve alignment with other groundfish license categories starting on February 21, 2009. Note 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 ITQ allocated in the previous 2009/2010 fishing year rather than the 2010/2011 fishing year.

The “carry-over” provision is a management tactic intended to allow individual quota holders the opportunity to delay catching current fishing year ITQ until the following year (an underage), and to accommodate over-runs of ITQ in the current fishing year (an overage). For Sablefish, the carry-over rules have changed in two ways since their inception. First, the allowable percentages of overage and underage have varied over time. For example, the practice was introduced in 1994 when a 5% carry-over was permitted. The carry-over percentage was increased to 10% in 1995. Beginning with the 2006/2007 Sablefish fishing year, Sablefish licensed vessels were permitted to carry-over up to 15% of uncaught ITQ. 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. A one-time 100% carry-over was permitted for the Sablefish license category into the 2009/2010 integrated groundfish fishing year. Trawl vessels fishing their T-quota Sablefish are permitted an overage/underage of 30% of the vessel's ITQ holdings (Section 5.5 of DFO 2014a). Carry over amounts can be substantial, each year depending on how individuals manage their quota, e.g., approximately 620 t (1,368,158 lb) in the 2015/16 fishing year (*pers. comm.* A. Keiser, DFO, Vancouver, BC, 2015).

Sablefish are caught incidentally in the directed Pacific Halibut (*Hippoglossus stenolepis*), directed “ZN” rockfish (*Sebastes* sp.), and the Lingcod (*Ophiodon elongatus*) and North Pacific Spiny Dogfish (*Squalus suckleyi*) longline hook fisheries prosecuted under a Schedule II license. Prior to 2006, Sablefish could not be landed under these license categories. A three-year pilot integrated groundfish management plan was put into place beginning April 2006. The objective of the pilot plan was to improve groundfish stock management through improved monitoring of both retained and released catch, reduced at-sea discarding, and the requirement for harvesters fishing all gear types to be accountable for all catch. Here “accountability” means achieving an adequate standard of catch estimation for retained and released catches of all species. The program was supported throughout the groundfish fishery, and the fishing industry was involved in designing and implementing new monitoring standards. The standards specified 100% at-sea video monitoring for non-trawl vessels with fishery-independent auditing of video, 100% fishery-independent dockside monitoring, individual transferrable quotas for Lingcod, North Pacific Spiny Dogfish and individual quotas (IQs) in rockfish fisheries (Koolman et al. 2007). These measures were in addition to measures already in place for groundfish fisheries managed under ITQs. A temporary quota reallocation process was developed to address catch accountability between the various commercial groundfish gear-based licenses for all species managed under quotas. The pilot program was extended to four years; the 2010/2011 fishing year was the first year of permanency for the Commercial Groundfish Integration Program (DFO 2010).

Beginning in 1996, at-sea observers were introduced for Option A trawl license vessels to provide fishery-independent estimates of catch (retained and discarded). Later, non-trawl groundfish license categories joined the 100% at-sea electronic monitoring (EM) program: the Pacific Halibut “L” license category on March 2, 2006, directed Lingcod and North Pacific Spiny Dogfish fisheries under schedule II license privileges on April 1, 2006, the Sablefish K license category on August 1, 2006, and the rockfish inside and outside ZN license categories on March 31, 2007. For these license categories, logbooks completed by fishermen are accepted as the basis for estimating at-sea catch beginning in 2006 because the EM program provides fishery-independent auditing of logbook accuracy through mandatory review of 10% of the video coverage from each trip (DFO 2010, Section 12). Although the video audit does not provide a complete census of the catch, there are increasingly punitive costs to individual fishermen associated with increased video review when logbooks fail to meet agreed-upon tolerances for reporting accuracy. Mandatory fishery-independent dockside validation of retained catch applies to all groundfish license categories including shoreside landings of Pacific Hake. Weights of Pacific Hake and bycatch delivered offshore to Joint Venture vessels are determined by two at-sea observers who estimate catch weight and species composition and convert frozen product weights back to round weight using conversion factors established by the observer after testing.

Table A-1. Management history by Sablefish fishing year. Various quota amounts are the initial allocation prior to carryover adjustments for all groundfish fisheries; for this reason, commercial landings may exceed TAC in a 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. Sablefish landings cannot be compared directly to the TAC due to the offset between K and T fishing years from 1999/2000 to 2007/2008. In 2008/2009 a common fishing year was established. The amounts shown for 2013/14 to 2015/16 include Section 10 Use of Fish allocations to account for research mortality. First Nations harvest occurred before 2001 but amounts were not specified. A small allocation for aquaculture purposes is not included in this table. Catch recommendations were derived from stock assessments, Sablefish Advisory Committee (SAC) recommendations or a management procedure (MP) selected through a Management Strategy Evaluation (MSE) process. Data for 2015/2016 noted in italics are complete to Dec 10, 2015.

Year	Type	Assessment Yield Rec.	TAC	K Quota	T Quota	First Nations	Research	Comm. 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	

Year	Type	Assessment Yield Rec.	TAC	K Quota	T Quota	First Nations	Research	Comm. Landings FY	Date Open	Date Closed	Days Open	FY Days
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	ITQ	-	4670	4260	410	-	-	4905	21-Apr-90	31-Dec-90	255	255
1991	ITQ	2,900-5,000	5000	4560	440	-	-	5112	01-Jan-91	31-Dec-91	365	365
1992	ITQ	2,900-5,000	5000	4560	440	-	-	5007	01-Jan-92	31-Dec-92	366	366
1993	ITQ	2,900-5,000	5000	4560	440	-	-	5110	01-Jan-93	31-Dec-93	365	365
1994	ITQ	2,900-5,000	5000	4521	433	-	-	5002	01-Jan-94	31-Dec-94	365	365
1995	ITQ	2,725-5,550	4140	3709	356	-	29.48	4179	01-Jan-95	31-Dec-95	365	365
1996	ITQ	690-2,580	3600	3169	304	-	81.65	3471	01-Jan-96	31-Dec-96	366	366
1997	ITQ	6,227-16,285	4500	4023	386	-	45.36	4142	01-Jan-97	31-Dec-97	365	365
1998	ITQ	3,286-4,761	4500	4023	386	-	45.36	4592	01-Jan-98	31-Dec-98	365	365
1999-00	ITQ	2,977-5,052	4500	6395	386	-	45.36	7012	01-Jan-99	31-Jul-00	578	578
2000-01	ITQ	3,375-5,625	4000	3555	350	-	45.36	3884	01-Aug-00	31-Jul-01	365	365
2001-02	ITQ	4,000	2800	2657	342	45	45.36	3075	01-Aug-01	31-Jul-02	365	365
2002-03	ITQ	4,000, revised to 2100-2800	2450	1883	206	45	45	2206	01-Aug-02	31-Jul-03	365	365
2003-04	ITQ	Decision table	3000	2647	254	45	54	2983	01-Aug-03	31-Jul-04	365	365
2004-05	ITQ	Decision table	4500	3995	384	45	75	4249	01-Aug-04	31-Jul-05	365	365
2005-06	ITQ	Decision table	4600	4056	389	45	110	4498	01-Aug-05	31-Jul-06	365	365

Year	Type	Assessment Yield Rec.	TAC	K Quota	T Quota	First Nations	Research	Comm. Landings FY	Date Open	Date Closed	Days Open	FY Days
2006-07	ITQ	SAC Advice	3900	3417	328	45	110	4004	01-Aug-06	31-Jul-07	365	365
2007-08	ITQ	SAC Advice	3300	2938	282	45	35	3429	01-Aug-07	31-Jul-08	365	365
2008-09	ITQ	SAC Advice	1509	1454	-	45	31	1514	01-Aug-08	20-Feb-09	204	204
2009-10	ITQ	SAC Advice	2450	2160	207	45	38	2159	21-Feb-09	20-Feb-10	365	365
2010-11	ITQ	MSE Analysis	2300	2023	194	45	38	2396	21-Feb-10	20-Feb-11	365	365
2011-12	-	MP Applied	2300	2030	195	45	30	2142	21-Feb-11	20-Feb-12	365	365
2012-13	-	MP Applied	2293	2030	195	45	23	1962	21-Feb-12	20-Feb-13	365	365
2013-14	-	MP Applied	1992	1670	163	45	84	1844	21-Feb-13	20-Feb-14	365	365
2014-15	-	MP Revised	2129	1821	175	45	84	1751	21-Feb-14	20-Feb-15	365	365
2015-16	*-*	*MP Applied*	*1992*	*1670*	*163*	*45*	*80*	*1823*	*21-Feb-15*	*20-Feb-16*	*365*	*365*

A.2. CATCHES

Catches are summarized by calendar year rather than fishing year due to several changes in the start date and duration of fishing years over the history of Sablefish management. The current fishing year definition of Feb 21 to Feb 20 was not adopted as a standard in case there are fishing year adjustments in future and because there is little difficulty caused by applying stock assessment modelling on a calendar year time step, i.e., catch that occurs from Jan 1 to Feb 20 does not impact management procedure choice. Only estimated catch to Dec 31 is required to project stock biomass into the following model year. Note that the terms “landings” and “retained catch” are used synonymously in this document.

Catches from fishing at seamounts are excluded since seamount harvest is not included within the coastal quota management area. From 1913 to 1964 only retained catch (landings) data are available. Beginning in 1965 to present, it is possible to extract commercial fishery catch data from six Pacific Region databases for longline trap (“trap”), longline hook (“longline”) and trawl gear types. More than one database may be used for a given year because in some years all available catch data do not reside in a single database. For trawl gear, at-sea observer logs are used preferentially over fisher logs when both types of data are available. The databases, applicable years, and types of data are listed below:

1. **GFCatch.** Legacy database that includes commercial daily fisher logbooks, landing records derived from sales slips or validation records, interviews with vessel skippers and waterfront observations for all gears from 1965 to 1995 (Rutherford 1999). *GFCatch* includes trawl logbooks from 1954 to 1995, trap logbooks from 1979 to 1995, longline hook logbooks from 1979 to 1986.
2. **PacHarv3.** Legacy database containing landings records derived from commercial sales slips from 1987-1994 for longline hook and 1982-2002 for “other” gears.
3. **PacHarvSable.** Legacy Sablefish catch database that includes fishery logbooks for longline trap and hook gears from 1990 to March 2006 and dockside validated landings records from 1995 to 2002. *PacHarvSable* also includes fishing by foreign countries for all gear types from 1965 to 1980, synthesized in part from previous databases and historical data files.
4. **PacHarvHL.** Legacy hook and line catch database that contains:
    a. fisher logbooks for commercial Zn and Schedule II license categories for 1996 to March 2006, and
    b. some at-sea observer logs and dockside validated landings for Pacific Halibut from 1991 to 2002.
5. **PacHarvest.** Legacy Regional database that contains commercial trawl observer logs, some fisher logs, and dockside validated landings records from 1996-Mar 31, 2007.
6. **GFFOS.** Groundfish stand-alone database derived from Pacific Region Fisheries Operation Systems (FOS) database that includes:
    a. commercial groundfish trawl observer logs and fisher logs from April 1, 2007 to the present,
    b. commercial fisher logs from April 1, 2006 to present for Pacific Halibut, Sablefish, combination Pacific Halibut and Sablefish, North Pacific Spiny Dogfish, Lingcod, rockfish outside and inside,
    c. dockside validated landings records from 2003 to present for the Sablefish license category and combined Sablefish and Pacific Halibut fishing,

d. dockside validated landings from 2006 to present for Pacific Halibut, and

e. dockside validated landings from April 1, 2006 to present for North Pacific Spiny Dogfish, Lingcod, rockfish outside and inside.

The management plan (DFO 2014a) specifies optional use of a measurement grid to determine if Sablefish are of legal size for non-trawl license categories; at-sea observers on trawl vessels verify that retained Sablefish are of legal size. Measurement grids are designed to allow fishery-independent video verification of fish size prior to release. In non-K licensed groundfish fisheries, any releases are considered legal size and counted as such in the post-fishing audit process. The extent to which the measurement grid is used during commercial fishing is not reported. Sablefish released on a directed Sablefish trip under a K license are assumed to be sub-legal and do not have to be measured. A new initiative for the trawl license category implemented for the 2010/2011 fishing year to increase responsibility for releases of fish that are below marketable size does not apply to Sablefish. This is because Sablefish less than 55 cm fork length are deemed to be sub-legal by regulation, rather than unmarketable (see clause 10.3 of DFO 2014a).

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 by fixed longline trap or longline hook gear. The liced catch categories are considered at-sea releases since 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. This catch categorization was made possible by the logbook and catch monitoring requirements introduced in 2006.

Fishery-independent 100% at-sea observer coverage applied to the trawl license category (Option A) predated the groundfish integration pilot project by 10 years. Thus, estimates of retained and released Sablefish are available for Option A trawl from 1996 to 2015. Groundfish vessels 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 vessels, and therefore releases are thought to be under-estimated prior to 2006. Prior to 1996, at-sea releases reported in the GFCatch database are considered badly under-estimated for all license categories and do not represent reliable estimates of released catch (Fargo 2005).

A.2.1. Retained Catches

After 1920 and prior to 1965 retained catches of Sablefish (Table A-2, Figure A-1, Figure A-2) averaged less than 1,000 t. Beginning about 1965 the Canadian domestic fishery increased effort on Sablefish (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 hook fleets from Japan, the US, the USSR and the Republic of Korea (McFarlane and Beamish 1983, Table A-1). 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 to utilize yield surplus to Canadian domestic fleet needs despite the establishment of the Economic Exclusion Zone in 1977. Total landings have ranged from 1,713 t (2014) to 7,408 t (1975) since 1969 and averaged about 4,741 t over the 1969 to 1999 period. Landings have declined from 4,642 t in 2005 to 1,713 t in 2014 in response to TAC reductions over the same period.

A.2.2. Released Catch

At-sea releases of Sablefish (Table A-3, Figure A-1, Figure A-2) were reported in logbooks on a voluntary basis for all groundfish fishery sectors before 1996; beginning in 1996 at-sea observers were required for trawl vessels (Option A only). Other groundfish sectors relied on fishery-dependent logbooks until 2006 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 large 1977 year class (McFarlane and Beamish 1983, Table A-3). Releases of Sablefish reported by the trawl sector increased in 1996, when the at-sea observer program was implemented (Table A-3). However, the amount of Sablefish releases reported by other groundfish sectors did not change markedly until 2006 when auditing of at-sea electronic monitoring was broadly introduced.

We use at-sea observer (trawl sector 1996-2015) and EM audited (non-trawl sectors 2006-2015) logbook data in this analysis (Table A-3, Figure A-2). 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 Sablefish releases 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 ITQ management), as well as the actual number of Sablefish released at sea.

Mortality associated with releases of sub-legal Sablefish is not deducted from the quota holdings for any sector since they must be released by regulation. However, mortality attributable to releases of legal Sablefish is deducted from ITQ holdings using mortality rates that depend on gear type (DFO 2009). For trawl gear, the ITQ deduction is calculated at a rate of 10% of legal-size releases for the first two hours of the tow and an additional 10% prorated for each portion of an hour thereafter. For example, a 2.25 h tow results in a mortality rate of 12.5% of the legal releases applied against the vessel's ITQ. Deductions of 9% and 15% of legal-size releases are applied to ITQ for longline trap and longline hook gear, respectively, regardless of set duration. These mortality rates were not established on scientific grounds but were intended by managers to provide an incentive to retain legal-size Sablefish (DFO 2014a).

Table A-2. Sablefish retained catch (t) by calendar year aggregated by gear type. Data in italics and marked with an asterisk for 2015 are complete to November 13, 2015.

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	2914.3
1969	5	0	4882.3	191.3	0	0	5073.6
1970	6	0	5284.1	269.9	0	0	5554
1971	7	0	3173	350.3	0	0	3523.3
1972	8	0	4635.7	1270.3	0	0	5906
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	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
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
1984	20	3275.4	365.1	187	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	928.6	623.4	0	0	5324
1990	26	3072.4	1371.8	460.7	10.1	0	4915
1991	27	3494.4	1179.2	438.8	6	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	5008.5
1995	31	3282.2	474.3	427.4	4.8	0	4188.7
1996	32	2984.3	280.4	190.9	4.9	0	3460.6
1997	33	3553.6	431.1	156.3	4.1	0	4145.1
1998	34	3772	443.6	376.1	5.6	0	4597.3
1999	35	3677.3	627.9	403	4.7	0	4713
2000	36	2745.3	752.2	326.1	7.3	0	3830.9
2001	37	2742.8	564.5	299.6	3.4	0	3610.4
2002	38	2161.9	564.4	267.1	16.2	0	3009.5
2003	39	1419.2	640.5	227.6	19.9	22.4	2329.5
2004	40	2128.5	467.4	344.7	16.2	8.6	2965.4
2005	41	3196.5	1146.7	277.1	13.6	8.3	4642.3
2006	42	2773.5	1306.3	441.8	12	10.7	4544.2
2007	43	2140	971.5	288.9	9.1	10.5	3419.9
2008	44	1487	1246.5	352.9	9.6	12.4	3108.5
2009	45	1174.4	1107.7	223.2	6.4	12	2523.6
2010	46	975.7	1095.3	208.7	7.3	11.4	2298.4
2011	47	803.9	1082.4	175.7	0	11.1	2073
2012	48	891.6	1150.4	154.7	0	11.3	2207.9
2013	49	841.4	877.3	184	0	32.1	1934.8
2014	50	572.5	984.9	132.4	0	22.9	1712.7
*2015**	*51*	*912.6*	*1194.9*	*121.5*	*0*	*0*	*2228.9*

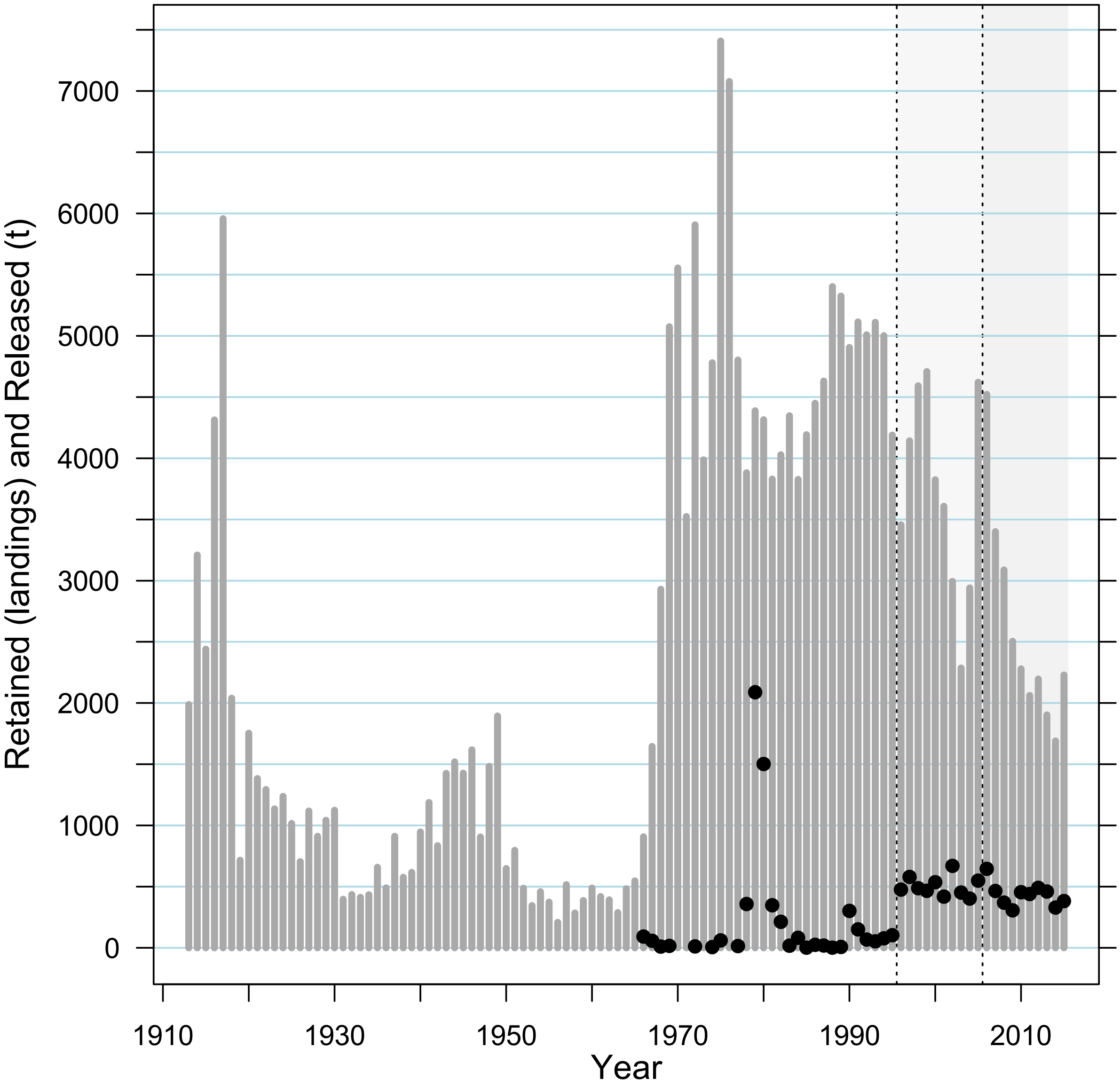


Figure A-1. Annual Sablefish retained catch (t) from 1913 to 2015 from commercial sources (gray bars). Annual released catches (black circles) from 1965 to 2015 are shown as reported. Vertical dotted lines demarcate the trawl at-sea observer period from 1996 to 2006 and the start of catch monitoring for all groundfish sectors in 2006. Catch data for 2015 are complete to November 13, 2015.

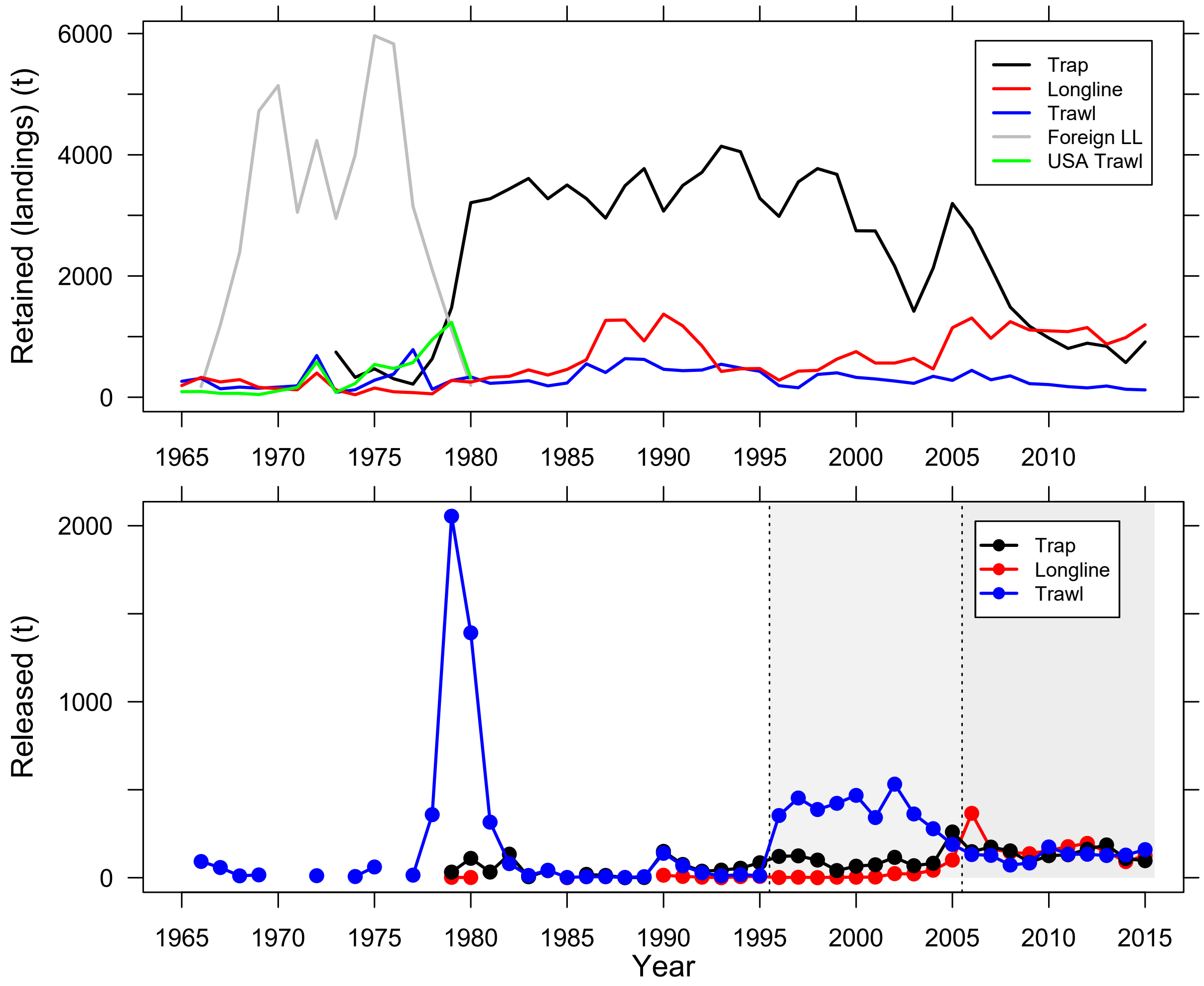


Figure A-2. Annual commercial retained catches (t) of Sablefish from domestic Canadian and foreign fisheries from 1965 to 2010 (upper panel). Released catch is shown for Canadian trap, longline hook and trawl fisheries (lower panel). Vertical dotted lines indicate the start of 100% at-sea observer coverage in 1996 for the trawl sector and start of 100% at-sea monitoring for all sectors in 2006. Data for 2015 are complete to November 13, 2015.

Table A-3. Sablefish released catch (t) by gear type for calendar years 1974 to 2015. Data in italics for 2015 (marked with an asterisk) are complete to November 13, 2015. Releases are not reported prior to 1974. Data are reported by at-sea trawl observers 1996 to 2015 and via logbooks audited by the at-sea electronic monitoring program 2006-2015 for trap and longline gears.

Year	Time Step	Trap	Longline	Trawl	Total
1974	10	0	0	6.8	6.8
1975	11	0	0	61.2	61.2
1976	12	0	0	0	0
1977	13	0	0	14.8	14.8
1978	14	0	0	358.4	358.4
1979	15	32	1.7	2054	2087.7
1980	16	110	1.2	1391.3	1502.5
1981	17	32.3	0	315.6	347.9
1982	18	133.6	0	79.9	213.5
1983	19	5.3	0	12.8	18.1
1984	20	40.3	0	42.7	83
1985	21	0	0.1	1.9	2
1986	22	19	0	5.4	24.4
1987	23	13.2	0	5.6	18.8
1988	24	0.5	0	1.6	2.1
1989	25	1.3	0	6.2	7.5
1990	26	149.7	14	139.1	302.8
1991	27	75.2	7.5	68	150.7
1992	28	37.3	3.1	28.1	68.5
1993	29	43	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
1998	34	100.1	0.5	387.5	488.1
1999	35	40.7	2.6	422.7	466
2000	36	65.5	3	468.1	536.6
2001	37	73.7	3.4	341.8	418.9
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	100.7	189.2	549.7
2006	42	148.2	365.8	132	646
2007	43	173.9	164.5	126.8	465.2
2008	44	152.7	145	71.8	369.5
2009	45	87	136.2	83.7	306.9
2010	46	125.4	154.7	174.7	454.8
2011	47	130.7	176.4	133.7	440.8
2012	48	161.3	195.2	133.5	490
2013	49	186.4	147.4	126.4	460.2
2014	50	108.2	91.8	128.9	328.9
*2015**	*51*	*97.1*	*125.7*	*160*	*382.8*

A.2.2.1 Trawl Releases

Estimates of released catch weight from the trawl sector (1996-2015) 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 2015 period ranged from ~70 t (2008) to ~532 t (2002) and exceeded retained trawl catches from 1996 to 2004 (Table A-3). After 2004, retained catch exceeded released catch, although incomplete data for 2015 indicate similar amounts of retained and released Sablefish catch. Since the trawl license category 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 between fishing masters as a possible contributing factor to reduced interception and subsequent release of sub-legal Sablefish over the past several years (i.e., avoidance behaviour). Most releases are categorized as sub-legal Sablefish and no liced Sablefish are reported from trawl gear. Reported trawl releases peaked in 2002 at 532 t, declined to a low of 72 t in 2008 and have reached 160 t for 2015 (as of November 13).

A.2.2.2 Trap And Longline Hook 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 license categories until 2006 (Table A-3). Although the non-trawl license categories joined the at-sea electronic monitoring program at different dates between March 2, 2006 and March 31, 2007, reported release data are taken as reliable estimates for calendar years 2006 to 2015 for this analysis. The Pacific Halibut and Sablefish license categories, which account for most of the longline Sablefish catch, joined March 2, 2006 and August 1, 2006, respectively. Non-trawl releases are generally reported in logbooks by count rather than by estimated weight. Regardless of gear type, for this analysis 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 2014a); the management plan value is used for calculating mortality of legal-sized Sablefish to be applied against ITQ for the non-trawl sectors (DFO 2010. The management plan weight was set at 3.63 kg (8 lbs) as a deterrent against releases of legal Sablefish.

Note that longline hook fishing also includes combination fishing under both Pacific Halibut and Sablefish licenses. Longline hook fisheries by the outside rockfish, Lingcod, North Pacific Spiny Dogfish, and inside rockfish hook fishery license categories represent minor contributions to total at-sea releases. Releases of Sablefish by the Pacific Halibut license category were relatively large during 2006. The Pacific Halibut fishery opened March 5, 2006, prior to the commencement of the Pilot Integration Program on April 1, 2006. While L licensed fishermen were accountable and responsible for releases of Sablefish beginning April 1, 2006 they did not have to cover their catches with quota in the few weeks between March 5 and April 1. Furthermore, since 2006 was the first year of integrated fishing, there was likely a period of adjustment before fishing behavior was altered by the requirement to be responsible for catches of Sablefish, i.e., to buy or lease quota to cover the retained catches or discard assigned mortality for legal size fish.

A.3. PRORATION OF RETAINED AND RELEASED CATCH FOR 2015

The Sablefish operating model is based on a calendar year; an estimate of retained and released catches by gear type is usually required for the terminal model year. For example, this document provides catches reported to November 13, 2015 so that an estimate of catches to December 31, 2015 would normally be required. We do not prorate retained and release catches for the purposes of this document because the objective of improving the operating model does not critically depend on the small amount of catch expected in the final 6 weeks of the 2015 calendar year. When the operating model is used in a feedback simulation the following algorithm is applied to estimate incomplete catches in terminal year, T:

a. Calculate the average proportion of catch to date in the 3 years preceding year T as

$$\bar{p} = \frac{1}{3}\sum_{t=T-3}^{T-1}\frac{C'_t}{C_t} ,$$

where C'_t is the retained catch to date in year t, and C_t is the retained catch in year t.

b. Estimate the retained catch in the balance of year T as

$$C''_T = \left(\frac{C'_T}{\bar{p}}\right) - C'_T .$$

c. Calculate the average proportion of retained catch by gear type $g=1,\ldots,G$ in the three years preceding year T as

$$\tilde{p}_g = \frac{1}{3}\sum_{t=T-3}^{T-1}\frac{C_{gt}}{C_t} .$$

d. Calculate the retained catches by gear type in the balance of the terminal year as

$$C''_{gT} = \tilde{p}_g C''_T .$$

e. Estimate the retained catch by gear type for the terminal year as

$$\tilde{C}_{gT} = C'_{gT} + C''_{gT} ,$$

where C'_{gT} is the catch to date by gear in year T.

f. Repeat steps (1-5) for released catch.

g. Assume the retained catch for the stratified random trap survey in year T is the same as year T -1.

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APPENDIX B. CATCH DISTRIBUTION AND CONCURRENT SPECIES

B.1. INTRODUCTION

This appendix provides graphical analyses of commercial catch of Sablefish (*Anoplopoma fimbria*) by spatial extent, season, and depth. Summaries of species co-occurrence in commercial catches that included Sablefish are also presented by gear type to characterize species composition and identify any catches of species of conservation concern. Some assessments have used similar analyses as a proxy for characterizing "habitat", but we note that all such presentations of fishery-dependent data strongly depend on choices made by fishermen. Thus, these data are not representative of the distribution of Sablefish in British Columbia, such as spatial or temporal habitat occupied by juvenile fish that are not typically targeted by commercial fishing. Similarly, species caught concurrently with Sablefish vary as a function of the area fished, as well as with time-varying management actions and changing market demands.

B.2. DATA SOURCES

B.2.1. Data Selection

Commercial fishery catch and effort data were extracted from *GFFOS,* a groundfish stand-alone database derived from Pacific Region Fisheries Operation Systems (FOS) database that includes:

a. Commercial groundfish trawl observer logs and fisher logs from April 1, 2007 to the present,

b. Commercial fisher logs from April 1, 2006 to present for Pacific Halibut (*Hippoglossus stenolepis*), Sablefish, combination Pacific Halibut and Sablefish, North Pacific Spiny Dogfish (*Squalus suckleyi*), Lingcod (*Ophiodon elongatus*), rockfish (*Sebastes*) outside and inside,

c. Dockside validated landings records from 2003 to present for the Sablefish license category and combined Sablefish and Pacific Halibut fishing,

d. Dockside validated landings from March 2002 to present for Pacific Halibut, and

e. Dockside validated landings from April 1, 2006 to present for North Pacific Spiny Dogfish, Lingcod, rockfish outside and inside.

Commercial groundfish trawl observer and fisher logs were extracted from the Pacific Regional database, PacHarvTrawl, to generate catch and effort data from 1996 to March 31, 2007.

Data recorded in at-sea observer logs are used preferentially over fisher logs when both types of data are available. The analyses presented in this appendix combine all longline hook records as a single gear type; longline hook effort is now dominated by directed fishing for Pacific Halibut and combined Pacific Halibut and Sablefish.

B.2.2. Species Catch Weight

Sablefish are caught by commercial longline hook, longline trap and trawl gear types. The species catch weight is based on the landed species weight from dockside monitoring records plus the non-retained weight recorded on observer or fisher logs. The landed weight is apportioned to individual tows according to the proportions by weight recorded on the observer or fisher log. For example, suppose the landed weight of species A is 100 kg, and the observer or fisher log reports that 10% of that species by weight was caught on tow number one and 90% was caught on tow number two of a total of two tows. The catch weight of species A on tow number one is given as 10 kg and the catch weight of species A on tow number two is given as 90 kg. This choice is made because the recorded landed weight from dockside monitoring is considered more accurate than the weights recorded in at-sea observer or fisher logs which are usually visual estimates. When a species is recorded as retained in the at-sea observer or fisher log, but is not recorded in the landing records, the retained weight recorded in the fisher log is used. Similarly, the recorded fisher logbook weights are used for the weights of non-retained species.

B.3. CATCH DISTRIBUTION

B.3.1. Spatial Distribution

Sablefish is caught along the entire coast of British Columbia with the largest removals often occurring in offshore waters at the north-west tip and west coast of Haida Gwaii and deep canyons or troughs off the West Coast of Vancouver Island (Figure B-1, Figure B-2). Note that the distribution of longline hook gear extends into (a) Queen Charlotte Sound and Strait, (b) Hecate Strait, and (c) the relatively sheltered inside waters of the mainland inlets (Figure B-1). In contrast, the K licensed longline trap fleet voluntarily ceased fishing mainland inlets in 1994 to protect areas inhabited by juvenile Sablefish and does not fish Hecate Strait or inlets. The longline hook fleet is largely dominated by directed fishing for Pacific Halibut, combination fishing for Pacific Halibut and Sablefish, and to a lesser degree fishing for rockfish (*Sebastes* sp.) under a Rockfish Outside license, and species such as Lingcod and North Pacific Spiny Dogfish longline hook fished under a Schedule II license.

B.3.2. Seasonal Distribution

The weekly depth distributions of sets that caught Sablefish are shown for longline hook, longline trap and bottom trawl gear in Figure B-3. For longline hook gear, the distributions of depths of fishing become shallower in the mid-March through mid-November, coincident with the opening of the Pacific Halibut fishery. Deeper fishing using longline hook gear during the period from December through February is likely directed at Sablefish. Longline trap fishing changes depth distribution as Sablefish become available at shallower depths on the continental shelf in summer and into the fall, but fishing remains distributed within about 400 to 700 m depth throughout the year. Fishing by bottom trawl gear becomes quite shallow in June through October as the mixed fresh fillet rockfish market is supplied but is distributed at deeper depths from December through April when the fishery directs towards species such as Arrowtooth Flounder (*Atheresthes stomias*), Dover Sole (*Microstomus pacificus*) and thornyheads (*Sebastolobus*). The occasional very deep sets during summer months are likely directed at thornyheads.

B.3.3. Depth Distribution

Commercial fishing effort for the three gear types that catch Sablefish differ markedly in their depth distribution and degree of species specificity (Figure B-4). Longline hook and trawl gears tend to catch most Sablefish at shallower depths than longline trap gear, which catches 90% of Sablefish between 404 and 827 m. However, Sablefish are encountered by trawl gear as deep as about 750 m, likely when fishing for Dover Sole and thornyheads. Trap gear tends to be highly selective for Sablefish as almost every set encounters Sablefish. In contrast, fishing using longline hook and trawl gears is necessarily multi-species and is not exclusively located in habitat preferred by Sablefish.

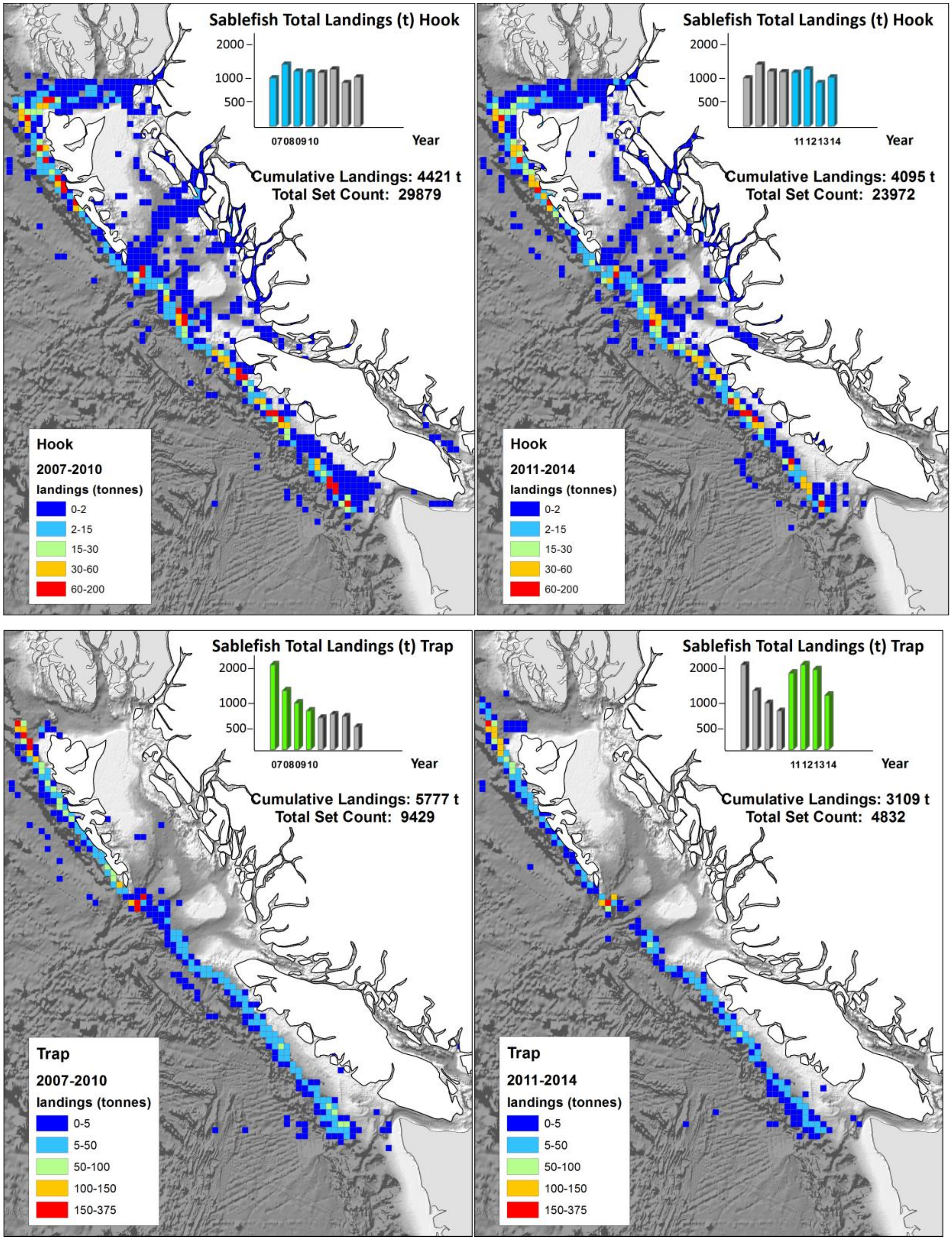

Figure B-1. Landed catch (t) of Sablefish summarized on a 10 x 10 km^2 grid by year ranges 2007-2010 and 2011-2014 for longline hook (upper panels) and longline trap gears (lower panels). Histograms show the total landings by year. Cumulative landings and total set counts are listed for each year range.

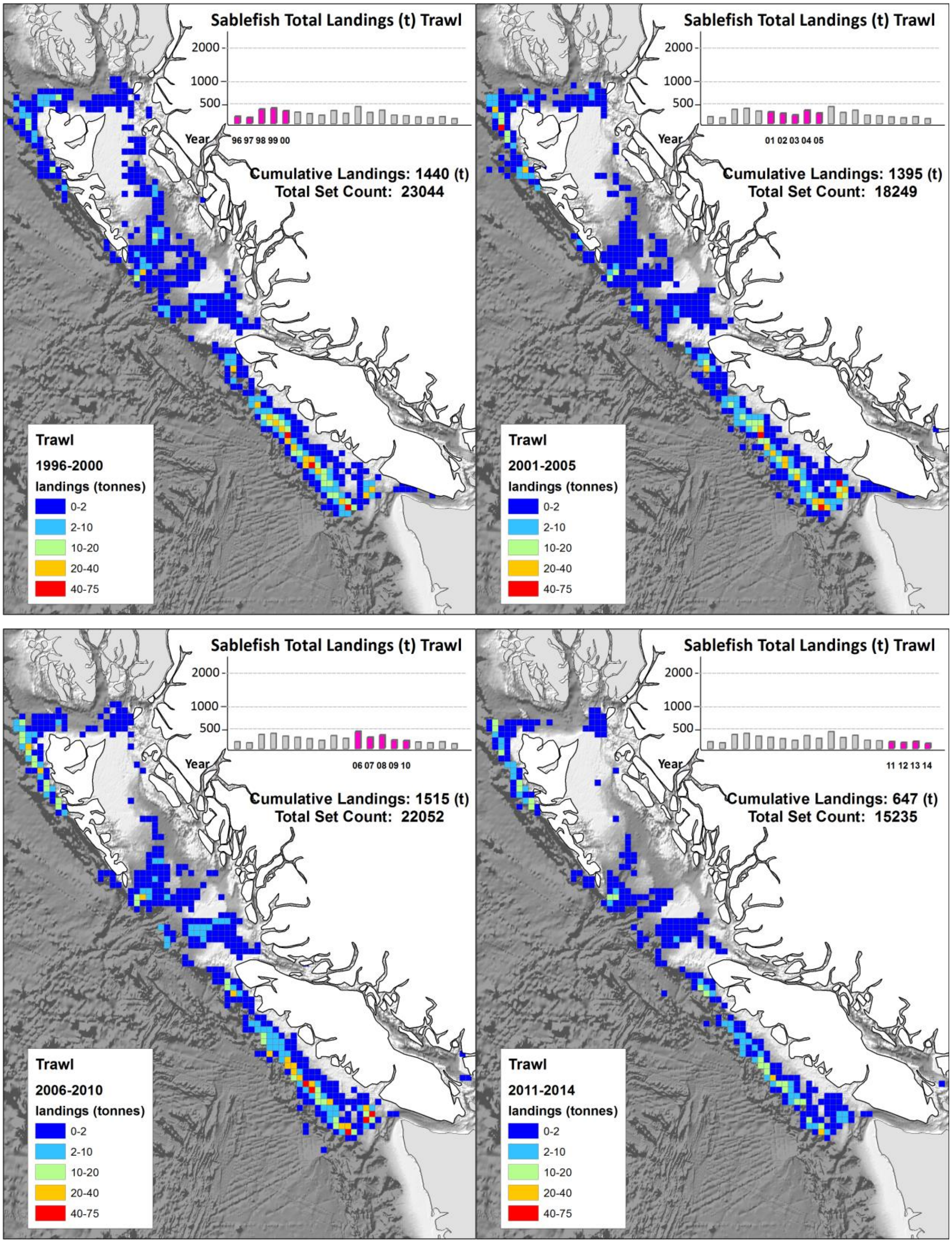

Figure B-2. Landed catch (t) of Sablefish summarized on a 10 x 10 km^2 grid by year ranges 1996-2000 (upper left panel), 2001-2005 (upper right panel), 2007-2010 (lower left panel) and 2011-2014 (lower right panel) for bottom trawl gear. Histograms show the total landings by year. Cumulative landings and total set counts are listed for each year range.

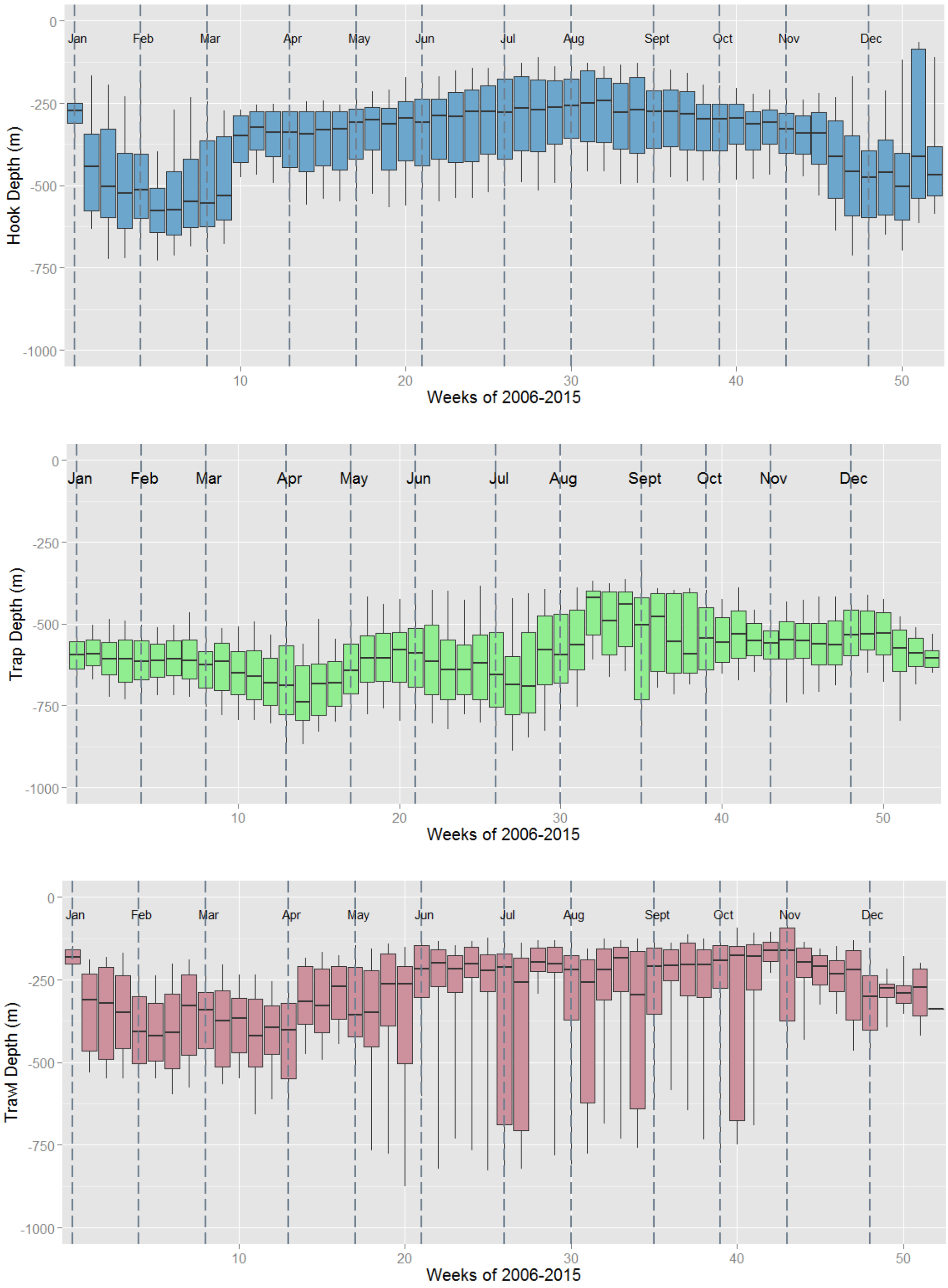

Figure B-3. Distribution of Sablefish depth-of-capture by week of the calendar year for 2006 to 2014 coastwide for longline hook (upper panel), longline trap (centre panel), and bottom trawl gears (lower panel). Boxplots show the 10%, 25%, 50%, 75%, and 90% quantiles of depth distribution using the lower whisker, lower hinge, median, upper hinge, and upper whisker, respectively.

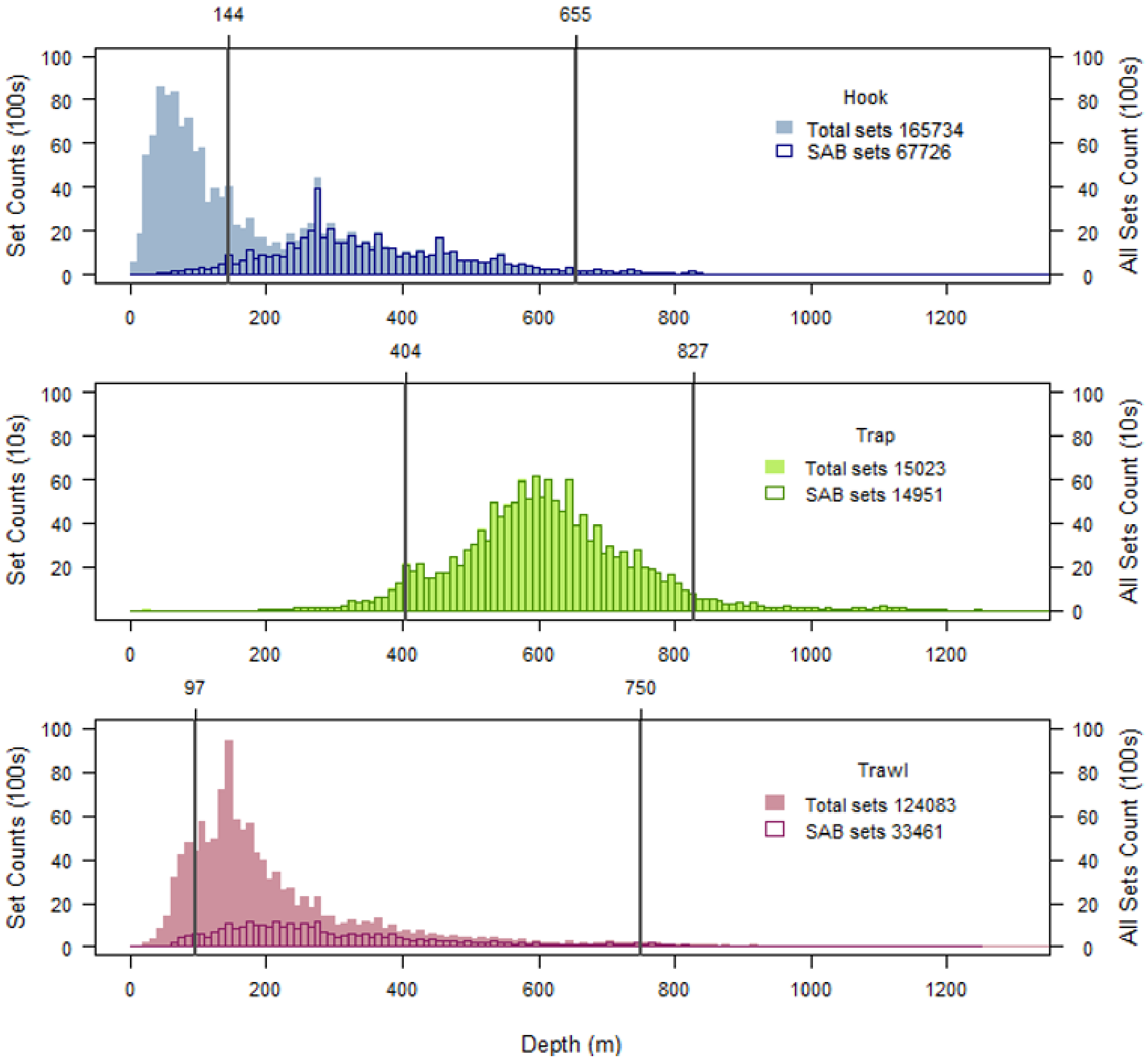

Figure B-4. Depth distribution of all sets (solid bars) and sets that captured Sablefish (outlined bars) for commercial longline hook (top panel), trap (center panel) and trawl (bottom panel) gear types. Data are summarized for commercial fisheries in British Columbia between 2006 and October 2015. Vertical lines denote the 5th and 95th percentiles of the depth distribution. The total number of sets and total number of sets that captured Sablefish (SAB sets) are listed in each figure panel.

B.4. SPECIES CO-OCCURRENCE

Summaries of species co-occurrence in commercial catches that included Sablefish are presented by gear type to characterize species composition and identify catches of species of conservation concern (Figure B-5). Longline trap catches are dominated by Sablefish, reflecting the strong selectivity of trap gear for Sablefish, with the sibling species complex of Rougheye Rockfish (*Sebastes aleutianus*) and Blackspotted Rockfish (*Sebastes melanostictus*) ranking second. This rockfish complex, only identified as 2 species in 2008 (Orr and Hawkins 2008), has been identified as Special Concern by the Committee On the Status of Endangered Wildlife In Canada (COSEWIC) due the lack of species-specific information (Fisheries and Oceans Canada 2011). The occurrence of other species in longline trap catches is minor.

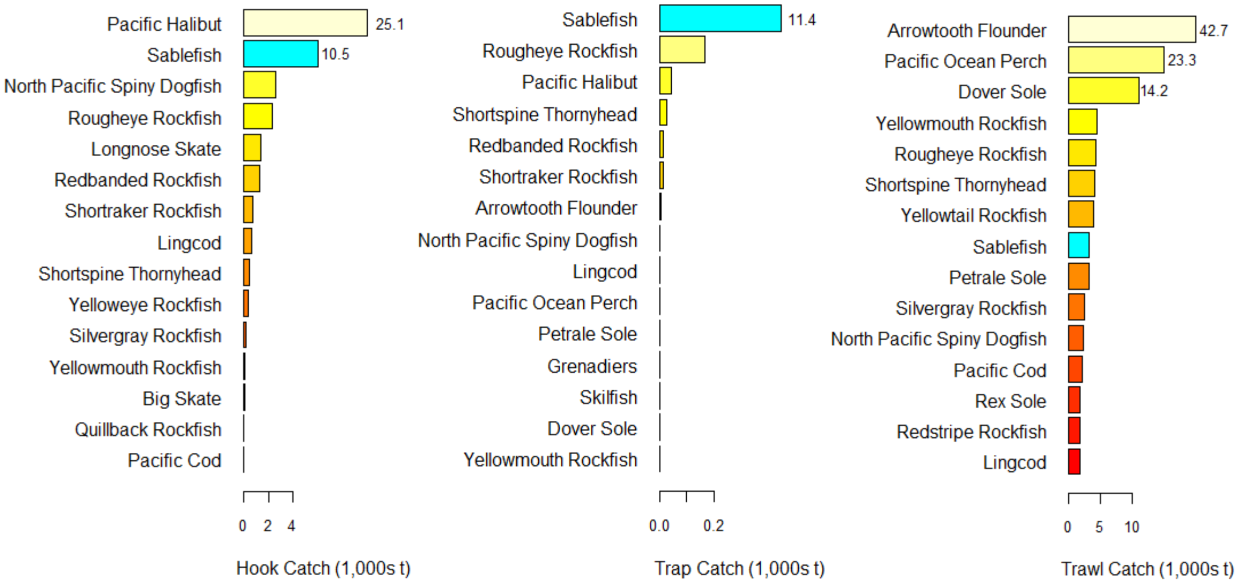

Figure B-5. The top 15 species ranked by total catch weight (000s t) co-occurring in sets that caught Sablefish by longline hook (left panel), longline trap (center panel) and bottom trawl gear (right panel) for the calendar years 1996 to 2014 combined. Note that the bars for some top-ranked species have been truncated to fit on the plot; actual total catch weights are indicated to the right of the truncated bars for those species.

B.5. BOTTOM TRAWL FOOTPRINT

In February of 2012 a collaborative agreement was signed between the Pacific Marine Conservation Caucus and the Canadian Groundfish Research and Conservation Society that established a coast wide fixed boundary within which bottom trawlers agreed to restrict their fishing “footprint” (Figure B-6). The implementation of the footprint boundary may have affected the distribution of Sablefish catches and species co-occurrence in bottom trawl tows. This possibility was examined by contrasting the spatial distribution of catches for tows that caught Sablefish in the three years prior to, and three years following, establishment of the footprint boundary.

Although the total landings from 2012 to 2015 declined to 489 t in comparison to 625 t from 2009 to 2012, this reduction is in part due to lower total landings of Sablefish in the latter period. There is some indication that the footprint has eliminated deeper blocks in Dixon Entrance, off the west coast of Haida Gwaii and off the west coast of Vancouver Island, but these areas did not account for significant amounts of retained Sablefish. Our conclusion is that the footprint has not markedly reduced the accessibility of Sablefish to the bottom trawl fleet in comparison to the 2009 to 2012 pattern of fishing. Inspection of Figure B-7 for the 1996 to 2005 periods suggests that even when the Sablefish TAC was approximately double the current level, bottom trawl fishing occurred largely within the footprint established in 2012.

In addition, the species co-occurring with Sablefish in bottom tows during the two time periods was compared (Figure B-8). There are only minor changes in the rank order of species caught concurrently with Sablefish by bottom trawl gear; the rank order of the top three species is unchanged. The amounts of other species caught coincidentally with Sablefish are similar; changes in rank order are likely a result of annual effects, market conditions, and constraints imposed by individual quota holdings.

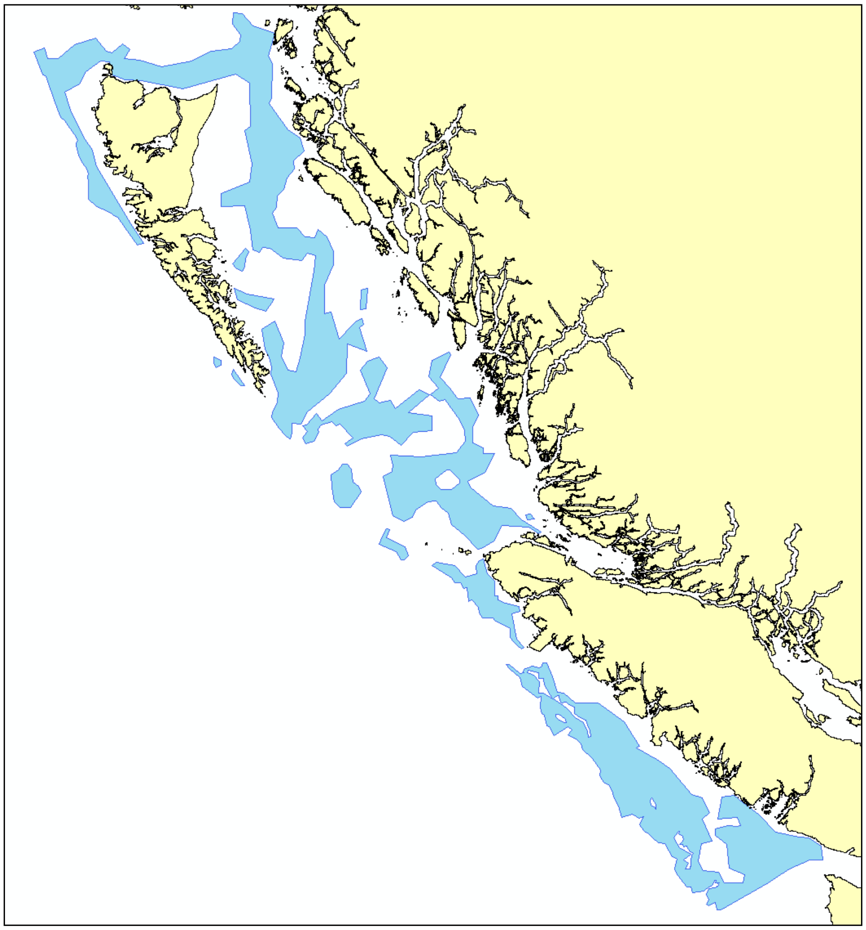

Figure B-6. Area included in the bottom trawl “footprint” boundary (blue shaded region) established in 2012.

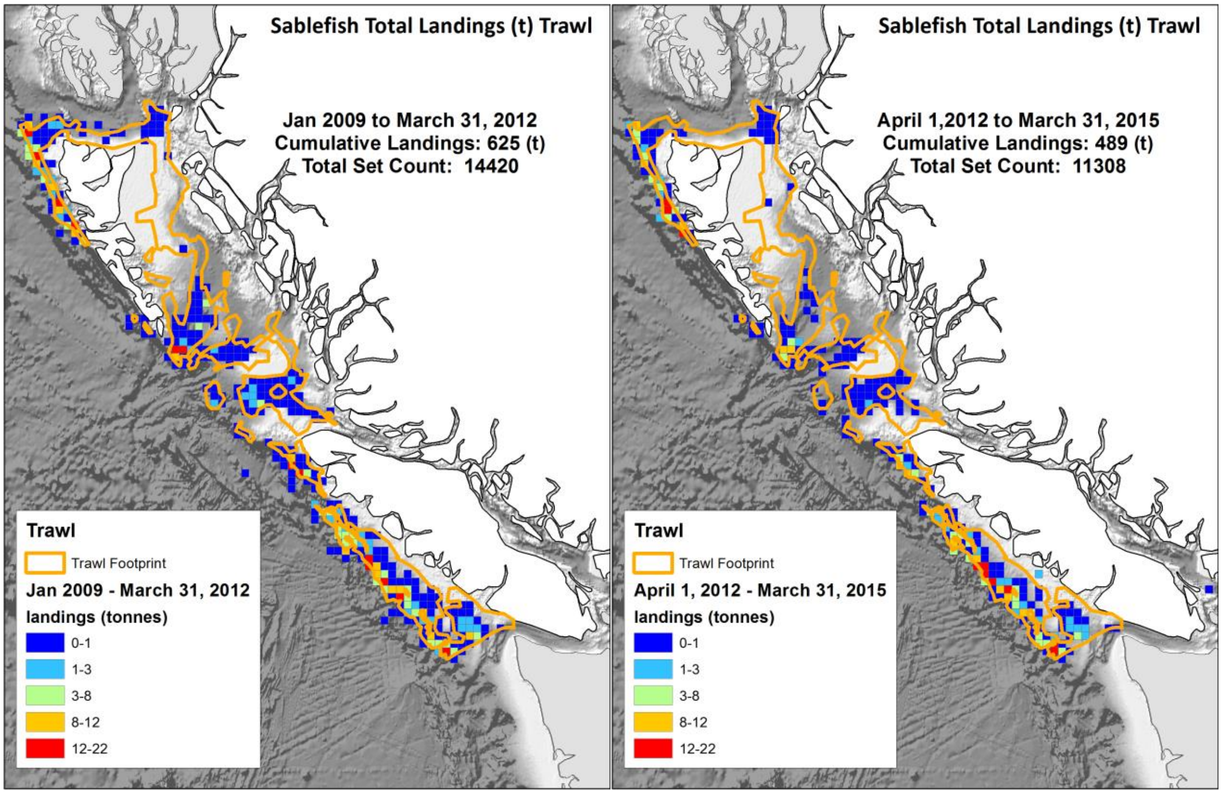

Figure B-7. Landed catch distribution of Sablefish (t) by bottom trawl gear for Jan 2009 to March 31, 2012 (left panel) and April 2012 to March 2015 (right panel) for bottom trawl gear. Data are aggregated using a 10 x 10 km^2 grid with the bottom trawl footprint boundary indicated by the orange solid line.

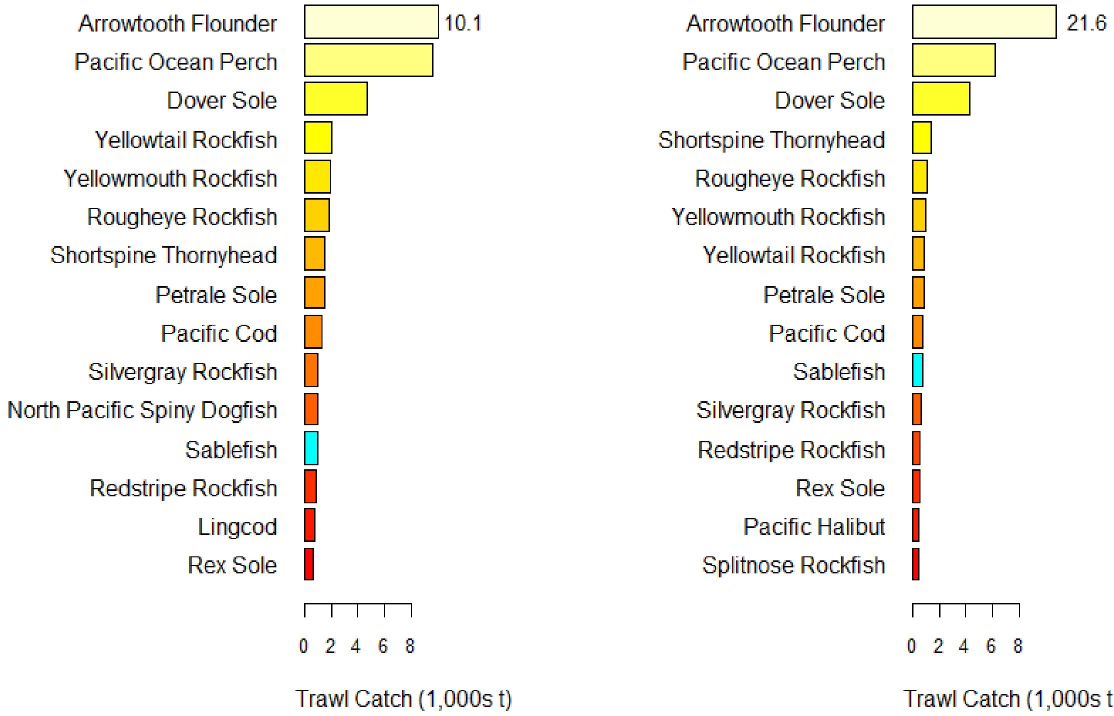

Figure B-8. The top 15 species ranked by total catch weight (000s t) co-occurring in sets that caught Sablefish by bottom trawl gear from Jan 2009 to March 31, 2012 (left panel) and Apr 2012 to Mar 31, 2015 (right panel). Note that the bars for some top-ranked species have been truncated to fit on the plot; actual total catch weights are indicated to the right of the truncated bars for those species.

B.6. REFERENCES CITED

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APPENDIX C. STOCK INDICES

C.1. INTRODUCTION

Fishery-dependent catch and effort data, and data from two fishery-independent surveys, were used to derive three relative abundance indexing series for Sablefish (*Anoplopoma fimbria*) in British Columbia (BC) waters. Annual catch per unit effort indices were derived from:

1. annual nominal trap fishery catch and effort (1979-2009),
2. the standardized (Std.) trap survey (1990-2009), and
3. the stratified random sampling (StRS) survey (2003-2014).

All three indexing series use longline trap gear (hereafter “trap” gear). Catch per unit effort (CPUE) is calculated in units of kg/trap for each set. Attributes of other surveys conducted in BC that capture Sablefish are listed in Table C-1; information summarized in the table was used to screen surveys for potential sources of abundance indexing data. For example, inspection of Table C-1 indicates that the West Coast Vancouver Island Synoptic Survey (01 WCVI Syn.):

1. is a bottom trawl (BT) survey that follows a stratified random sampling design (Design=StRS),
2. was conducted in *T*=6 years over the 2004-2014 period (Year Range) in areas 3CD (Figure C-1) and a portion of Area 5A (Areas),
3. completed between n=106 and n=178 tows in each survey year (average number of tows is 152) at depths between 43 m and 803 m (Depth Range),
4. produced total catches of Sablefish per survey that ranged between 1,837 kg and 5,900 kg (Catch Range) with an average (Avg) total Sablefish catch of 4,093 kg per survey,
5. produced Sablefish catch per unit effort (CPUE) values that ranged between 0.3 and 1,837 kg/set (CPUE Range) with an average (Avg) of 51.6 kg/set. Note that for this survey in 2004 there was a total catch weight of Sablefish of 5,900 kg but a single set caught 1,837 kg. Coincidentally in 2008 the total catch weight of Sablefish was 1,837 kg, the lowest in the time series,
6. resulted in proportions of sets that caught no Sablefish ranging between 0.27 and 0.55 over the 6 survey years (Prop. Zeros Range),
7. resulted in coefficients of variation (CVs) that ranged between 0.15 to 0.32 (CV Range) over survey years; and
8. does not have a time series of age data (Age=N).

The Queen Charlotte Sound and west coast Vancouver Island shrimp surveys were excluded because of the restricted depth ranges relative to the depth range inhabited by adult Sablefish. Similarly, the Hecate Strait Assemblage survey (Choromanski et al. 2005) has both a restricted depth range and limited areal coverage in the inside waters of Hecate Strait. Most longline hook surveys were determined not to be suitable for Sablefish abundance indexing for reasons indicated in Table C-1. The Strait of Georgia (SoG), Hecate Strait Pacific Cod (*Gadus macrocephalus*) survey (Sinclair and Workman 2002), and WCVI thornyhead survey (Schnute et al. 2004) were conducted in three or fewer years and were therefore not considered.

We elected not to include the remaining surveys in the operating model fits at this time for four main reasons. First, each indexing series added to the model requires selectivity to be estimated and, for all but series (a-c) above, a time-series of age data are not available.

Second, the spatial, temporal and depth coverage of some surveys (a) does not include the offshore coastal biomass of adult Sablefish, (b) occurs only in a portion of the coast, or (c) consists of sets that occur at depths shallower than typically occupied by adult Sablefish. For example, the series of “synoptic” trawl surveys (surveys 01-04 in Table C-1, Figure C-2) are not conducted annually. The Queen Charlotte Sound (QCS, areas 5A-C, 5E, Workman et al. 2007) and Hecate Strait (HS, areas 5CD, Workman et al. 2008a) occur in the same year, with the WCVI (areas 3CD, 5A, Workman et al. 2008b) and West Coast Haida Gwaii (WCHG, area 5E, Olsen et al. 2008) surveys occurring in the following year. These surveys have the potential to index Sablefish, provided an ageing time series can be obtained for estimation of selectivity and when the length of the time series are increased. The International Pacific Halibut Commission (IPHC) setline survey is another potential source of abundance indexing data; this survey has the advantage of being conducted annually coastwide. However, the depth range of the IPHC survey extends only to 460 m and therefore does not encompass the depth ranges occupied by adult Sablefish offshore. Also, the numbers of Sablefish caught per 100 hooks (Figure C-3) or in terms of weight (Table C-1) are relatively small. Perhaps the largest impediment to using this survey is the lack of an ageing time series to allow selectivity to be estimated, rather than assumed, since there are insufficient tag-recovery data from this survey to estimate selectivity.

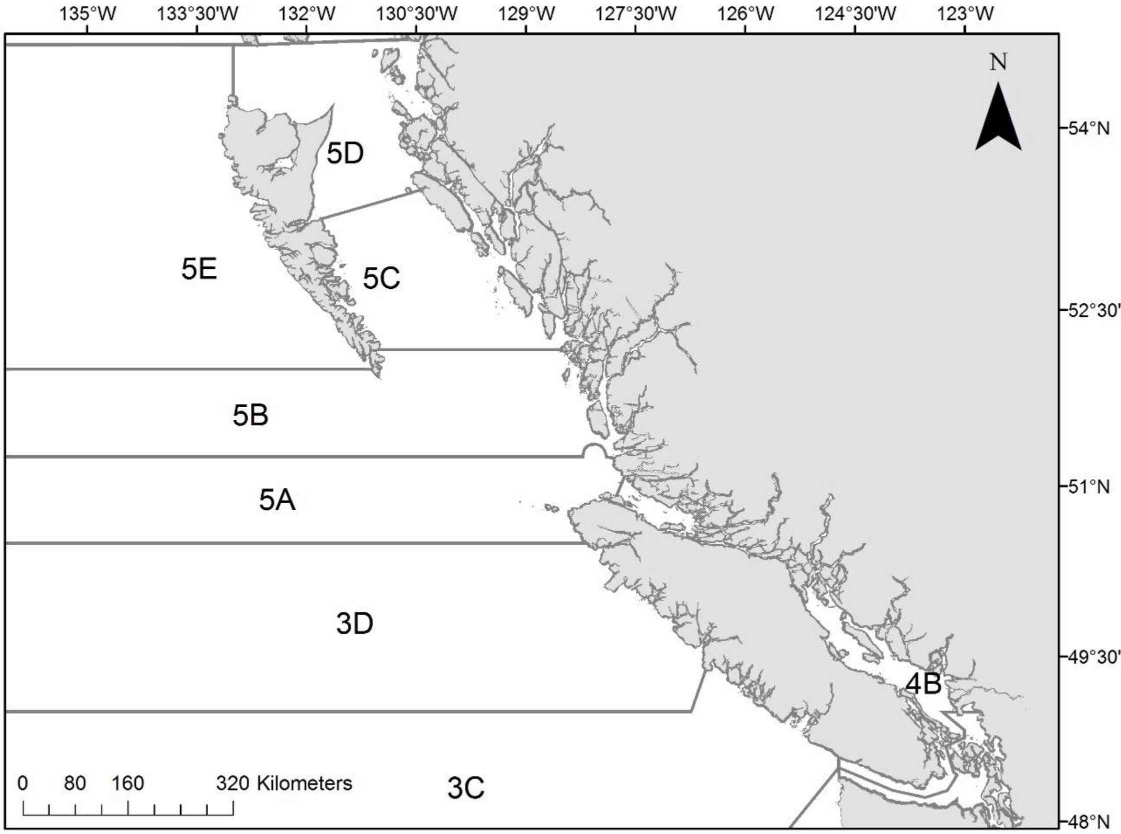

Figure C-1. Major areas for management of the British Columbia groundfish fishery.

Table C-1. Attributes of fishery-independent surveys including: design, gear, year range, number of survey years (T), number of sets, and catch statistics. Design is stratified random (StRS), fixed station (Fixed) or Systematic with random start position (Sys). Gears coded as bottom trawl (BT), longline hook (HK), or trap (Trap). IPHC is Int'l. Pacific Halibut Commission, PHMA is Pacific Halibut Mgmt. Assoc., IRF is inshore rockfish, Sable is Sablefish. Attributes causing rejection as abundance index are marked with an asterisk and shaded in grey. The Sablefish Standardized survey (Sable. Std.) and Sablefish Stratified Random Survey (Sable SR) marked in bold were selected as sources of abundance indexing series. The Sablefish Inlets Survey (Sable Inlets) occurs in only 4 mainland central coast inlets.

Survey	Design	Gear	Year Range (T)	Num. Sets Range (Avg)	Areas	Depth (m) Range	Total Catch (kg) Range (Avg)	CPUE (kg/set) Range (Avg)	Prop. Zeros Range	CV Range	Age Series
01 WCVI Syn.	StRS	BT	2004-2014 (6)	106-178 (152)	3CD 5A	43-803	1837-5900 (4093)	0.30-1836.8 (51.6)	0.27-0.55	0.15-0.32	N
02 QCS Syn.	StRS	BT	2003-2015 (8)	249-278 (266)	5A-C 5E	36-574	788-2277 (1542)	0.36-375.9 (12.3)	0.42-0.66	0.10-0.24	N
03 HS Syn.	StRS	BT	2005-2015 (6)	152-236 (180)	5CD	18-420	375-3947 (1708)	0.12-1675.2 (24.8)	0.39-0.68	0.23-0.60	N
04 WCHG Syn.	StRS	BT	2007-2014 (5)	63-141 (115)	5E	157-1290	890-2781 (2032)	0.40-468.4 (30.9)	0.37-0.54	0.15-0.28	N
05 SoG Syn.*	StRS	BT	2012-2012 (1)*	53- 53 (53)	4B*	64-392	5-5 (5)*	0.30-2.3 (1.1)*	0.91-0.91*	0.51-0.51	N
06 WCVI Shrimp*	Sys.	BT	1975-2014 (38)	62-168 (79)	3CD	75-161*	3-2503 (257)	0.09-945.3 (5.2)	0.04-0.93*	0.13-0.63	N
08 HS Assembl.*	Fixed	BT	1984-2003 (11)	88-161 (104)	5CD	18-232*	178-1385 (727)	0.10-734.0 (19.8)	0.42-0.77*	0.21-0.72	N
09 HS PCod*	StRS	BT	2002-2004 (3)*	200-201 (200)	5CD	22-168*	0-271 (136)	0.45-243.3 (19.6)	0.96-1.00*	-	N
10 WCVI Thorny*	StRS	BT	2001-2003 (3)*	63- 74 (70)	3CD	512-1570	5101-5755 (5375)	1.50-893.6 (86.4)	0.05-0.16	-	N
12 IPHC	Fixed	HK	2003-2014 (11)	166-170 (169)	3CD 5A-E	34-460	1716-5610 (3245.5)	1-274 (34.2)	0.39-0.52	-	N
13 PHMA South*	StRS	HK	2007-2014 (4)	165-194 (181)	4B 3CD 5AB	12-229	534-1209 (908.5)	1-130 (16.2)	0.65-0.75*	-	N
14 PHMA North*	StRS	HK	2006-2012 (4)	186-195 (190)	5B-E	15-141	526-1222 (770.0)	1-129 (16.6)	0.72-0.82*	-	N
15 IRF South*	StRS	HK	2005-2013 (4)	28- 69 (57)	4B*	38-100	-	-	1.00-1.00*	-	N
16 IRF North*	StRS	HK	2003-2012 (6)	17- 77 (50)	4B*	24-150	20-77 (41.4)	1-27 (6.5)	0.85-1.00*	-	N
17 Sable Inlets*	Fixed	Trap	1995-2014 (20)	18- 20 (19)	5B 5CD	326-808	6906-33102 (13924.3)	3-3456 (700.2)	0.00-0.05	-	N
18 Sable Std.	Fixed	Trap	1990-2010 (21)	24-105 (49)	3CD 5AB 5E	159-1564	2736-25984 (10008.7)	2-1890 (200.1)	0.00-0.06	-	Y
19 Sable StRS	StRS	Trap	2003-2013 (11)	74-110 (89)	3CD 5AB 5E	150-1400	14266-67704 (37129.3)	1-2307 (406.8)	0.00-0.02	-	Y

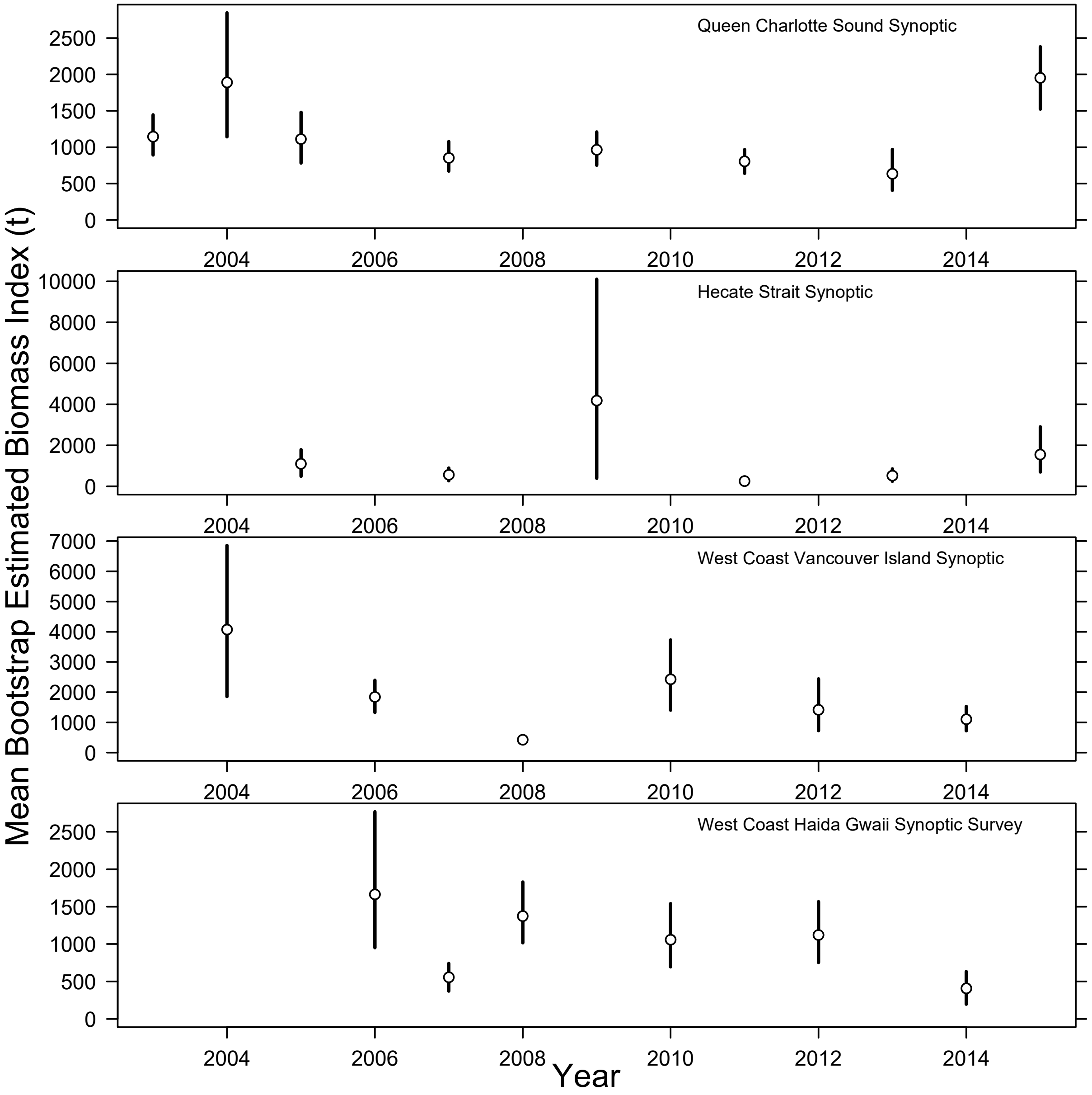

Figure C-2. Relative analytic biomass estimates for Sablefish from the four Synoptic Bottom Trawl surveys spanning the period 2003-2015. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted as solid vertical lines.

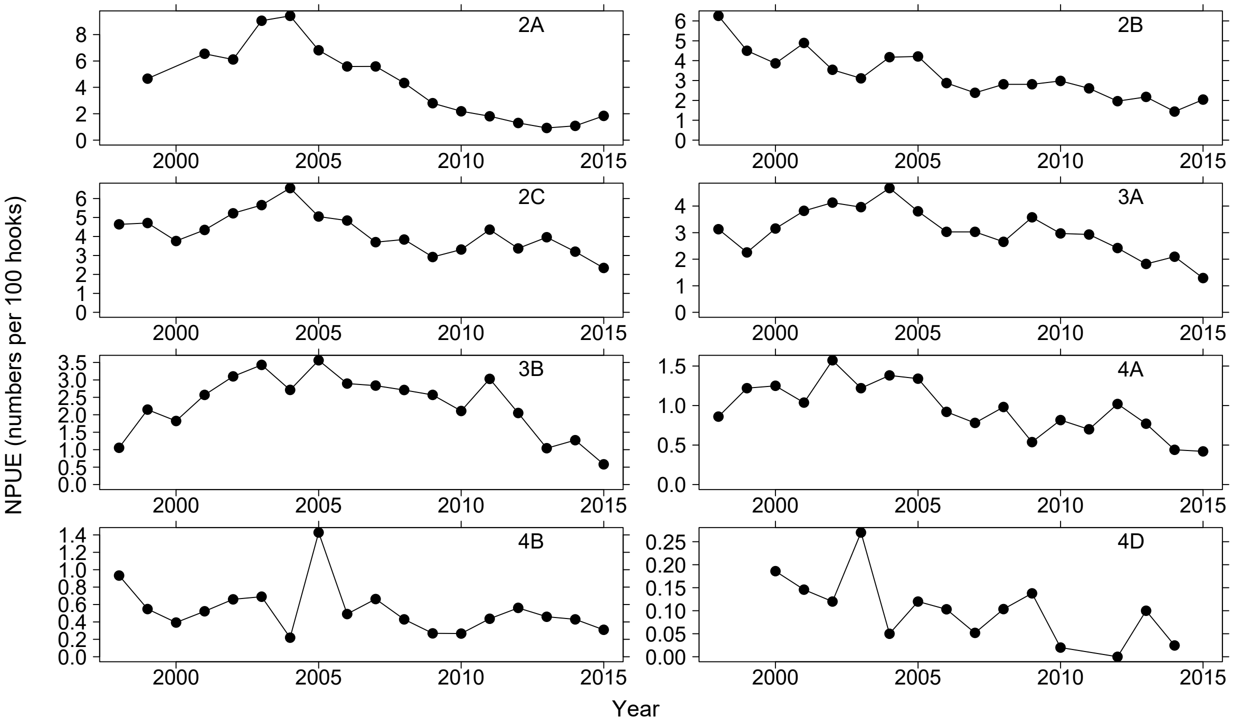

Figure C-3. Numbers of Sablefish per 100 hooks caught by year and area on the IPHC setline survey. Area 2B is British Columbia. Data provided courtesy the International Pacific Halibut Commission.

C.2. COMMERCIAL SABLEFISH TRAP FISHERY INDEX

Set by set trap fishery logbook data are not available until 1990. Prior to 1990, one fishing record can 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, however there is little difference in the annual 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, and
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.

The CPUE series was ended in 2009 as the number of trips by vessels fishing trap gear declined and to reduce reliance on fishery-dependent data for abundance indexing. Nominal trap CPUE fluctuated around ~15 kg/trap until the late 1980s when historic highs from ~20 to ~25 kg/trap were recorded (Figure C-4). Catch rates subsequently declined until 2001 but 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 2001/2002 fishing year. This reduction was in response to the historically low standardized survey index value observed in 2001 (Figure C-7). Nominal catch rates declined from near 20 kg per trap in 2003 to ~10 kg/trap by 2009.

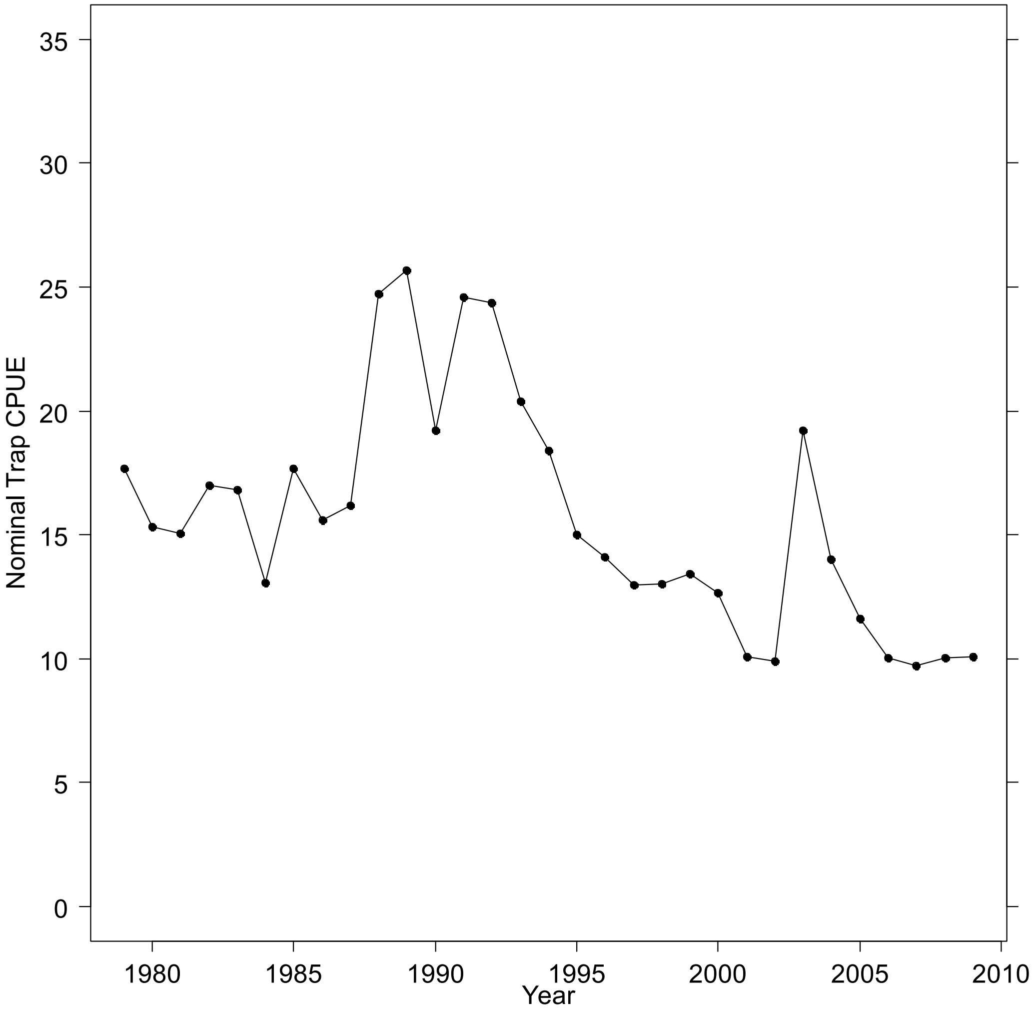

Figure C-4. Annual offshore nominal commercial trap fishery catch rates (kg/trap), 1979-2009.

C.3. FISHERY-INDEPENDENT SABLEFISH TRAP SURVEY INDICES

Two fishery-independent surveys that use longline trap gear are used to derive abundance indexing data for Sablefish in BC waters. The two surveys differ fundamentally in their design; the standardized survey (Std.) did not use a randomized statistical design while the stratified random survey (StRS) is area and depth stratified. The annual occurrence and seasonal timing of the two surveys is shown in Figure C-5. Each survey is described in detail below.

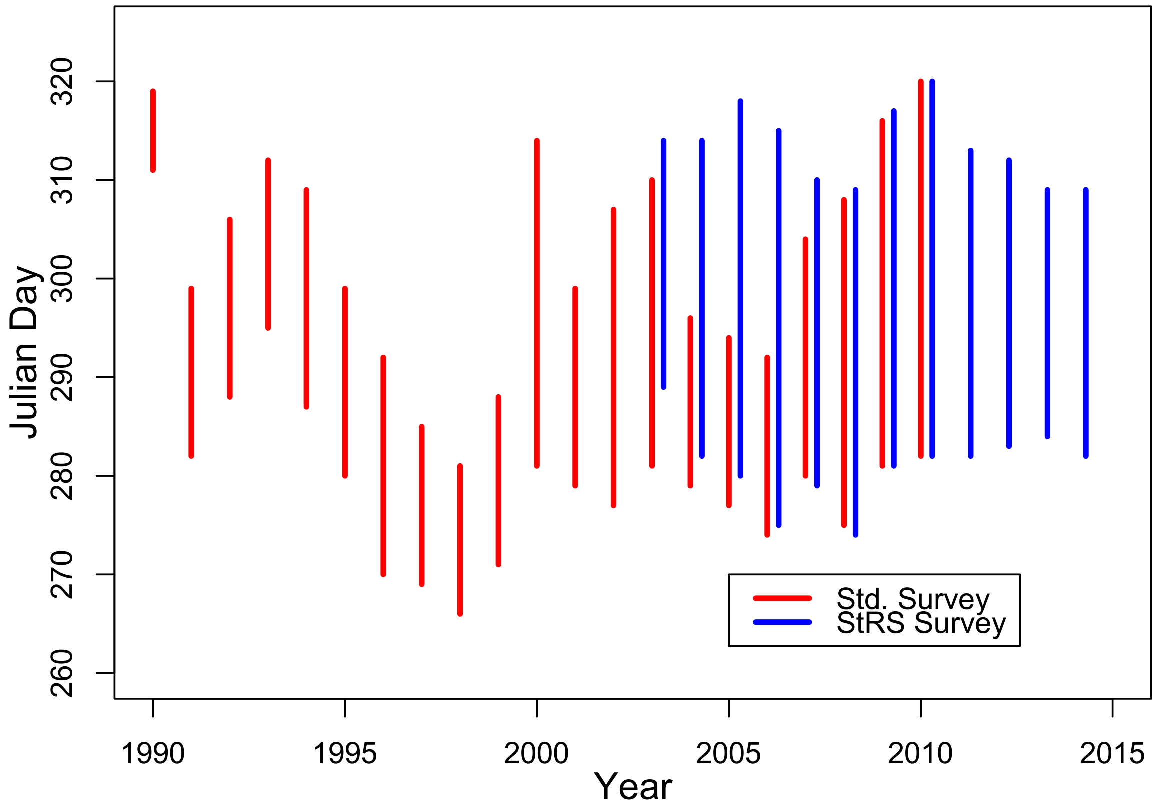

Figure C-5. The yearly and seasonal timing of the Sablefish standardized (Std.) and stratified random sampling (StRS) surveys. Each vertical line joins the start and end day of fishing for a survey each year.

C.3.1. Standardized Trap Survey

A "standardized" trap survey (Wyeth et al. 2006, 2007) was started in 1990 using consistent squid bait loading and was continued annually until 2010; similar survey work conducted in 1988 and 1989 used different baits. The standardized survey was a fixed locality survey, usually conducted by a chartered commercial Sablefish trap fishing vessel. Nine offshore survey localities were consistently occupied in each year of the survey except in 1990 when only southern localities were surveyed (Figure C-6). 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. Thus, the survey design was not randomized. Survey localities typically included high-relief bathymetric features such as gullies or canyons, which reflects the original intention to index Sablefish abundance in "core" fishing areas that represented what was believed to be prime habitat. Trap escape rings were sewn closed during survey fishing.

Over the course of the survey between 5 and 7 different depth intervals were fished within each locality, although only the five core depth intervals identified as D1-D5 were fished consistently over the history of the survey. Only depth intervals D1-D5 were occupied from 2007 to 2010. 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 was 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 1990-91 and 1993, and three selected localities in 2002 (Wyeth et al. 2007). Also, the spatial position of each set was 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 estimates are based on the mean of the catch per trap (kg/trap) observations for depth intervals D1-D5 calculated using empirical likelihood methods which do not require the assumption of a particular distribution (Owen 2001). 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 on the averages. The seasonal ranges in Julian days of the first and last sets completed in the standardized survey each survey year are shown in Figure C-5; seasonal timing is also shown for the stratified random survey discussed below.

Confidence intervals (95%) calculated using empirical likelihood methods are shown to represent the relative precision of survey index values (Table C-2). The coast-wide trends of survey catch rates show a decline over time from relatively high mean values in the early 1990s, fluctuating around 10 kg/trap beginning by 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 like those 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. Ageing data by sex is available from 1990 to 2009; no ageing data is available for 2010 because of the decision to discontinue the survey after 2010 and the priority to age commercial and StRS survey samples.

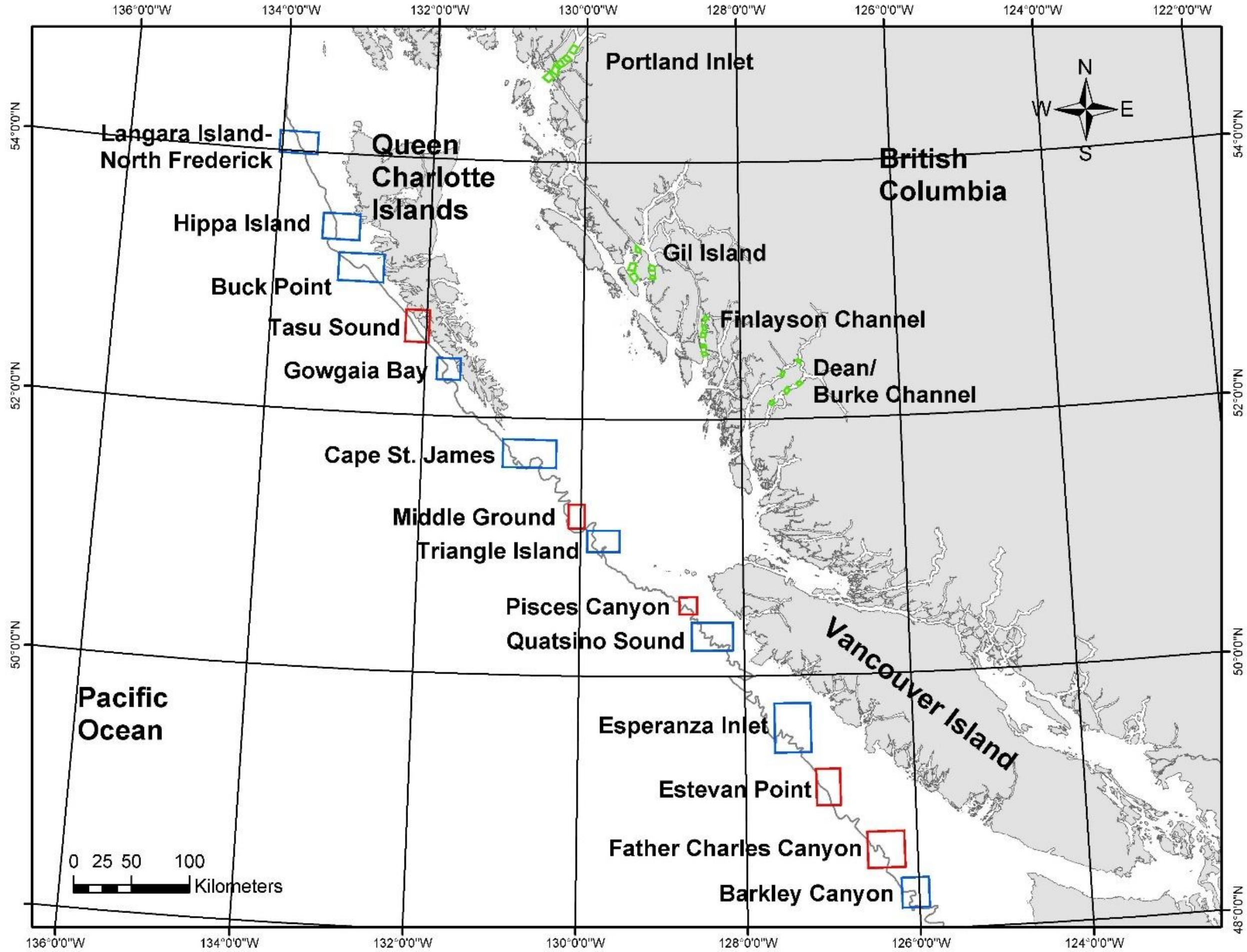

Figure C-6. Geographic boundaries of the traditional survey localities. Blue boxes indicate a Sablefish Standardized Survey locality, tagging localities (Wyeth et al. 2007) are indicated by red boxes and green boxes indicate the locations within the mainland inlet localities. The 1000 m depth contour is shown.

Table C-2. Empirical likelihood estimates of the annual mean catch per unit effort (kg/trap), 95% confidence intervals (CI), and coefficient of variation (CV) for the Sablefish standardized trap survey. The "Mean" column is taken as the relative abundance index.

Year	Mean	Lower CI	Upper CI	Ratio mean	Mean ratio	CV
1990	20.017	15.576	26.268	20.017	20.017	0.156
1991	19.336	13.802	26.200	19.367	19.336	0.177
1992	25.569	20.557	33.024	25.549	25.569	0.146
1993	36.509	30.175	43.207	36.521	36.509	0.092
1994	15.571	11.630	22.113	15.567	15.571	0.210
1995	13.665	10.640	17.037	13.554	13.665	0.123
1996	11.258	9.320	13.678	11.244	11.258	0.108
1997	7.721	5.343	11.185	7.743	7.721	0.224
1998	12.037	9.730	14.654	12.088	12.037	0.109
1999	7.720	5.801	10.223	7.689	7.720	0.162
2000	9.296	7.058	12.366	9.231	9.296	0.165
2001	3.092	1.880	5.248	3.076	3.092	0.349
2002	8.401	6.343	11.996	8.420	8.401	0.214
2003	28.656	19.768	39.925	28.556	28.656	0.197
2004	26.415	19.005	36.650	26.751	26.415	0.194
2005	19.432	14.169	25.708	19.427	19.432	0.161
2006	17.382	13.034	22.966	17.356	17.382	0.161
2007	10.348	8.111	13.735	10.373	10.348	0.164
2008	10.662	7.821	15.229	10.747	10.662	0.214
2009	7.087	5.033	10.274	7.132	7.087	0.225
2010	8.198	5.860	11.609	8.158	8.198	0.208

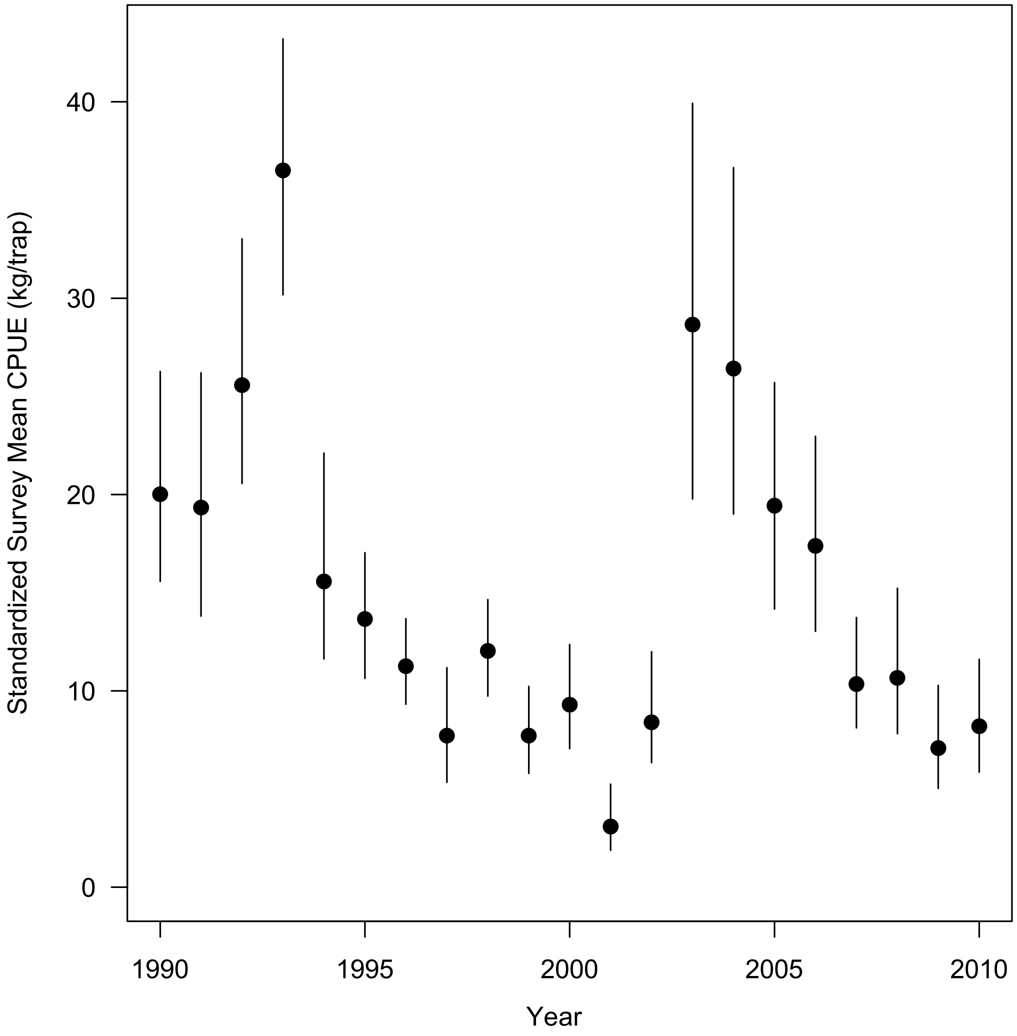

Figure C-7. Annual standardized survey catch rates (kg/trap) from 1990 to 2010. Annual mean catch rates are shown (lower panel) with empirical likelihood estimates of the 95% confidence interval to provide an indication of relative precision.

C.3.2. Stratified Random Trap Survey (2003-2014)

A second annual fishery-independent trap survey was initiated in 2003 and follows a depth and area stratified random sampling (StRS) design (Figure C-8). 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. 2007). 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 standardized survey. The survey design initially allocated 75 sets equally distributed among the 15 strata. Catch is completely enumerated and weighed by species by trap for 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 for ageing. Finally, Sablefish are tagged and released on each set. Like the standardized survey gear, trap escape rings are sewn shut however the StRS survey traps are baited with a combination of Pacific Hake (*Merluccius productus*) and squid to follow the practice 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 realized depth stratum or eliminated from the survey if no valid stratum was achieved.

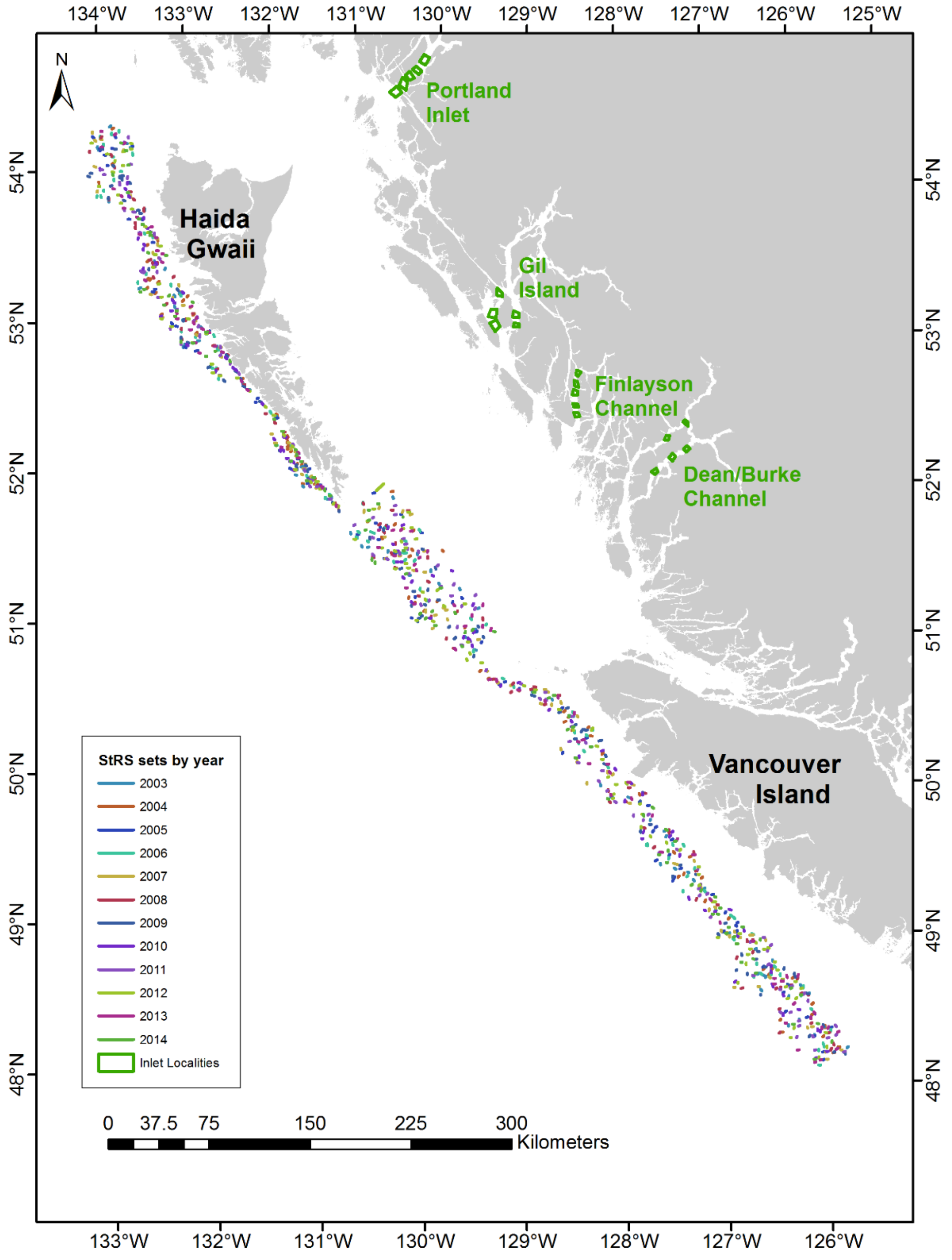

Figure C-8. Sablefish StRS set locations 2003-2014 and inlets survey program set localities.

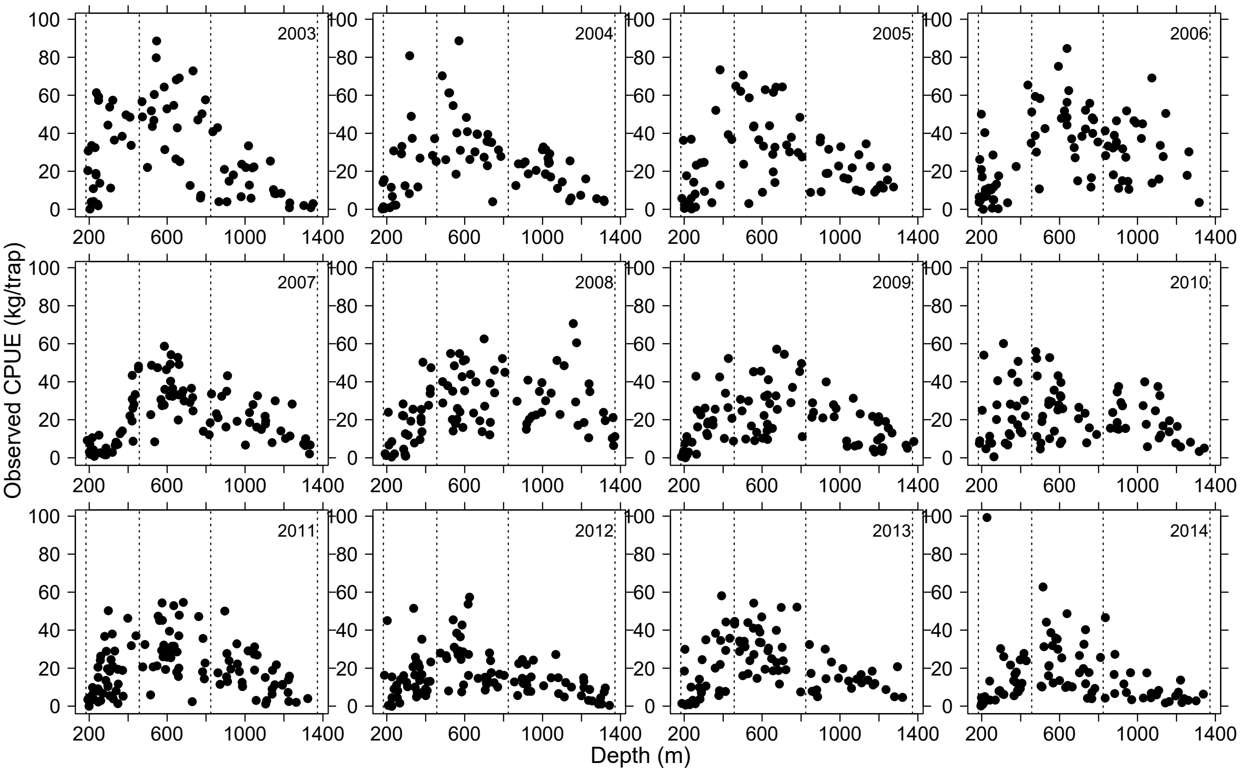

Figure C-9. Annual observed Sablefish CPUE (kg/trap) as a function of depth (m) for the StRS trap survey. Each filled circle represents one survey set. The vertical dotted lines demarcate survey depth strata.

Stratified random sampling mean index values and 95% confidence intervals (Table C-3) 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 (Efron 1982) 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 are shown in Figure C-10. A declining trend in survey catch rates occurred over the 2003-2014 time series punctuated by high observation in 2006 (see Hanselman et al. 2014 for a similar feature in the Gulf of Alaska longline hook survey).

Table C-3. 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 $\alpha = 0.05$ 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	df	Boot Mean	Boot Std. Err.	Boot Lower 95% CI	Boot Upper 95% CI
2003	28.363	5.137	2.266	0.806	0.080	23.830	32.897	60	28.490	2.255	23.944	32.782
2004	24.941	2.590	1.609	0.670	0.065	21.721	28.162	59	24.938	1.568	21.868	28.015
2005	23.789	2.944	1.716	0.690	0.072	20.356	27.223	59	23.807	1.734	20.390	27.188
2006	28.889	2.785	1.669	0.687	0.058	25.560	32.217	70	28.888	1.708	25.541	32.237
2007	20.476	1.738	1.318	0.774	0.064	17.850	23.102	75	20.471	1.300	17.929	23.023
2008	26.243	3.698	1.923	1.267	0.073	22.412	30.074	75	26.334	1.943	22.434	30.052
2009	18.299	1.062	1.030	0.566	0.056	16.246	20.353	74	18.316	1.018	16.304	20.295
2010	21.402	2.130	1.459	1.074	0.068	18.492	24.311	72	21.424	1.428	18.603	24.201
2011	19.851	1.170	1.082	0.705	0.054	17.703	21.999	94	19.803	1.105	17.686	22.016
2012	15.210	0.842	0.917	0.738	0.060	13.389	17.032	95	15.194	0.934	13.380	17.041
2013	19.729	2.286	1.512	1.076	0.077	16.716	22.741	74	19.723	1.552	16.687	22.771
2004	13.443	1.675	1.294	0.754	0.096	10.866	16.021	76	13.454	1.317	10.861	16.025

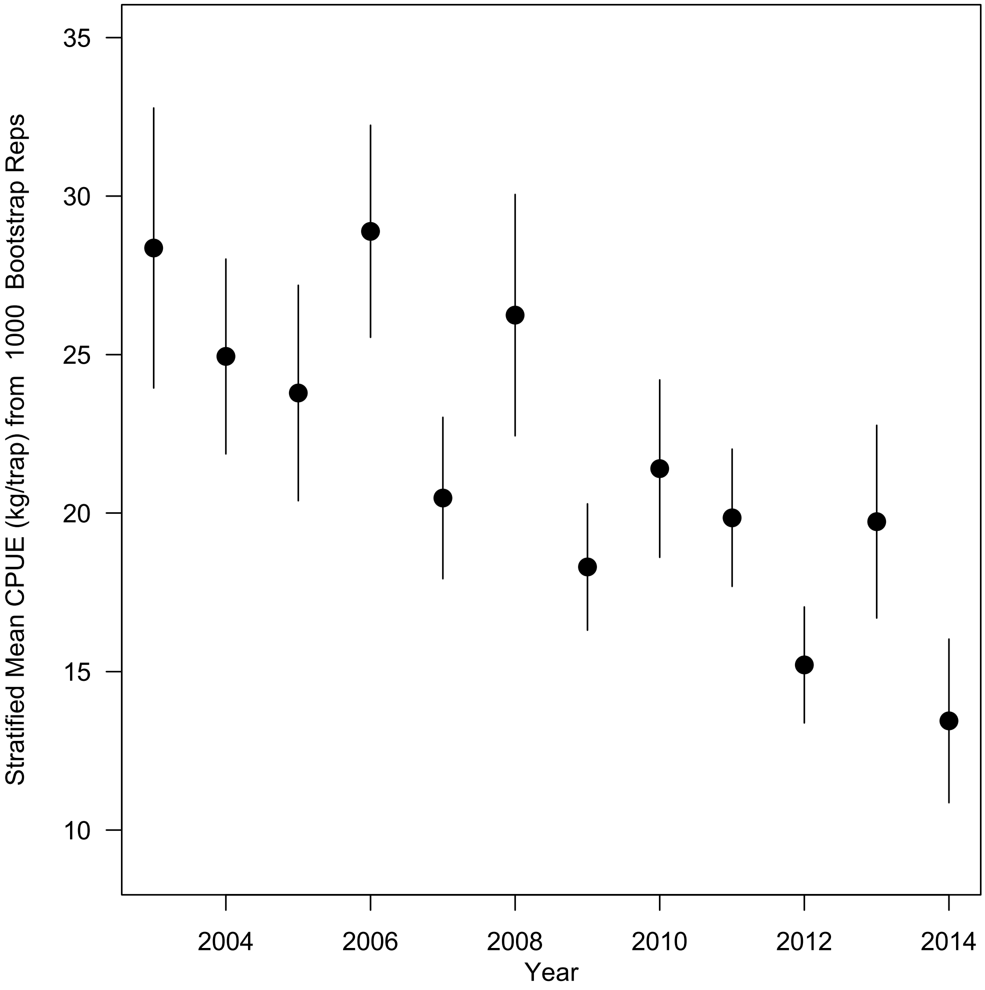

Figure C-10. Annual stratified random survey mean catch rates (kg/trap) from 2003 to 2014. Solid circles indicate the stratified mean. Vertical lines show the upper and lower 95% confidence limits.

C.4. SUMMARY

Considerations for interpretation of these indices include:

1. **Standardized survey:** A key issue for this survey is that the survey design places unknown sampling weights on the various spatial 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. **Stratified Random survey vs. Standardized survey:** The use of an area and depth stratified design, as well as increased sample size (74 to 110 sets per year), means that StRS CPUE may react differently than CPUE for the Std. survey in response to changes in underlying stock abundance. The two surveys use different baits and follow very different designs.

3. **Standardized survey vs. nominal fishery CPUE:** The commercial trap fishery nominal CPUE and standardized survey show similar patterns and variability, consistent with the placement of standardized survey sets in core fishing areas.

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APPENDIX D. BIOLOGICAL INFORMATION

D.1. INTRODUCTION

This appendix describes biological data information needed as inputs to the Sablefish operating model (Table D-1). Required parameters are either estimated from data or assumed based on review of the literature and stock assessments from the Gulf of Alaska (GOA), British Columbia (BC) and the U.S. west coast. Analyses of BC data are based on data extracted from the DFO Groundfish Science biological database *GFBio* on November 3, 2015.

Table D-1. Listing of biological summaries required for the operating model and rationale.

Relationship	Rationale	Section
Weight given length by sex	Conversion of fish length to weight by sex	D.2
Length-at-age by sex	Growth parameters for productivity calculations	D.3
Maturity-at-age by sex Maturity-at-length by sex	Computation of spawning biomass and age- or length-dependent states	D.4
Proportion-at-age by sex	Allocation of fish numbers to age class	D.5
Natural mortality by sex	Natural mortality priors or fixed values	D.6
Release mortality by gear	Mortality of fish captured and released	D.7

D.2. WEIGHT-LENGTH RELATIONSHIP

Records of Sablefish with observations of length, weight, and sex were used to calculate sex-specific and combined length-weight relationship (Table D-2, Figure D-1). Data were selected from the 2003-2014 Stratified Random Sampling (StRS) trap survey series (Wyeth et al. 2007).

A log-linear relationship with additive errors was applied to observations of individual Sablefish where weight (kg) and length (cm) pairs $\left\{W_{xi}, L_{xi}\right\}$ are available for sex $x = 1,2$ (males, females) and fish $i = 1, \ldots, n_x$ as

$$\ln\left(W_{xi}\right) = a_x + b_x \ln\left(L_{xi}\right) + \varepsilon_{xi} \quad ,$$

where a_x and b_x are the intercept and slope parameters for each sex, respectively. Errors were assumed to be identically and independently distributed as $N\left(0, \sigma_x^2\right)$. An initial model fit was performed to identify outliers for removal from the final fit for each sex; observations where the absolute value of the Studentized residual was greater than 5 were excluded and the model re-fit to the subset of the observed data pairs by sex.

Table D-2. Estimates of weight-length parameters for Sablefish by sex and area. Estimates for the current analysis of British Columbia StRS survey data (2003-2014) reflect the removal of outliers where the absolute value of Studentized residuals exceeded 5.

	Males		**Females**		
Area	***a***	***b***	***a***	***b***	**Source**
Gulf of Alaska 1996-2004, domestic longline hook survey	1.24e-05	2.96	1.01e-05	3.015	Hanselman et al. (2007)
British Columbia StRS longline trap survey	8.1563e-06	3.05972	4.9489e-06	3.18328	2003-2014 data
US West Coast bottom trawl surveys	3.32942-e06	3.27292	3.26728e-06	3.27596	Johnson et al. (2015)

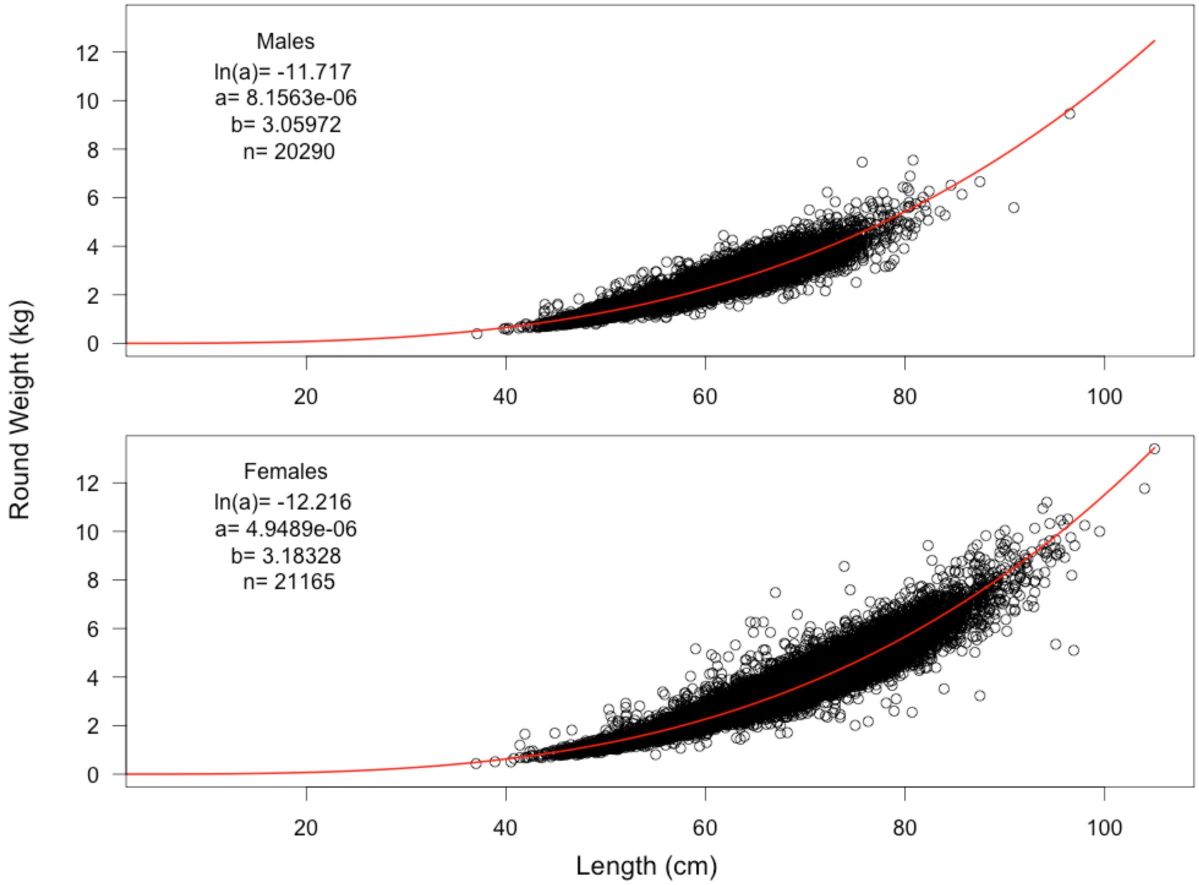

Figure D-1. Weight-length relationship for male (upper panel) and female (lower panel) Sablefish based on the coastwide StRS trap survey data from 2003-2014.

D.3. GROWTH

McFarlane and Beamish (1983) noted the remarkable growth of Sablefish in their first year of life 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 1977 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 by November averaged 40 cm fork length. Thus, these fish were close in size to age-2+ fish early in their third year of life. Sigler et al. (2001) estimated early life growth rates at 1.2 mm per day during the first spring and summer of life 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.

Length-at-age 1 is reported as 38.4 cm for U.S. west coast Sablefish 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. 2014).

Growth estimates for British Columbia Sablefish were obtained by fitting a von Bertanlanffy growth model with additive errors to sex-specific data collected from the stratified random survey (2003-2014). Sablefish ages were determined following the otolith burnt-section method of Chilton and Beamish (1982). Subject to survey trap gear selectivity, this survey is believed to sample fish representative of the offshore population because of the depth strata range, spatial strata, and annual randomization of the set locations within each depth-spatial stratum (Wyeth et al. 2007). In our growth formulation the average length at age $a=1,\ldots,A$ for sex $x=1,2$ is given by

(1) $$L_{ax} = L_{\infty,x} + \left(L_{1,x} - L_{\infty,x}\right)\exp\left\{-k_x\left(a_x - 1\right)\right\} ,$$

where for each sex $L_{\infty,x}$ is the average asymptotic size, $L_{1,x}$ is the length of a fish at age-1, and k_x is the average growth rate. We set $L_{1,x} = 32.5$ cm for both sexes following Cox et al. (2011), 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 $\left(L_{xi}, a_{xi}\right)$, the negative log-likelihood function for additive errors with a constant coefficient of variation can be stated as

(2) $$\Theta\left(k_x, L_{\infty,x}, \sigma_x\right) = n_x \log\sigma_x + \frac{1}{2\sigma_x^2}\sum_{i=1}^{n_x}\left(\frac{L_{xi} - L_{ax}}{L_{ax}}\right)^2 ,$$

where L_{xi} is the observed length of fish $i = 1,\ldots, n_x$ in the sample and σ_x^2 is the residual variance for each sex. The error structure implies the variance is proportional to fish length. Survey data are collected annually in October and November after the summer growth period, so ages were adjusted by adding the fraction of the calendar year elapsed at the time of capture to the assigned age. Fits to the length-age data are shown in Figure D-2.

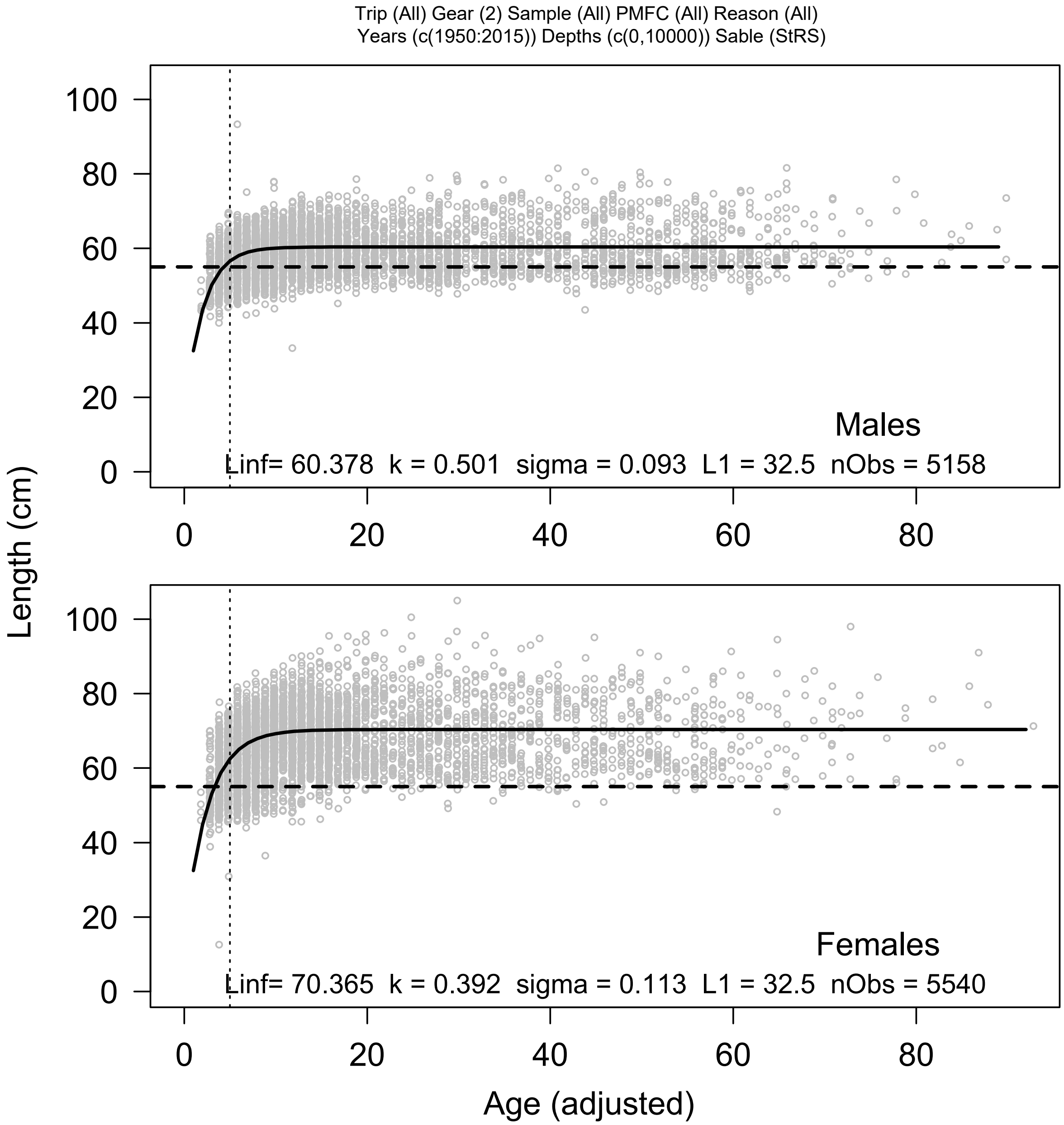

Figure D-2. Length-at-age for male (upper panel) and female (lower panel) Sablefish. Data are from the 2003-2014 stratified random sampling trap survey. The model fit is shown as a solid curved line. The 55 cm legal size limit is indicated by the horizontal dashed line. The vertical dotted line is positioned at age 5, approximately the age of 50% maturity reported in the literature.

Estimates of k are higher than those reported for Alaska and the U.S. west coast, possibly a result trap gear selectivity, which is likely to select for the fastest growing fish. 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. 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. In modelling, upward bias in growth estimates would tend to 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. by imposing the following assumptions:

1. Length at age-1 is fixed at L_1=32.5 cm for both sexes;
2. Average growth rates are set to k=0.29 (males) and k=0.25 (females) for the reference operating model configuration; and
3. Asymptotic lengths are set to $L_\infty = 68$ (males) and $L_\infty = 72$ cm (females).

Estimates of von Bertalanffy growth parameters published in the literature vary widely (Table D-3). The species exhibits sexual dimorphism with females larger at age than males after reaching maturity at about ages 5-7. However, published estimates may vary due to:

a. fitting the growth curve to mean length-at-age rather than observations from individual fish,
b. using samples collected by various gear types which introduces different biases due to selectivity,
c. sampling from different depths, locations or time periods (both within and among years), and
d. using different labs and age-readers for age determination.

For example, Hanselman et al. (2007) reported estimates of growth based on longline hook survey samples. Estimates based on data collected during 1981-1993 were compared to those obtained from data collected during 1996-2004. They concluded that maximum length had increased over time and applied their growth estimates to each period 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 are k=0.222 and L_∞=80.2 cm for females, and k=0.290 and L_∞=67.8 cm for males (Hanselman et al. 2014).

Growth estimates from the U.S. west coast assessment have changed over the last three assessments. Schirripa (2007) reported estimates of k=0.246 and L_∞=77.5 cm for females, and k=0.298 and L_∞=64.5 cm for males. Stewart et al. (2011) estimated growth parameters within the stock assessment model; base case model estimates of length at age 0.5, growth rate, and length at age 30 ($L_{0.5}, k, L_{30}$) were (25.8 cm, 0.335, 64 cm) for females and (25.8 cm, 0.419, 56.2 cm) for males. An update of the U.S. West Coast assessment (Johnson et al. 2015) resulted in similar estimates of (26.1 cm, 0.33, 64.15 cm) for females and (26.1 cm, 0.42, 56.28 cm) for males. Note that $L_{0.5}$ was set to be equal for the sexes because there is little difference in size between the sexes in length at age 0.5.

Table D-3. Published growth estimates for Sablefish from BC, Gulf of Alaska (GOA), and the U.S. West Coast including time of hatching (t_0) when provided, average growth rate (k) and asymptotic size (L_∞). Note for the 2011 and 2015 U.S. West Coast assessments the estimated parameters were lengths at age 0.5 and 30 ($L_{0.5}$, L_{30}) and average growth rate. Estimates shaded gray and marked with an asterisk are currently used as fixed inputs to the GOA assessment or estimated within the assessment model for the U.S. West Coast assessment.

Area	Sex	t_0 (years)	k	L_∞ (cm)	Source
BC	Males Females	-1.07 -0.77	0.290 0.249	66.7 81.5	Stocker and Saunders (1997)
Northern BC	Males Females	-	0.338 0.263	65.9 76.2	Saunders et al. (1995)
Southern BC	Males Females	-	0.29 0.249	66.7 81.4	Saunders et al. (1995)
GOA	Males Females	-2.35 -2.89	0.23 0.16	69.1 83.0	1981-1985 (Hanselman et al. 2007)
GOA	Males Females	-0.716 -0.959	0.379 0.265	67.3 79.3	1996-2004 (Hanselman et al. 2007)
GOA slope	Males Females	-	0.033-0.243 0.112-0.204	66.5-74.8 78.5-95.4	Ranges by area (Sigler et al. 1997)
GOA shelf	Males Females	-	0.069-0.344 0.169-0.403	63.7-70.9 70.7-75.6	Ranges by area (Sigler et al. 1997)
GOA	Males Females	-8.06 -6.15	0.12 0.106	70.2 86.7	1987-1989 longline hook survey samples (Kimura et al. 1993)
GOA	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	1996-2004, ranges by management area (Hanselman et al. 2007)
BC	Males Females	-	0.504 0.390	61.2 70.9	2003-2009 trap survey samples (Cox et al. 2011). Length at age-1=32.5 cm.
U.S. West Coast	Males Females	-1.82 -0.81	0.472 0.499	54.7 61.0	1983-1989, trawl and trap survey samples (Kimura et al. 1993)
U.S. West Coast	Males Females	-	0.298 0.246	64.5 77.5	Trawl survey and fishery sample (Schirripa 2007)
U.S. West Coast	Males Females	$L_{0.5}$=25.8 $L_{0.5}$=25.8	0.419 0.335	L_{30}=56.2 L_{30}=64	Trawl survey and fishery samples (Stewart et al. 2011)
GOA*	Males Females	-4.092 -3.629	0.227 0.208	65.269 75.568	1981-1993, longine hook samples (Hanselman et al. 2007; Echave et al. 2012)
GOA*	Males Females	-2.273 -1.949	0.290 0.222	67.774 80.220	1996-2004, longline hook samples, (Hanselman et al. 2007; Echave et al. 2012)
BC	Males Females	-	0.501 0.392	60.4 70.5	2003-2014 trap survey samples. Length at age-1=32.5 cm.
U.S. West Coast*	Males Females	$L_{0.5}$=26.10 $L_{0.5}$=26.10	0.42 0.33	L_{30}=56.28 L_{30}=64.15	Trawl survey, fishery samples (Johnson et al. 2015).

D.4. MATURITY

Sablefish on the U.S. west coast spawn from October through April, with peak spawning about January and February (Johnson et al. 2015). Sablefish in BC and Alaska are thought to spawn January through April (Mason et al. 1983; McFarlane and Beamish 1983; Hanselman et al. 2014), with peak spawning about February. Sablefish sampled during BC research surveys are assigned to maturity stages 1-12 based on visual (macroscopic) inspection of the gonads; stages 3-12 correspond to mature fish (Wyeth et al. 2007). Research survey data are primarily available from trap surveys conducted in October and the first half of November, perhaps just before, or at the onset of, the spawning season. Maturity status is not easily determined out of spawning season when mature and immature fish may be mixed; distinguishing differences in the appearance of the ovaries of immature fish with those in the resting stage is difficult.

We fit a simple logistic model to maturity at age data by sex (Figure D-3). 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 StRS samples are at the low end of the published range (Table D-4), which may be expected if trap gear selects for fast-growing Sablefish or there is bias in assignment of maturity stages to immature states. Thus, for modeling purposes 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) and Cox et al. (2011).

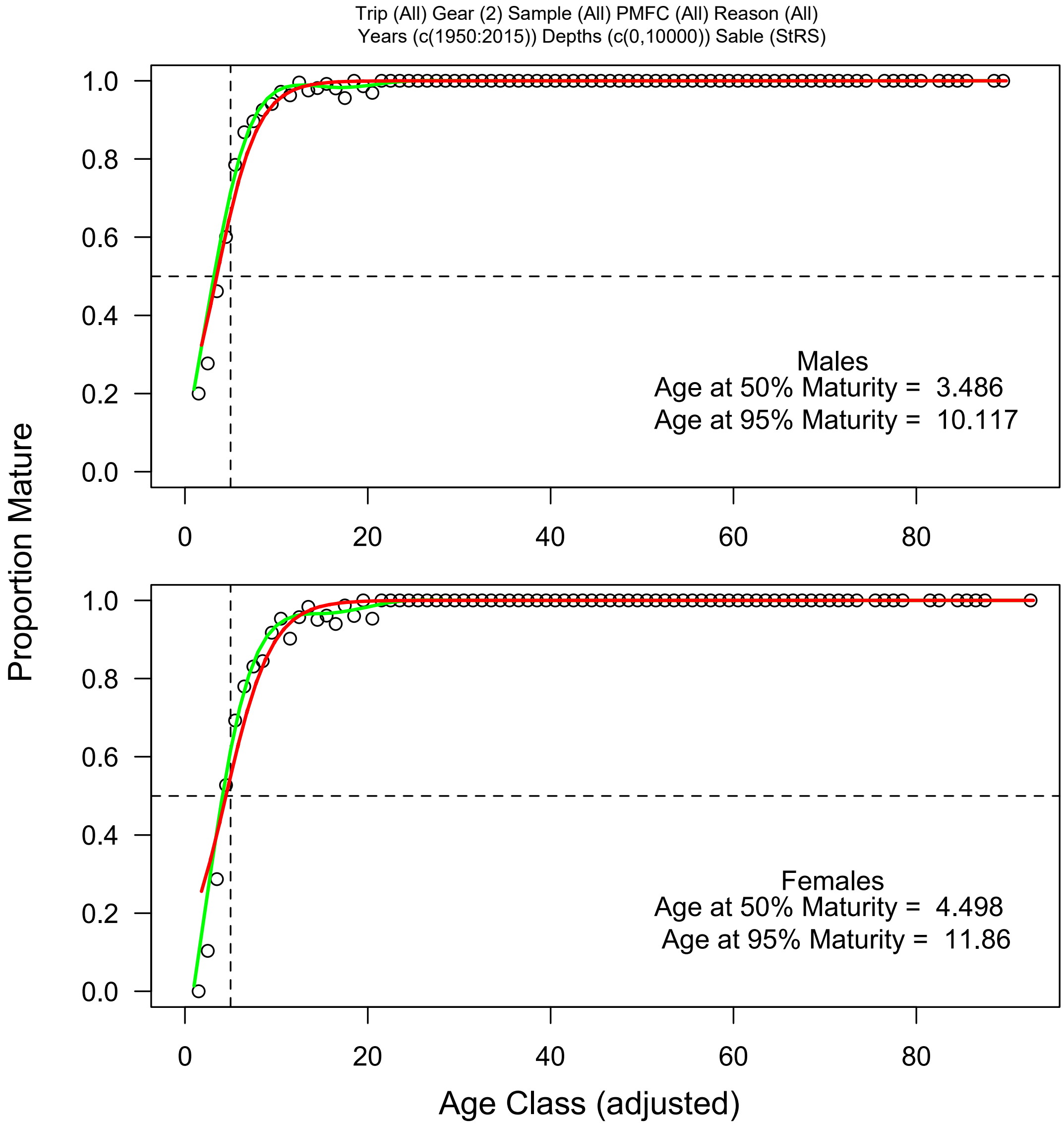

Figure D-3. Maturity at age for male (upper panel) and female (lower panel) Sablefish. Observed proportions at age are shown as open circles. The fitted maturity schedule is shown for a logistic model (red line) and smoothing spline (green line); estimates for the logistic model are shown within each figure panel.

Table D-4. Estimates of age and length at 50% maturity for Sablefish.

Area	Sex	Age at 50% Maturity (years)	Length at 50% Maturity (cm)	Source
GOA	Males	5	57	Sasaki (1985), used by Hanselman et al. (2014)
	Females	6.5	65	
BC	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	
	Combined	2.95	49.47	Cox et al. (2011)
	Males	2.63	48.24	
	Females	3.14	57.00	
	Males	3.5	49.2	2003-2014 stratified random trap survey samples
	Females	4.5	57.4	
U.S. West Coast	Males	5-7	-	Parks and Shaw (1987)
	Females		55.3	
	Males	3-8	49.0	Fujiwara and Hankin (1988)
	Females	3-8	56.4	
	Males	5-7	-	Schirripa (2007)
	Females		55.3	
	Males	-	-	Stewart et al. (2011), Johnson et al. (2015)
	Females	-	58	

D.5. PROPORTIONS AT AGE

Proportions-at-age by sex for the commercial trap fishery, standardized trap survey and stratified random trap survey are shown as Figure D-4 to Figure D-9, respectively. Specimens were assigned equal weight 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”, and
4. Samples were excluded if the sample could be identified as collected at a seamount or inshore waters (e.g., mainland inlets survey program).

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) and Cox et al. (2011) 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 operating model fits 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. Ageing data for the commercial trap fishery are incomplete for 2015 and were removed from the operating model fits due to low sample sizes. Standardized survey ages were included if the fish were derived from depth strata D1 through D5 so that the depth of sampling is consistent over the 1990 to 2009 time series (Wyeth et al. 2007). All ages available from the stratified random survey were included.

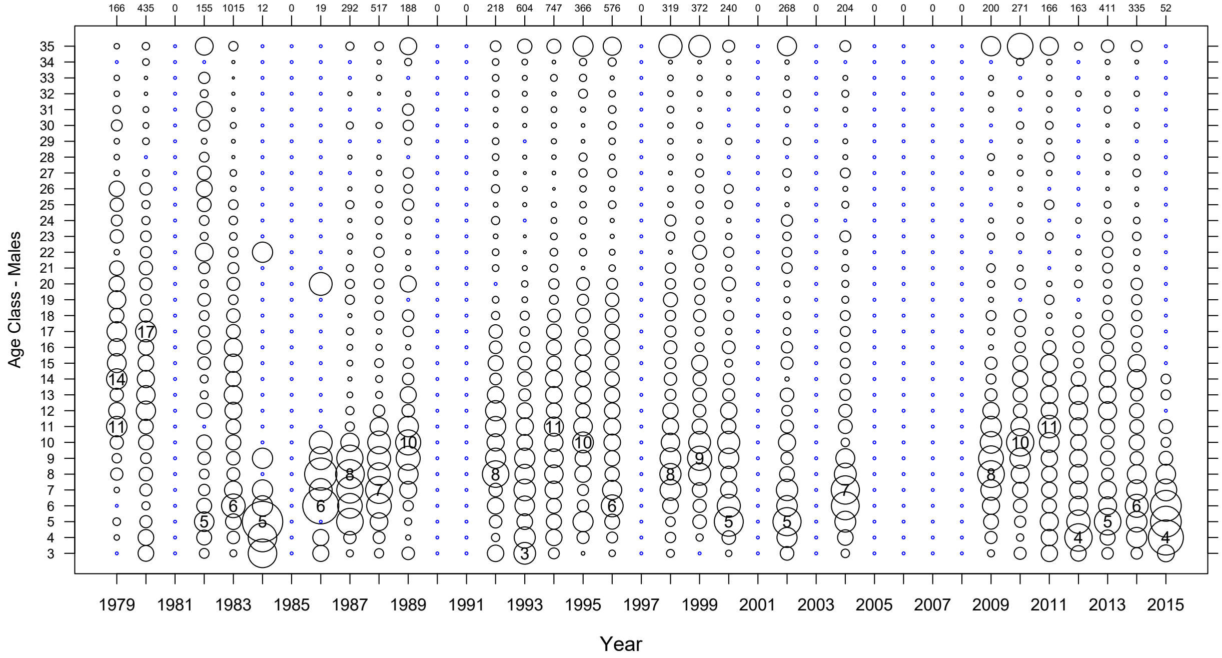

Figure D-4. Commercial trap fishery proportions at age for male Sablefish, 1982-2015. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers within sized-circles indicate the age class of the largest age proportion in a year. Numbers of fish aged in each year are indicated along the top axis of each panel.

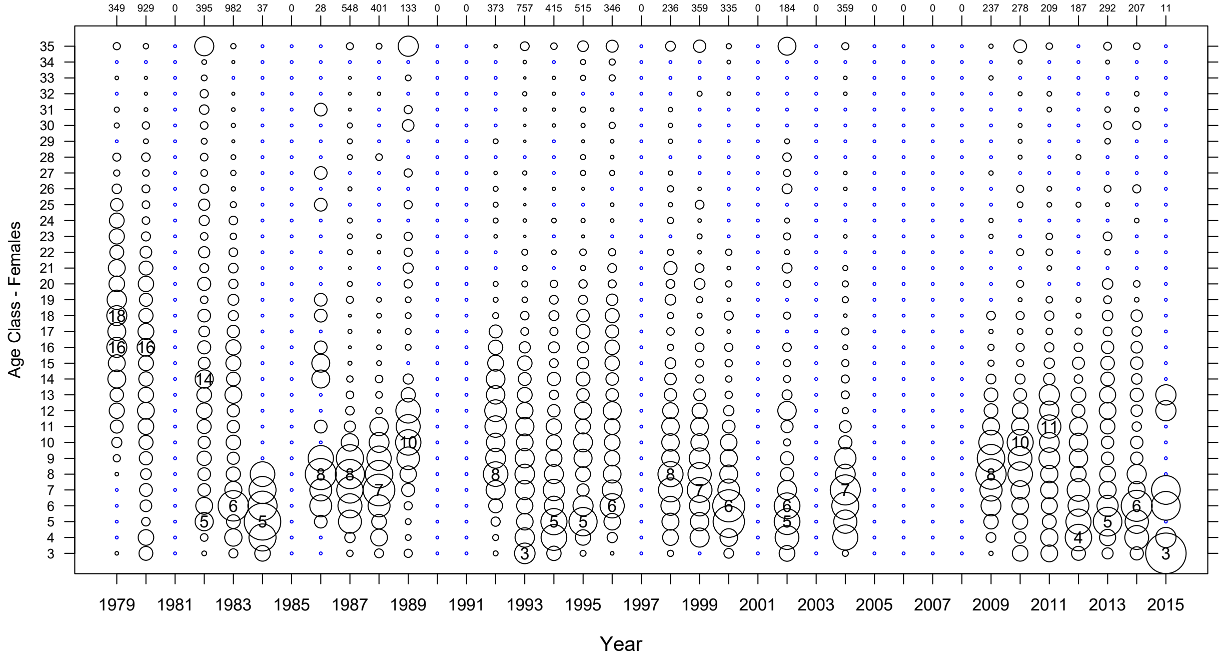

Figure D-5. Commercial trap fishery proportions at age for female Sablefish, 1982-2015. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers within sized-circles indicate the age class of the largest age proportion in a year. Numbers of fish aged in each year are indicated along the top axis of each panel.

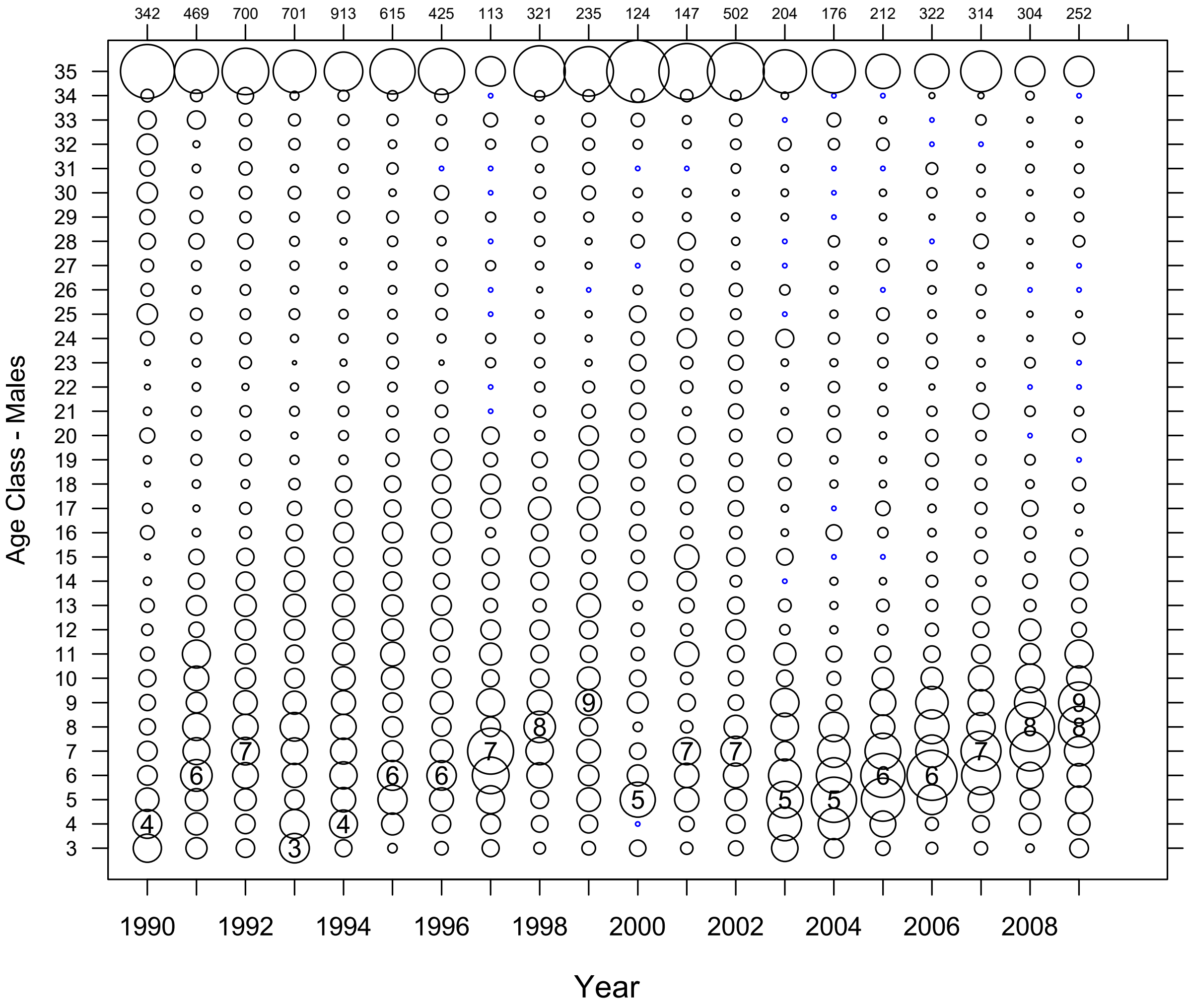

Figure D-6. Standardized trap survey proportions at age for male Sablefish, 1990-2010. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers within sized-circles indicate the age class of the largest age proportion in a year. Numbers within sized-circles indicate the age class of the largest age proportion in a year. Numbers of fish aged in each year are indicated along the top axis of each panel.

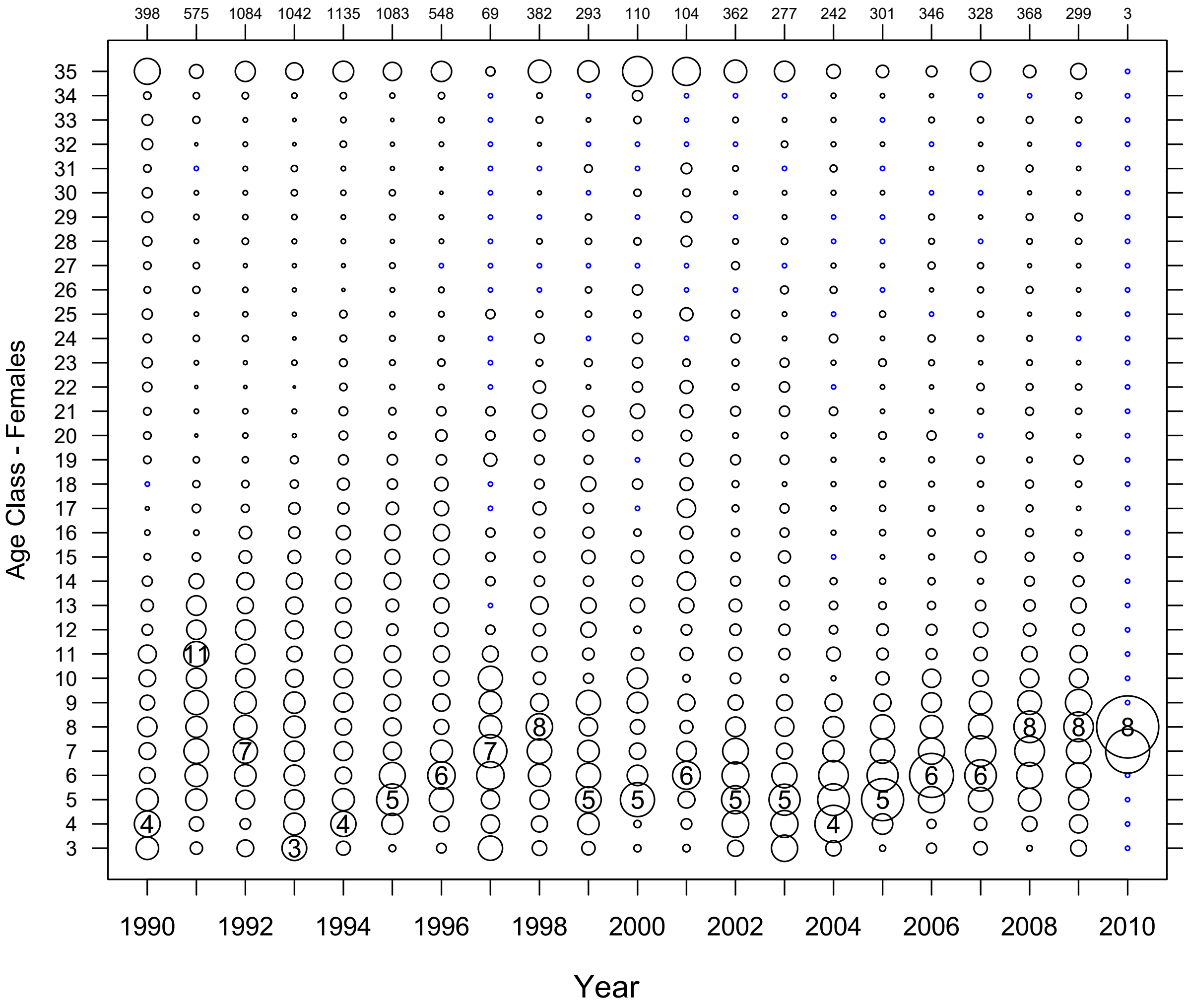

Figure D-7. Standardized trap survey proportions at age for female Sablefish, 1990-2010. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers within sized-circles indicate the age class of the largest age proportion in a year. Numbers of fish aged in each year are indicated along the top axis of each panel.

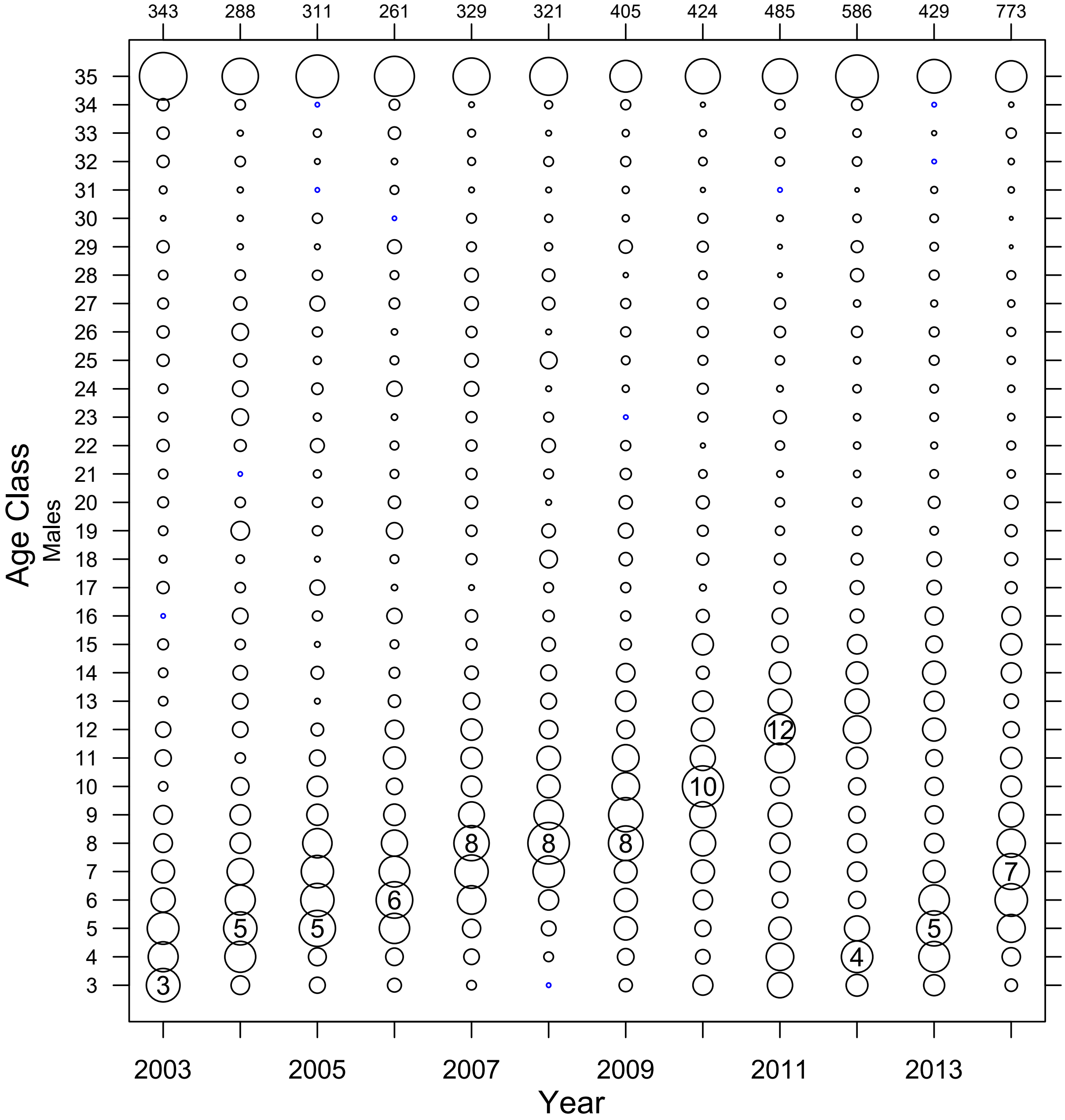

Figure D-8. Stratified random trap survey proportions at age for male Sablefish, 2003-2014. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers within sized-circles indicate the age class of the largest age proportion in a year. Numbers of fish aged in each year are indicated long the top axis of each panel.

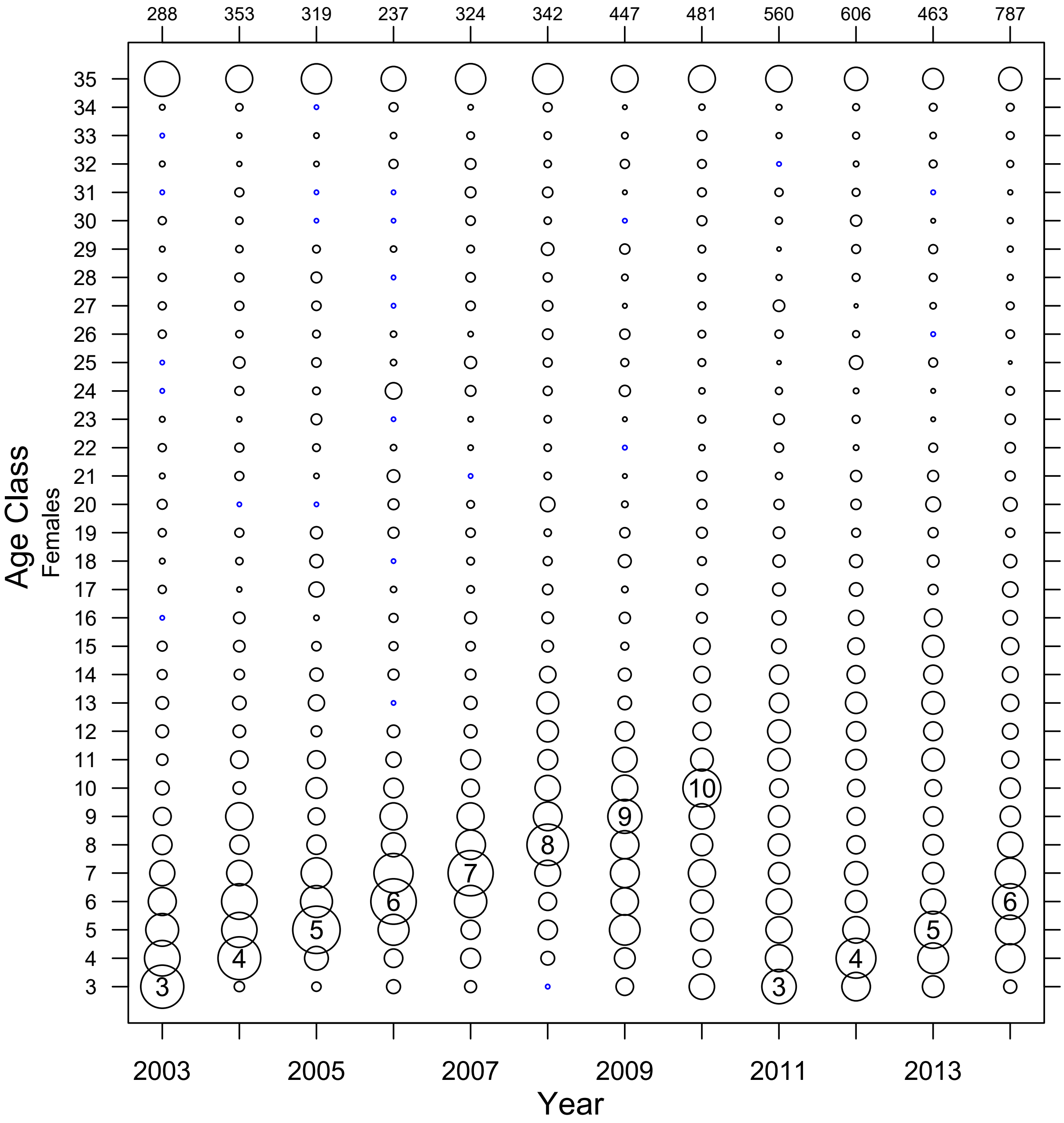

Figure D-9. Stratified random trap survey proportions at age for female Sablefish, 2003-2014. The minimum age is set to 3 and the plus group at age class 35. The sized-circles are scaled to the proportions at age. Numbers within sized-circles indicate the age class of the largest age proportion in a year. Numbers of fish aged in each year are indicated long the top axis of each panel.

D.6. NATURAL MORTALITY

The maximum age reported for Sablefish in Alaska is 94 years (Kimura et al. 1998), 87 years in British Columbia, and 102 years (female) along the U.S. west coast (Stewart et al. 2011). 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 by the Alaskan assessment model 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 beginning with Hanselman et al. (2009) through Hanselman et al. (2014).

The first application of stock synthesis to U.S. West Coast Sablefish used a value of M = 0.15 (Methot and Hightower 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 U.S. West Coast Sablefish in 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 to 2007 (e.g., Schirripa 2007). Sex-specific natural mortality was estimated (with an informative prior) at 0.08 for females and 0.065 for males for the 2011 assessment (Stewart et al. 2011). The most recent assessment by Johnson et al. (2015) resulted in estimates of M = 0.08 for females and 0.06 for males. Stock assessments in British Columbia adopted a fixed M = 0.08 (e.g., Haist et al. 2005, Cox et al. 2009, Cox and Kronlund 2009). Cox et al. (2011) estimated a combined-sex natural mortality of 0.06 for their baseline operating model scenario but also included scenarios with fixed M = 0.08.

D.7. 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 and Parker 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 post-release due to cumulative stress effects or predation while the fish are recovering. 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 factors is difficult to quantify under the full range of fishing conditions. For this reason, release mortality for Sablefish has been studied primarily through controlled laboratory experiments (e.g., Davis et al. 2001, Olla et al. 1998) with relatively few field studies (e.g., Erickson et al. 1997, Rutecki and Meyers 1992, Thorson 1972).

Rutecki and Meyers (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 experimental 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 trawl codend 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 Davis et al. (2001) and industrial fishing conditions (e.g., longer exposure to air, higher temperatures, handling practices), were not replicated. Thus, it is likely that mortality rates were under-estimated relative to commercial fishing using trawl gear.

Davis and Parker (2004) and Davis (2005) suggest that changes to fish behaviour due to 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 of Sablefish (small 32-49 cm and large 50-67 cm) 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 in mortality 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 h after exposure. Normal behaviour had not generally resumed by 24 h after exposure and small fish had more impairment than large fish at that time. Air exposure considerations are likely to impact trawl-caught fish to a greater degree than for Sablefish caught by hook and line gear. 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 used in British Columbia 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 h 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 the bottom temperature was 6°C - 8°C and the 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. Like other studies, mortality rates were greater for small Sablefish over periods of 1, 2, 4, and 6 days.

In general, the limited empirical data on at-sea release mortality of Sablefish indicate that

a. release mortality is lowest for trap gear, intermediate for longline hook gear, and highest for trawl gear,
b. small, sub-legal Sablefish (< 55 cm fork length in British Columbia) 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
c. behavioural changes and injury-related infection may cause substantial delayed mortality, particularly for small Sablefish due to post-release predation or disease.

Under the current Sablefish management plan (DFO 2014) 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. The release mortality used to calculate the deduction varies by gear type; trap and longline hook gears are 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 prorated for each subsequent hour. The trawl gear 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 BC integrated fishery management plans may substantially under-estimate the actual mortality of released Sablefish. In particular, the mortality rates in the management plan 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 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 release mortality rates as specified in DFO management plans 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 0.16/yr for trap gear, 0.35/yr for longline hook gear, and 1.6/yr for trawl. These equate to total annual mortality rates of 15%, 30%, and 80%, respectively. In comparison, the most recent assessment of Sablefish for the U.S. west coast (Johnson et al. 2015) assumed that release mortality is 100% for age-0 less than 28 cm. For fish above 28 cm the release mortality was assumed to decline rapidly to 20% for the longline hook and trap gears, and to 50% for trawl gear. The effective release mortality rates over all sizes were 60% for longline hook and trap gears, and 75% for trawl gear.

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APPENDIX E. SELECTIVITY ESTIMATED FROM TAGGING DATA

E.1. INTRODUCTION

Size-selectivity of commercial fisheries is sometimes confounded with other model parameters within age- or length-based population dynamic models (Sigler 1999). Tag release-recovery data can be used to estimate fishery size-selectivity directly by comparing the size-distribution of tag recoveries to the known size distribution of tag releases (Hamley and Reiger 1973; Myers and Hoenig 1997). In this Appendix, we estimate size-selectivity from tags released on Sablefish surveys and recovered by the commercial fisheries (i.e., longline trap, longline hook, and trawl). We compare the relative performance of logistic, normal, and gamma selectivity functions based on stationary and time-varying parameterizations.

E.2. DATA PREPARATION AND MODELING

Selectivity was estimated from tag release-recovery data collected from 1996 through 2012. Releases in each year (R_t) are pooled across all trap survey types (i.e., traditional tagging program, standardized trap survey, stratified random survey, and inlets survey program; Wyeth et al. 2004). Recovered fish were separated into 50 mm length classes between 450 mm and 900 mm based on their release length. Release (instead of recovery) lengths were used because fish recovered from commercial fisheries are frozen at-sea and thawed for on-shore sampling, which can lead to errors in measuring their true recovery length. Recovery gears included commercial longline trap, longline hook, and trawl. Commercial trawl recoveries exclude the first length class (450-500 mm) because of small sample sizes or zero observations in some years that prevented all time-varying models from converging. Natural mortality was assumed constant for all size-classes included in the analysis.

Annual recoveries were restricted to Sablefish recaptured within one year of release and separated by the recovery gear (g) and length class (j). Restricting fish to one year at liberty removes the need to simultaneously estimate growth and mortality rates required to estimate selectivity from multi-year recoveries. Thus, it was assumed that individual fish remain within their release length class in the year following release. For the size classes considered in the analysis this assumption is unlikely to be violated for fish age-5 and older. For example, based on von Bertalanffy growth fits to BC Sablefish data (Cox et al. 2011) an age-5 fish is expected to grow on average from 593 to 623 mm by age-6, an increase of 30 mm. An age-10 fish is expected to grow on average 6 mm in one year. In contrast, an age-1 fish (about 320 mm fork length) is expected to grow 100 mm by age-2.

The annual expected number of Sablefish recaptured within each length class, $\hat{C}_{g,t,j}$, was computed as the product of fisheries-specific size-selectivity, $s_{g,j}$, exploitation rate, $f_{g,t}$, and the total number of released fish in the previous year, $R_{t-1,j}$, i.e.,

$$\text{(1)} \qquad \hat{C}_{g,t,j} = s_{g,j} f_{g,t} R_{t-1,j} \quad .$$

For each fishery, models describing asymptotic and dome-shaped curves were compared using three parametric functions, each involving stationary and time-varying parameterizations. Asymptotic selectivity was specified using the following Logistic (L) function with three parameterizations (one stationary and two time-varying):

$$\text{(2L.1)} \qquad s_{g,j} = \frac{1}{a_g + e^{-b_g\left(l_j - a_g\right)}} \left(\max\left(s_{g,j}\right)\right)^{-1} \qquad \text{(Logistic; stationary)} \ ,$$

$$s_{g,t,j} = \frac{1}{a_{g,t} + e^{-b_g\left(l_j - a_{g,t}\right)}}\left(\max\left(s_{g,j}\right)\right)^{-1} \quad \text{(Logistic; time-varying } a_{g,t}\text{)} \ , \tag{2L.2}$$

$$s_{g,j} = \frac{1}{a_g + e^{-b_{g,t}\left(l_j - a_g\right)}}\left(\max\left(s_{g,j}\right)\right)^{-1} \quad \text{(Logistic; time-varying) } b_{g,t}\text{)} \ , \tag{2L.3}$$

where a is the length class in which 50% of individuals are fully selected, b is the slope of the curve, l_j is the median of the j^{th} 50 mm length-class, and t indicates year.

Dome-shaped selectivity models were estimated with both Normal (N) and Gamma (G) functions, each of which was parameterized using one stationary and two time-varying formulations as

$$s_j = \frac{1}{\sigma_g\sqrt{2\pi}}e^{\frac{-\left(l_j-\mu_g\right)^2}{2\sigma_g^2}}\left(\max\left(s_{g,j}\right)\right)^{-1} \quad \text{(Normal; stationary)} \ , \tag{2N.1}$$

$$s_{g,t,j} = \frac{1}{\sigma_g\sqrt{2\pi}}e^{\frac{-\left(l_j-\mu_{g,t}\right)^2}{2\sigma_g^2}}\left(\max\left(s_{g,j}\right)\right)^{-1} \quad \text{(Normal; time-varying } \mu_{g,t}\text{)} \ , \tag{2N.2}$$

$$s_{g,t,j} = \frac{1}{\sigma_g\sqrt{2\pi}}e^{\frac{-\left(l_j-\mu_g\right)^2}{2\sigma_{g,t}^2}}\left(\max\left(s_{g,j}\right)\right)^{-1} \quad \text{(Normal; time-varying } \sigma_{g,t}\text{)} \ , \tag{2N.3}$$

where μ is the fully-selected length class, σ is the function's standard deviation, l_j is the median of the j^{th} 50 mm length-class, and t indicates year. Similarly, equations for the Gamma function are given by

$$s_{g,j} = l_j^{\left(c_g-1\right)}e^{\left(c_g - d_g l_j - 1\right)}\left[\frac{c_g-1}{d_g}\right]^{-\left(c_g-1\right)}\left(\max\left(s_{g,j}\right)\right)^{-1} \quad \text{(Gamma; stationary)} \ , \tag{2G.1}$$

$$s_{g,t,j} = l_j^{\left(c_{g,t}-1\right)}e^{\left(c_{g,t} - d_g l_j - 1\right)}\left[\frac{c_{g,t}-1}{d_g}\right]^{-\left(c_{g,t}-1\right)}\left(\max\left(s_{g,j}\right)\right)^{-1} \quad \text{(Gamma; time-varying } c_{g,t}\text{)} \ , \tag{2G.2}$$

$$s_{g,t,j} = l_j^{\left(c_g-1\right)}e^{\left(c_g - d_{g,t} l_j - 1\right)}\left[\frac{c_g-1}{d_{g,t}}\right]^{-\left(c_g-1\right)}\left(\max\left(s_{g,j}\right)\right)^{-1} \quad \text{(Gamma; time-varying } d_{g,t}\text{)} \ , \tag{2G.3}$$

where c_g is a shape parameter, d_g is a rate parameter, l_j is the median of the j^{th} 50 mm length-class, and t indicates year where it occurs. Parameters were estimated on the log-scale by minimizing the negative logarithm of the binomial likelihood for the expected number of recovered tags within each length-class,

$$-LL = -1\sum_{t=1}^{T}\sum_{j=1}^{J} C_{g,t,j}\log\left(\frac{\hat{C}_{g,t,j}}{R_{t-1,j}}\right) + \left(R_{t-1,j} - C_{g,t,j}\right)\log\left(1 - \frac{\hat{C}_{g,t,j}}{R_{t-1,j}}\right) \ , \tag{3}$$

where $C_{g,t,j}$ is the observed number of recovered tags within each length-class.

Optimization was performed using the Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm within the **`optim`** function in R (R Development Core Team 2015). The variance of each parameter was computed using the delta method as

$$(4) \qquad \sigma_u{}^2 = \left(\frac{du}{dv}\right)^2 \sigma_v{}^2$$

where σ_u^2 is the variance of the natural-scale selectivity parameter estimate, du/dv is the derivative of the transformed function with respect to the selectivity parameter, and σ_v^2 is the log-scale variance of the parameter estimates taken from the diagonal of the Fisher information matrix (i.e., the negative of the inverse Hessian matrix).

Akaike's Information Criterion (AIC) was computed for each selectivity model using

$$(5) \qquad \mathrm{AIC} = 2k - 2\log LL \ ,$$

where k is the number of estimated parameters and M_l is the model likelihood. Within nested models, lower AIC values indicate higher statistical support adjusted for the number of parameters in the model. The parsimony of the fit for each selectivity model was compared using the difference between the AIC score and the smallest AIC score of all the models used within each fishery (ΔAIC).

E.3. MODEL RESULTS

Selectivity models did not converge for the Logistic function with time-varying $b_{g,t}$ (Eq. 2L.3) for either the longline trap and longline hook fisheries. Commercial trawl selectivity models did not converge for any logistic functions (Eqs. 2L.1, 2L.2, 2L.3), or the Normal function with time-varying σ_t (model 2N.3). The difference in AIC values for each converged model relative to the model with the lowest AIC value within each fishery is listed in Table E-1. Parameter estimates for the selectivity function with the lowest AIC value for each gear type are listed in Table E-2. Normal curves with a time-varying standard deviation (2N.3) produced the lowest AIC value for tags returned by the commercial longline trap and longline hook fisheries. A stationary Gamma selectivity function (2G.1) produced the lowest AIC score for commercial trawl gear. Figure E-1 shows the corresponding selectivity curves for each of these models and Figure E-2 shows the corresponding time-varying parameter estimates.

Table E-1. Relative AIC values for each selectivity model by gear type where is Δ AIC the difference in AIC values between each model and the model with the lowest AIC value within each gear type. Values in parentheses indicate the raw AIC value.

Selectivity Model	Time Varying	Longline Trap	Δ AIC (AIC) Longline Hook	Trawl
Logistic				
2L.1	No	992.67 (109,527.80)	25.92 (43,245.86)	-
2L.2	Yes	327.37 (108,862.50)	25.92 (43,245.86)	-
Normal				
2N.1	No	644.27 (109,179.40)	3.94 (43,223.88)	31.70 (13,988.62)
2N.2	Yes	28.47 (108,563.60)	10.29 (43,230.23)	3.56 (13,960.48)
2N.3	Yes	0 (108,535.13)	0 (43,219.94)	-
Gamma				
2G.1	No	677.27 (109, 212.40)	6.65 (43,226.59)	0 (13,956.92)
2G.3	Yes	20.47 (108,555.60)	11.38 (43,231.32)	2.97 (13,959.89)
2G.3	Yes	54.27 (108,589.40)	13.13 (43,233.07)	3.88 (13,960.80)

Table E-2. Parameter estimates and standard errors (SE) for the selectivity curve models with the lowest AIC scores for each gear type. In the case of the trawl fishery, parameter estimates from model 2N.2 are also presented for comparison to the time-varying longline trap and hook models.

Gear	Selectivity	Parameter	Estimate	SE
Trap	2N.3	μ	703.56	1.86
		σ_{1996}	125.25	6.49
		σ_{1997}	208.32	19.12
		σ_{1998}	151.26	8.33
		σ_{1999}	95.60	3.10
		σ_{2000}	80.88	2.01
		σ_{2001}	91.57	3.04
		σ_{2002}	108.75	4.59
		σ_{2003}	79.32	3.50
		σ_{2004}	76.81	2.37
		σ_{2005}	79.78	2.63
		σ_{2006}	75.48	2.70
		σ_{2007}	88.51	3.17
		σ_{2008}	97.01	4.83
		σ_{2009}	98.74	9.29
		σ_{2010}	89.90	6.00
		σ_{2011}	106.23	9.14
		σ_{2012}	111.36	7.67
Hook	2N.3	μ	715.29	4.55
		σ_{1996}	106.73	9.74
		σ_{1997}	105.7	8.68
		σ_{1998}	106.29	9.1
		σ_{1999}	108.59	8.39
		σ_{2000}	119.02	6.78
		σ_{2001}	105.49	7.04
		σ_{2002}	128.77	13.05
		σ_{2003}	92.55	7.24
		σ_{2004}	116.34	8.63
		σ_{2005}	99.39	6.53
		σ_{2006}	111.24	9.39
		σ_{2007}	105.91	8.92

Gear	Selectivity	Parameter	Estimate	SE
		σ_{2008}	99.67	7.18
		σ_{2009}	97.18	10.8
		σ_{2010}	135.05	19.27
		σ_{2011}	105.97	8.37
		σ_{2012}	153.51	17.51
Trawl	2G.1	c	7.04	4.25
		d	1.20e^{-3}	67.9e^{-3}
Trawl	2N.2	σ	229.93	64.88
		μ_{1996}	423.25	197.04
		μ_{1997}	462.47	130.31
		μ_{1998}	272.18	228.34
		μ_{1999}	543.62	87.09
		μ_{2000}	656.9	85.02
		μ_{2001}	403.65	145.58
		μ_{2002}	343.33	170.92
		μ_{2003}	455.43	126.7
		μ_{2004}	651.21	96.98
		μ_{2005}	521.29	137.65
		μ_{2006}	693.17	163.58
		μ_{2007}	743.27	134.74
		μ_{2008}	663.84	104.13
		μ_{2009}	744.22	156.57
		μ_{2010}	451.31	229.88
		μ_{2011}	569.3	228.63
		μ_{2012}	648.27	236.22

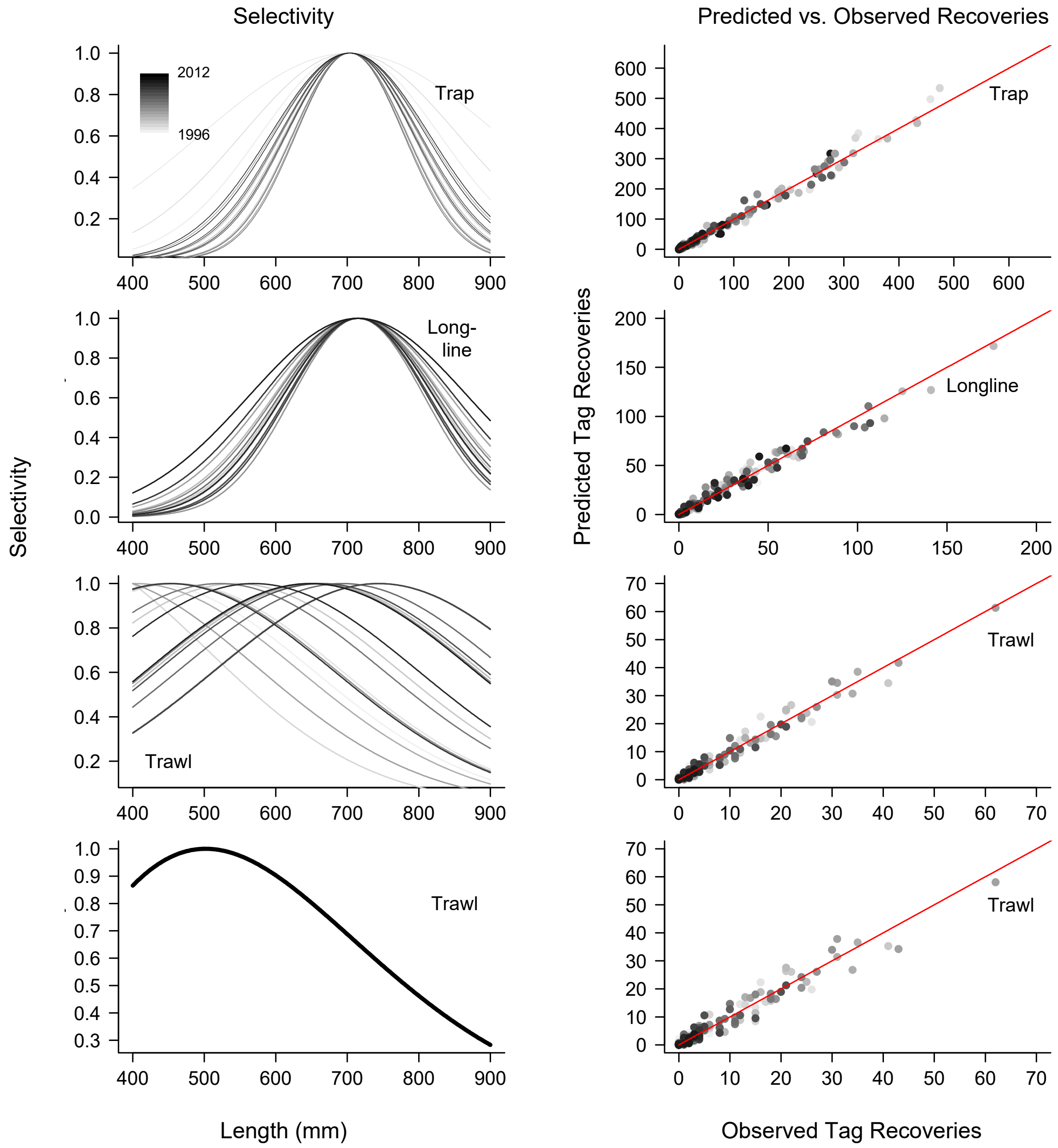

Figure E-1. Selectivity functions fitted to tagged Sablefish returned within one year of release by longline trap, longline hook, and trawl gears, respectively. Left panels show the estimated selectivity models for each gear type with the lowest AIC score (2N.3 for both longline trap and longline hook; 2N.2 and 2G.1 for trawl). In the case of trawl, two models are displayed because the AIC scores were similar. Right panels plot the model predicted versus observed tag recoveries. The 1:1 line indicates perfect prediction.

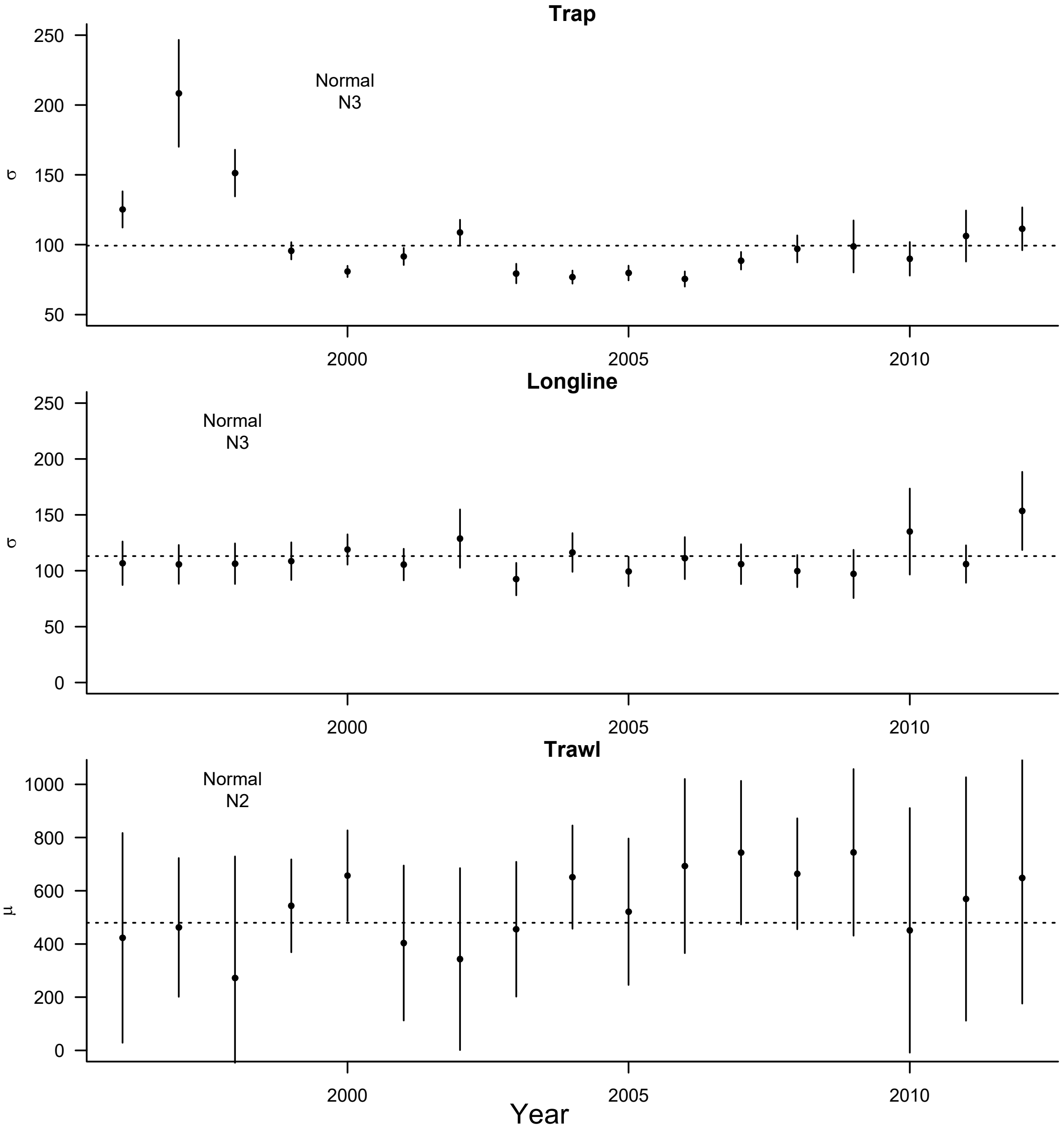

Figure E-2. Time-varying parameter estimates for selectivity functions fitted to data for tagged Sablefish returned within one year of release by longline trap (upper panel), longline hook (center panel), and trawl gears (bottom panel). Only the time-varying selectivity models with the lowest AIC value for each fishery are displayed. Estimates of σ_t are shown for the fits to commercial trap and longline gears for the model assuming a Normal curve with time-varying σ_t (i.e., model 2N.3). Estimates of μ_t obtained by fitting the model assuming a Normal curve with time varying μ_t (i.e., model 2N.2) are shown for commercial trawl tag-recoveries. Dashed horizontal lines on each figure panel indicate the parameter estimate from the corresponding non time-varying model.

E.4. DISCUSSION

For both the longline trap and longline hook fisheries, selectivity dome-shaped models (Normal, Gamma) consistently produced lower AIC values than asymptotic models for both stationary and time-varying parameterizations. Possible hypotheses to explain dome-shaped selectivity include:

a. larger Sablefish prefer deeper habitats where less fishing occurs,

b. larger tagged Sablefish move out of areas in which fisheries operate, including outside Canadian waters, and

c. larger tagged Sablefish are reported less frequently because of the market value of large fish.

Time-varying parameterizations were favoured, based on the AIC criterion, for all model types for longline trap gear, whereas there was little evidence for improvements in fit using time-varying parameterizations for the longline hook fishery. Estimates of σ_t showed no trend over time, whereas estimates of σ_t declined rapidly over the first few years for the longline trap fishery before varying around the estimate for the stationary model (Figure E-2).

Selectivity estimates obtained for the trawl fishery clearly indicate selection for smaller fish than either the longline trap or longline hook fisheries, but there are not substantial differences in AIC scores between the selectivity models (Figure E-1). Time-varying parameterizations of either Gamma or Normal selectivity models did not provide significantly better fits than the stationary parameterization for the trawl fishery data. This result may be due to low tag-recovery rates and, therefore, small sample sizes for trawl fishery data. Although linear trend lines fit to parameter estimates from time-varying parameterizations (not shown here) were statistically significant in models 2N.2, 2G.2, and 2G.3, the overall variation explained by linear trends is less than 50%. This result suggests that other unidentified factors may also be important for explaining differences among selectivity parameter estimates over time.

In addition to small sample size effects, small young fish may be more likely to be recaptured in length-classes larger than their release class within one year at liberty, a violation of the assumption that fish are recaptured in their release length class. However, younger, fast-growing Sablefish are to some extent not fully recruited to commercial fishing grounds and depths fished by longline trap and hook gear until age-5+, although they can be vulnerable to trawl gear while in shallower nearshore waters.

E.5. REFERENCES CITED

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APPENDIX F. AGEING ERROR MATRIX

F.1. INTRODUCTION

This appendix presents the calculations used to create an ageing error matrix for BC Sablefish (and age readers from DFO) based on an asymmetric geometric model in Hanselman et al. (2012; Figure F-1) developed for Gulf of Alaska Sablefish (i.e., and age readers from the National Marine Fisheries Service, NMFS). Parameters obtained from that paper are given in Table F-1.

Provided that a fish is not older than the plus-group age A, the probability of a fish with true age i being assigned to an observed age j is given by

$$Q_{j,i} = \begin{cases} s_{r,i}p_{r,i}\left(1-p_{r,i}\right)^{\left|\delta_{j-i}-X_r\right|} & \delta_{j-i} \geq X_r \\ \left(1-s_{r,i}\right)p_{l,i}\left(1-p_{l,i}\right)^{\left|\delta_{j-i}-X_l\right|} & \delta_{j-i} \leq X_l \\ 0 & \left|\delta_{j-i}-X_r\right| > 10 \end{cases},$$

where X_r is the smallest ageing error on the right-hand side of the true age, $X_l = X_r - 1$ is the largest error on the left-hand side of the true age, $s_{r,i}$ is the total proportion of the distribution lying to the right-hand side of the true age i, $\left(p_{r,i}, p_{l,i}\right)$ are geometric distribution parameters for the right- and left-hand sides, respectively, and $\delta_{j-i} = j - i$ is the difference between the true and assigned ages.

For the plus-group age (i=A), we sum probabilities over all the possible true ages that could contribute to an assigned age *j*,

$$Q_{j,i} = \begin{cases} s_{r,i}p_{r,i}\left(1-p_{r,i}\right)^{\left|\delta_{j-i}-X_r\right|} + \sum\limits_{k=\delta_{j-i}+1}^{k=\delta_{j-i}+9} s_{r,i}p_{r,i}\left(1-p_{r,i}\right)^{\left|k-X_r\right|} & \delta_{j-i} \geq X_r \\ \left(1-s_{r,i}\right)p_{l,i}\left(1-p_{l,i}\right)^{\left|\delta_{j-i}-X_l\right|} + \sum\limits_{k=\delta_{j-i}}^{k=X_l}\left(1-s_{r,i}\right)p_{l,i}\left(1-p_{l,i}\right)^{\left|k-X_l\right|} + \sum\limits_{m=X_r}^{m=X_r+10} s_{r,i}p_{r,i}\left(1-p_{r,i}\right)^{\left|m-X_r\right|} & \delta_{j-i} \leq X_l \end{cases}.$$

Table F-1. Parameter values obtained from Hanselman et al. (2012) for the asymmetric geometric model of Sablefish ageing errors.

Ages	**Pl**	**pr**	**sr**
3-5	1	0.47	0.87
6-7	0.76	0.58	0.64
8-9	0.58	0.52	0.50
10-35	0.38	0.44	0.37

Based on this model of NFMS readers and known-aged samples, fish older than age-2 tend to be aged slightly older than their true age until about age-7, then slightly younger than their true age, although the bias is quite small. The lack of systematically large ageing bias led Hanselman et al. (2012) to conclude that a simpler "naive" model would probably do just as well at capturing the key impacts of ageing errors. This is promising for BC Sablefish because a naive model can be developed directly from among-reader ageing deviations rather than known-aged fish.

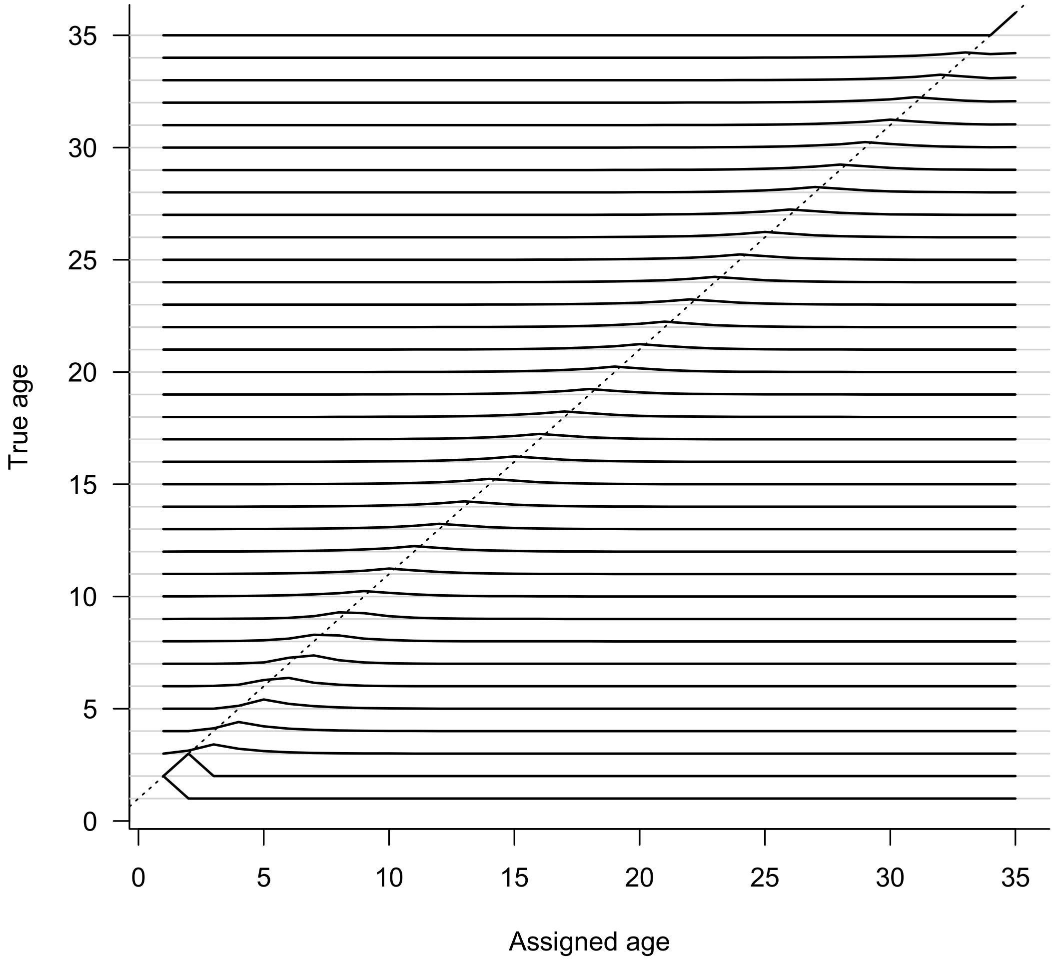

Figure F-1. Ageing error distributions based on the asymmetric geometric model of Hanselman et al. (2012). Horizontal gridlines are 1 unit apart and, therefore, represent the absolute probabilities of true age fish being given particular assigned ages. Age-1 and 2 fish are perfectly aged. Most of the distribution maxima are approximately 0.25.

F.2. REFERENCES CITED

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