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Sablefish Stock Assessment for 2000 and Recommended Yield Options for 2001

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Abstract

This document represents a major assessment for B.C. sablefish. The principle data source on trends in abundance is the tagging program, and in particular the percentage of tags returned in the year following tagging. Coastwide, this percentage remained steady at 9-11% from 1991 to 1997, rose to 19% in 1998, and decreased to 8% in 1999.

Three analytical methods, all based on the tag release-recapture data, are used to estimate stock abundance. The methods differ in the degree that biological and fishery structure is incorporated in the estimation process, and in the choice of tagging data subsets used in the analyses. Different tagging data subsets are chosen to minimize potential bias in the alternative estimation methods.

All three methods suggest that B.C. sablefish decreased in abundance from the early 1990's through 1997, followed by a substantial increase in 1999. These trends are consistent with those observed in commercial fishery CPUE and survey CPUE indices, except that the fishery and survey indices did not show significant increases in 1999. However, the fishery CPUE is not adjusted for the effect of escape-rings, used in the commercial fishery in 1999, and therefore will not reflect abundance trends.

Stochastic stock projections are conducted for the 2000 to 2002 period at three levels of harvest (3800 t, 4000 t, 4500 t). The expectation, at all harvest levels, is an increase in abundance for both stocks.

Résumé

Ce document porte sur une évaluation détaillée de la morue charbonnière des eaux de la Colombie-Britannique. Le programme d'étiquetage, en particulier le pourcentage d'étiquettes retournées l'année suivant l'année d'étiquetage, a servi de source principale de données sur les tendances de l'abondance. À l'échelle de la côte, ce pourcentage est demeuré stable de 1991 à 1997, se situant entre 9 et 11 %; il a ensuite grimpé à 19 % en 1998, puis a chuté à 8 % en 1999.

Trois méthodes d'analyse, toutes reposant sur les données issues des étiquettes posées et retournées, sont utilisées pour estimer l'abondance des stocks. Les méthodes diffèrent en leur degré d'inclusion de la structure biologique et halieutique dans le processus d'estimation et en leur choix de sous-séries de données d'étiquetage utilisées. L'utilisation de différentes sous-séries permet de minimiser le biais potentiel dans les autres méthodes d'estimation.

Les trois méthodes suggèrent que l'abondance de la morue charbonnière dans les eaux de la Colombie-Britannique a diminué du début des années 90 à la fin de 1997, pour ensuite augmenter considérablement en 1999. Ces tendances correspondent aux tendances observées des indices de la CPUE de la pêche commerciale et des relevés, sauf que la pêche et ces indices n'indiquent pas une augmentation importante en 1999. Comme la CPUE de la pêche n'a toutefois pas été corrigée de l'effet des anneaux d'échappée, utilisés par les pêcheurs commerciaux en 1999, elle ne reflète pas les tendances de l'abondance.

On fait des prévisions stochastiques de l'abondance du stock pour la période 2000-2002 à trois niveaux de prises (3 800 t, 4 000 t et 4 500 t). À tous ces niveaux, on prévoit que l'abondance des deux stocks augmentera.

Introduction

This document represents a major assessment for B.C. sablefish. The document is comprised of five sections, the first of which summarizes fishery and biological information. The next three sections describe three alternative methods that are used to estimate B.C. sablefish abundance. All three methods utilize tag release and recapture data, which has been the primary indicator of sablefish abundance trends since the 1995 assessment. Prior to that time commercial CPUE was used as a tuning index, but concern that CPUE did not reflect true abundance trends led to the development of assessment methods based on the tag-recapture data. The final section of the document presents results of stock projections.

The methods differ in the degree that biological and fishery structure is incorporated in the estimation process, and in the choice of tagging data subsets used in the analyses. Different tagging data subsets are chosen to minimize potential bias in the alternative estimation methods (Table 1.1). The first method (Section 2), which uses tag-recovery data from the first year following release, assumes the ratio of recoveries to catch is equal to the ratio of releases to population size. This method requires no assumptions about fishery or biological dynamics and is the least likely to produce biased abundance estimates. However, because it uses only tag recovery data for the first year abundance estimates are potentially more variable. The second method (Section 3, Appendix A) is an integrated catch-age mark-recapture model that has been developed for the B.C. sablefish assessment. This is the most complex of the methods, modeling the age, sex, and spatial structure of the stocks. We do not believe that this model can provide credible stock assessments while we treat the B.C. sablefish data as if it represents discrete populations. The third method (Section 4, Appendix B) is a tag-recapture analysis that extends the concept the Section 2 analysis is based on to fit the multi-year tag recovery data. This method uses population dynamics equations to model the survival of the tag release groups. Stock projections (Section 5) are conducted using this model. Note that throughout this document the term “vulnerable stock” refers to the stock component that can be caught with trap gear (no escape rings) and is thus vulnerable to tagging.

For the 1999 fishery, escape-rings were required by regulation in all commercial trap gear. The use of escape-rings will influence the stock assessment data, both in the size distribution of fish caught in the fishery and in the number of fish examined for tags. We analyze a prior study of escape-ring selectivity (Saunders and Surry 1998) to estimate parameters required for the stock assessments (Appendix C). The three assessment methods all make adjustments for the escape-rings used in the 1999 fishery.

1. Fishery and Biological Information

1.1 Landing Statistics

The commercial fishery for sablefish has been active since the late nineteenth century and was described in detail by McFarlane and Beamish (1983). Annual catches as high as 6000 t were realised during the 1910's, however landings remained modest from 1920 to 1965, ranging between 200 t and 1900 t (Table 1.2). A detailed description of the development of the B.C. sablefish fishery and the management system is presented in Haist et al. (1999b).

1.2 Commercial CPUE Estimates

Bi-monthly estimates of commercial trap fishery CPUE (sum of catch divided by sum of trap), from log-book data are shown in Figure 1.2 for the period 1978-1999. No adjustment has been made to the 1999 estimates to account for the effect of escape-rings on CPUE. Intra-annual variation in CPUE is considerable, with higher catch rates often obtained during the Jan./Feb. and Nov./Dec. periods.

1.3 Trap Surveys

Since 1984, biological samples have been collected annually during October/November, using chartered trap vessels, with the goal of sampling exploited stocks from the west coast of Vancouver Island to the Queen Charlotte Islands. Initial samples were collected during the course of normal commercial fishing. In 1986 a more structured survey design, including eight indexing sites and three depth strata was developed. The three depth strata were shallow (<300 fm), medium (301-400 fm) and deep (>400 fm). The purpose was to investigate the variation in size and age-related parameters associated with area and depth. In 1990 the number of depth strata was expanded to include 250-349 fm, 350-449 fm, 450-549 fm, and 550-649 fm, and in 1991 an additional shallow (150-249 fm) stratum was added. The index sites from south to north were Barkley Canyon, Esperanza, Solander (1994 & 95 only), Quatsino, Triangle Island, Cape St. James, Gowgaia, Buck Point, Hippa Island and Langara (Figure 1.1). It has not been possible to sample all sites each year. The five southern sites were occupied in 1988, all eight in 1989, the three southern-most sites in 1990, six sites in 1991, eight in 1992, eight in 1993, ten in 1994 and 1995 and nine in 1996-98.

A standardized method of gear deployment has been used throughout the surveys and is described in Smith et al. (1996). Briefly, each set consisted of 25 Korean traps attached to a groundline at 46m intervals, baited with 1-1.5kg of frozen squid in bait bags, and soaked for 24 hours. The catch in number and weight were recorded for each trap and have been used to develop indices of abundance. Biological sub-samples of length, sex, maturity and otoliths for age determination were collected. Depth specific age compositions have been incorporated into the model reconstruction and are discussed under the stock reconstruction. Approximately 2/3 of the traps were randomly selected for tagging and the subsequent recapture data form the basis for the tagging analyses.

Survey CPUE, averaged over the three mid-depth strata (250 fm - 550 fm) that encompass the depth range where most of the commercial catch is taken is also shown in Figure 1.2. The commercial and survey indices show reasonable coherence in the CPUE trends.

The trap survey was extended to include sites in Hecate Strait inlets in 1994. The mean inlet CPUE varied little between 1994 and 1997, then increased significantly in 1998 and 1999 (Figure 1.3). The number of locations surveyed is not consistent over the survey period which will effect the comparability of the mean estimator (Table 1.3). However, estimates of the standard errors of the means, calculated for both a stratified random survey and for a simple random survey design, are small (Table 1.3), providing support for the significance of the observed increase in 1999.

The length frequencies of fish sampled during the 1999 Hecate Strait survey show modes at 52 cm and 58 cm for male and female sablefish, respectively (Figure 1.3). Similar modes were observed in the 1999 northern B.C. offshore survey. The year-class(es) that these modes represent appear to be substantially larger than the preceding year-classes.

2. Estimating abundance trends based on tag returns in the year following tagging

For several years we have been tracking the return of tags in the year following tagging as an index of exploitation rate (Haist et al. 1998). In the following analysis we advance this approach by estimating total stock size, absolute exploitation rate and surplus production making the simplifying assumption that the population of fish tagged the year before is representative of the vulnerable sablefish population.

2.1 Data used in Analysis

The data used in this analysis are discussed below.

- Tag releases - North and South in fall - exclude spring releases, releases prior to September
- Trap tag recoveries in calendar year after tag release - 260 duplicate recoveries
- Estimate tag return rate from trap vessels
- Landings by trap vessels and estimates of sorting of small fish

<u>Tag releases</u>

For this analysis we excluded all releases that were made in the inlets or the sea mounts. We also excluded releases not made in September, October, November or December. Table 2.1 shows the number of tags released by time of release and location.

We see that there has been extensive tagging in the spring of 1996 and 1997. These releases are excluded from this analysis to minimize the potential for movement prior to tag recovery.

Trap tag recoveries in calendar year after tag

We evaluated recoveries from trap vessels only. Table 2.2 shows the number of tags returned by trap vessels by year of release and year of recovery.

For the purpose of our analysis we are interested only in the diagonal row one year after year of release.

Estimate tag return rate from trap vessels

We continue to use the estimates of tag return rates from a study of vessel to vessel differences in tag return rates (Appendix B in Haist et al. 1999b). The estimates of these return rates are shown in Figure 2.1.

Landings by trap vessels and sorting of small fish.

Table 2.3 shows the return of landings by trap vessels. Some small fish are captured in traps and then released. Tags from these fish are retained, which means that we are examining a greater proportion of the population than the landings represent. Elsewhere in this report (Appendix C) we discuss estimates of the sorting of small fish on deck which provides our estimate of the tonnes of fish examined for tags.

2.2 Methods

The first step in the analysis is to calculate the percent of tags caught in the calendar year following the year of release. We allow for 10% tagging mortality and 10% tag shedding (Beamish and McFarlane 1988), which means that 81% of fish that are reported to be tagged are indeed alive and tagged in the next calendar year. Equation 1 shows the formula for estimation of the % of tags returned.

$$\%\ returned = \frac{\#returned}{0.81 \times \text{tag return rate}} \Big/ \#released \qquad (1)$$

The major assumptions of this equation is that there was no mortality between tagging and the beginning of the year other than that associated with tagging mortality, and that we can treat the processes during the first year (natural mortality, fishing mortality and emigration) as discrete. Our conclusions regarding trends in abundance and absolute level of exploitation are not sensitive to these assumptions; the fishing mortality between tagging and the beginning of the calendar year is low, and using a discrete model and thus ignoring natural mortality and emigration during the first year affects our estimate of tag return rate only in the 2nd decimal place.

Figure 2.2 shows the estimated proportion of tags returned by year.

We can now estimate the total abundance of the population by dividing the tonnes of fish examined for tags by the percent returned by trap.

$$\text{abundance} = \frac{\text{tonnes sorted by trap}}{\text{\% returned by trap}} \qquad (2)$$

The key assumption in this calculation is that fish tagged the calendar year before have the same vulnerability to harvest as the entire population. This is probably not true, the long-term tag returns indicate that fish become less vulnerable to harvest in the first five years after tagging (Haist et al. 1999 b), and thus we expect that our estimates of abundance are underestimates of the total population size.

Figure 2.3 shows the estimated trends in abundance from calculation of equation 2.

The implied exploitation rate can be calculated by dividing the estimated abundance (Figure 2.3) by the total landings by all gear types. This is shown in Figure 2.4.

2.3 Discussion

The key feature of our analysis is the apparent decline in abundance from 1993 to 1998, and the apparent increase in 1999. These general trends are consistent with CPUE and survey catch rates, but more exaggerated. The dramatic increase in abundance in 1999 shown in tag returns is much stronger than that seen in CPUE and the survey. The strong decline seen between 1993 and 1998 takes place at a very high rate, approximately 20% per year, is more than would be expected based on natural and fishing mortality alone, even if we allow for zero recruitment. It implies no somatic growth. Such a decline is possible if there was little recruitment and net emigration to the U.S. The great increase in 1999 also is too much to be explained by anything but substantial immigration from the U.S.

The absolute level of stock abundance and exploitation rates are reassuring. With the exception of the 1998 point, exploitation rates do not exceed 10%. Spawning biomass per recruit (SSBR) analyses suggest that with exploitation rates in the range of 11 to 13% you would retain 40% to 45% of the virgin sablefish spawning biomass (Saunders et al. 1996). The 40-45% level is considered a conservative reference target for groundfish, even when there is serial correlation in recruitment (Clark 1993). Note that the SSBR analysis does not imply that stocks will stabilize at 40% to 45% of virgin biomass, rather, in the absence of a stock recruitment relationship, spawning stock biomass would fluctuate around the 40-45% of virgin level. Given a stock-recruitment relationship, the expectation would be for the stock to fluctuate about a level lower than the 40-45% level.

3. Integrated Model Analyses

Development of catch-age analysis for the assessment of B.C. sablefish focused on two objectives in recent years. Firstly, to develop a model structure consistent with the observed spatial and bathymetric structure of the populations and secondly, to incorporate mark-recapture analysis so that fishing mortality rates are better determined. The Integrated Model, which integrates catch-age and mark-recapture analysis, was first used in the 1998 sablefish assessment (Haist et al. 1999a). The model is an extension of the tuna model presented by Fournier et al. (1998). The model is a spatially and sexually disaggregated age-structured model that simultaneously fits to catch, age-composition, and tag recovery data.

Inconsistencies in the stock reconstructions obtained with the Integrated Model (1998 assessment) suggested the model structure did not capture all the pertinent features of the sablefish population dynamics. In particular, the stock abundance trajectories, obtained when fitting to the full tag release data series (releases beginning in 1979), showed contradictory trends to those obtained when fitting to a subset of the tag release data (releases beginning in 1991). Additionally, to fit the high attrition rate observed in the tag recovery data, the model moved fish to, and accumulated them in, regions of estimated low fishing mortality.

One obvious inconsistency in the model structure was that while the model explicitly included emigration, it did not account for immigration. Without US tag release and recovery data it is not possible to estimate immigration into B.C. waters. For the 1999 sablefish assessment, the Integrated Model was fit using only tag recovery data for the calendar year following release. The rationale for this was that potential bias in the assessment, as a result of not accounting for immigration, would be minimized. This approach alleviated the problem of obtaining different stock trajectories with different tag release time-series, but did not produce more realistic estimates of the relative abundance of available sablefish across the depth strata. Less than 10% of the vulnerable biomass is estimated to occur in the mid-depth region where most of the catch is taken.

We do not believe that we can obtain reasonable assessment results with the Integrated Model as long as we treat sablefish in B.C. as discrete stocks. Fitting only tag recovery data for the first calendar year following release reduces the amount of information used in the estimation. Potentially the model is over-parameterized, in particular relative to the distribution of the population across the depth strata. We do present results of Integrated Model analysis to maintain consistency with previous assessments.

3.1 Integrated Model Structure

The major modification to the Integrated Model for the current assessment is the inclusion of retention selectivity parameters. These parameters account for the effect of escape-rings in commercial traps on the age and sex composition of the catch. A complete description of the model is presented in Appendix A, and in this section we only describe changes in the model and data structures from that used previously (Haist et al. 1999b).

The formulation of the Integrated Model used for the current assessment is similar to the one used in the 1999 *base case* model fit. The model is fit to tag recovery data for the calendar year following release only. For this assessment we reduced the penalty weight on the tag-reporting rate in the terminal year (i.e. the estimate differing from one). The reason for this is, it is unlikely that all tagged fish are returned, even with high co-operation from the fishermen. Also, we have added a penalty function for the final three recruitment estimates (2 yr-olds in 1997 to 1999) differing from the average recruitment over the time series. There is no age-sex composition data after 1996 so the estimates of recruitment for the final three years are driven by the tag recovery data.

3.2 Integrated Model Data

The B.C. coast is treated as six distinct regions that separate the coast geographically into a southern and a northern area, and bathymetricly into three depth zones. The depth zones are; <500 meters (shallow), 500-800 meters (mid-depth), and >800 meters (deep). Analyses are conducted separately for the northern and southern region. Data used in the current stock assessment is similar to that used previously (Haist et al. 1999b) with data updated through 1999 where available.

B.C. sablefish landings data are available since 1918, but complete information on the depth of capture is available only since 1980. For the current analyses we use landings data from 1972 to 1998 (Table 3.1). For the 1972 to 1980 period, only data on gear type and the general area (i.e. northern or southern B.C.) of catch is available, so for these years we allocate the landings to depth zones based on the gear-specific depth distribution of the catch in the early 1980's.

Age and sex composition data are available for the period 1980-1996 (Table 3.2). The data is primarily from research surveys and other research cruises, but does include some commercial fishery samples (all random, ungraded samples).

The tagging program for sablefish in B.C. was initiated in 1977 with the primary objective of stock identification through analysis of tag movement. Prior to 1991 there was considerable variation in the locations and timing of tag releases (Murie et. al 1995a; Murie et al 1995b). Since 1991 the tagging program has been carried out with a consistent design in terms of both locations and timing of releases (Smith et al. 1996). Tag release and recovery data used in the current analyses consists of the tag releases between 1979 and 1982 that covered a broad geographic area, and those from 1991 through 1998 that followed the systematic design. Additionally, for the earlier period, release groups were restricted to those that occurred within the general areas utilized by the commercial fishery. Tag release data used for theses analyses (Table 3.3) include both the spring and fall releases shown in Table 2.1, with the exception that fish with unknown length at time of release are not included. Tag release data is stratified by the same depth zones as the remainder of the Integrated Model analysis (see first paragraph of this section).

Tag recovery information from 65 release groups are utilized in the analysis. For some tag recoveries, the information is incomplete (e.g. recovery year, recovery area, or recovery depth missing). The number of tags released are adjusted by the proportion of recoveries with full information to account for tag recoveries that can not be used in the analysis. This number is further reduced by the recoveries that occur during the same year that the tags were released (Table 3.3).

3.3 Integrated Model Analyses

Stock Reconstructions

The Integrated Model was fit separately to the Northern and Southern B.C. sablefish data. The observed and predicted number of tag recoveries, by depth stratum of release and recovery, are shown in Figures 3.1 and 3.2. In general, there are no clear patterns or trends in the residuals. Relative fits are better for the tags released and recovered in the mid-depth stratum because the total numbers are higher for this region. For the Northern B.C. analysis, the predicted recoveries for tags released in the deep stratum and recovered in that stratum are consistently higher than the observations.

The predicted and observed age and sex compositions are shown in Figures 3.3 through 3.6, for the two stock assessment regions. For both stocks, the analysis suggests that a strong year class (2 year-olds in 1997) is recruiting to the fishery. Unfortunately, there are no age data since 1996 to challenge these estimates. However, length frequency data from the northern B.C. survey do show a strong mode of smaller fish. The estimated size of this year-class (1995) is substantially higher than any estimated over the period since 1972 (Table 3.4). The estimates are unrealistic, so we did another fit to the data with a higher penalty weight on the deviations of the last recruitments from the average value (see Appendix A for discussion of penalty weight). This forced the last three recruitment estimates in the time series to be close to the average value, but increased the size of the 1994 year-class (Table 3.4, 2 year-olds in 1996). Note that while the estimated size of the 1994 year-class with the high penalty weight is much smaller than the estimated 1995 year-class with the low penalty weight, the impact of the higher penalty weight is minimal on the fit to the 1999 tag recovery data. This is because 5 year-olds are more vulnerable to the fishery than 4 year-olds.

Retrospective Pattern

A retrospective analysis was conducted for both stock assessment regions. This analysis involves removing the terminal years' data from the analysis successively, and re-fitting the model. Hence, we can see how the current model would have performed had it been used previously. The retrospective analysis is conducted using data series terminating in 1995 through 1999.

For the Southern B.C. sablefish region, the analysis terminating in 1995 suggests a significantly higher population in 1995 than analyses terminating in later years (Figure 3.7). The stock trajectories, obtained with data terminating in 1997 through 1999, show little drift.

For the Northern B.C. region, the estimated abundance increased successively with data series terminating in 1995 through 1997 (Figure 3.7). For the analyses terminating in 1998 and 1999, estimates of biomass for the earlier part of the time series were similar to those obtained from the analysis terminating in 1995.

Stock Projections

We do not present stock projections based on the Integrated Model analyses. This is because we are concerned that the Integrated Model may produce biased abundance estimates, as discussed in the introduction to this section. Additionally, the estimates of recruitment of 2 year-olds in 1997 are unrealistically high.

4. Mark-Recapture Model Analyses

We implement a simple mark-recapture model that extends the analyses presented in section 2 to fit the *multi-year tag recoveries* from each tag release group. To do this, assumptions regarding the population dynamics of the tag release groups and of the vulnerable population are required. The model estimates the survival of tagged fish "cohorts" over time. The total vulnerable population, which shares parameters with the tag "cohorts" (fishing and natural mortality), is also modeled. In addition to fishing and natural mortality, tag "cohorts" are assumed to have additional losses due to tagging mortality (immediately upon tagging) and due to on-going tag shedding (see Appendix D). The total tag releases are adjusted for tagging-induced mortality and for recaptures that occur during the calendar year of tagging. Tag reporting rates, estimated for the 1991-1998 period are incorporated in the analysis (Figure 2.1). We estimate two additional reporting rates, one for 1980 and one for 1990, and assume there is a linear trend over the time interval. The model estimates "new fish" that enter the vulnerable population each year. These "new fish" estimates include recruitment and immigration. A complete description of this model is presented in Appendix B.

4.1 Model Priors

The mark-recapture model is implemented as a Bayesian analysis. That is, we specify priors for all model parameters and estimate their posterior distributions given the model structure and data. The rationale for the prior distributions we choose are described below and the distributions are shown graphically in Figures 4.4 and 4.5.

The parameters that determine the initial population size and annual "new fish" in the population (ie. recruits, immigration, fish becoming more vulnerable to fishery either through movement or behavior) are assumed to have uniform distributions over the interval from 1 to infinity. While the upper limit is illogical, the mark-recapture data provide solid information on the upper limits of abundance so we avoid specifying an artificial upper bound.

Uniform distributions are also assumed for the 1980 reporting rate, the 1990 reporting rate, and the reporting rate multiplier. The reporting rate multiplier adjusts the reporting rates that were estimated for the 1991 to 1999 period (Figure 2.1). The procedure used to obtain these estimates are likely to produce minimum estimates (Haist et. al. 1999b,

Appendix B) and the uniform prior between 1 and 1.3 allows the "true" values to range between their estimated points and 1. The priors for the 1980 and 1990 reporting rates, uniform between 0.25 and 0.95, are *ad hoc*.

The parameters determining the instantaneous natural mortality rate (M), the tagging mortality rate (m), and the tag-shedding rate (s) are assumed to be log-normally distributed. For the tag-shedding rate parameter, the distribution (mean and variance) is estimated through analysis of double-tagged sablefish (Appendix C). The mode for the natural mortality rate (mode= 0.1) and the tagging mortality rate (mode=0.12) are based on values used in stock assessments and other analyses of west coast sablefish (Methot et al. 1994, Sigler et al. 1999). The variance estimates for ln(m) (0.4) is chosen to be substantially higher than ln(M) (0.2) because while age-composition data provides an approximate range of appropriate values for M, there is no information on which to base estimates of m.

4.2 Data Selection

We consider two potential issues that may influence the survival and return of tagged sablefish. The first is that fish captured in deeper waters have a lower probability of survival after tagging and release than fish tagged in shallower waters. Table 4.1 shows the recapture rates (total number recaptured/ total number released) for fish caught in depths greater than 750 m. and the recapture rates for all tagged fish. The ratios of recapture rates for these two groups should be close to one if they have similar probabilities of surviving tagging and of being recaptured. Differences in recapture rates may result from differences in survival following tagging or from differences in exploitation rates in conjunction with incomplete mixing. With the exception of tags released between 1991 and 1994 the recapture rate ratios are all close to 1 (Figure 4.1). To avoid possible bias, tag releases in depths greater than 750 m. are not included in the analysis.

The second potential source of bias we consider is that tags from larger fish are more likely to be reported than tags from smaller fish. The smaller fish that are caught are released while larger ones are landed. Fishermen maintain that small fish with tags, which would normally be released because of their size, are kept and the tags turned in. If this is strictly true then the recapture rates for fish that are small at the time of tagging should be similar to those for fish that are large. To minimize the effect of fish growth, only recaptures during the calendar year of tagging and the following year are included in these recapture rate estimates. Table 4.2 summarizes the data used for this analysis and Fig. 4.1 shows the ratio of recapture rates for fish >68cm at the time of tagging to the recapture rates for fish <68 cm. For the 1979-1982 period the ratios are all greater than 1; for the 1991-1997 release period the ratios vary around 1. The increase in the ratio for the 1998 releases can be attributed to the use of escape-rings in commercial traps in 1999. Certainly these data suggest that smaller tagged fish were less likely to be returned than larger fish for the earlier tag releases. Thus, the tag release data used in the mark-recapture analysis is restricted to fish that were >68 cm at the time of tagging, and released in depths < 750 m (Table 4.2). Note that the tag release data used for these analyses include both the spring and fall releases shown in Table 2.1, with the exception that fish with unknown length at time of release are not included.

The catch data used in this analysis is shown in Table 3.1 (total catch for Northern B.C. and for Southern B.C.)

4.3 Model Analyses

The Bayesian analysis is conducted separately for Northern B.C. and Southern B.C. data. The fits to the tag return data, from the maximum of the posterior distribution fit, are shown in Figures 4.2 and 4.3. In general, the fits show no strong pattern in the residuals that would suggest model mis-specification and potential bias. For both stocks, the rate of decrease in tag recoveries is higher through the early 1980's than through the 1990's.

The prior and posterior distributions of model parameters are shown in Figures 4.4 and 4.5 for the two stock assessment regions. The modes of the posterior distribution for the natural mortality rate and the tag shedding rate are at higher values than the priors for both stock assessment regions. The model does not explicitly account for emigration, so the natural mortality rate parameter and tag-shedding rate parameter may be accounting for movement out of the fishing areas.

The posterior distribution of vulnerable biomass, 1980 to 1999, is shown in Figure 4.6 for the two assessment regions. Both stocks appear to have been at relatively low levels during the early 1980's, increasing through 1987, followed by a steady decline in abundance. The northern stock appears to have increased slightly over the past two years. The level of uncertainty in the stock abundance estimates is highest between 1985 and 1991, a period where there are no new tag releases.

5. Comparison of Methods and Stock Projections

The three methods we use to estimate sablefish stock abundance provide different perceptions of the stock trajectories in recent years (Figure 4.7). This is not surprising given they employ different assumptions and use different data sources. Clearly, the two methods that incorporate population dynamics structure do not capture all the critical elements of the dynamics, in particular the immigration and emigration process. The abundance trends from the *first year tag recapture* analysis are most similar to the commercial and survey CPUE trends. However, the CPUE trends do not show the increase in 1999 that is suggested by the tag recovery data. For the commercial CPUE index this may be explained by the use of escape-rings during the 1999 fishery. The escape-rings allow approximately 50% of the fish that enter a trap to leave it, prior to gear recovery (see Appendix C).

The Northern B.C. stock trajectory obtained with the mark-recapture analysis that fits *multi-year tag returns* shows remarkably good agreement with the Alaska sablefish assessment (Figure 4.7, Alaska assessment data from Sigler et al. 1999). Given the evidence that northern B.C. and Alaskan sablefish comprise a single population (Kimura et al. 1998), it might be expected that stock trends would be similar in the two regions. The Alaskan assessment is driven by survey data that span the 1960 to 2000 time period. The Integrated Model analysis suggests that Northern B.C. sablefish abundance has decreased steadily since 1972, however this result is probably due to the assumption that the initial population is stationary.

Stock Projections

Stock projections are conducted using only results from the mark-recapture model fit to *multi-year tag recaptures*. Because the mark-recapture analysis that fits *first-year tag recaptures* does not incorporate population dynamics assumptions, it does not provide a basis on which to project future stock trends. We do not conduct stock projections using the Integrated Model because of concerns with potential bias with this method (Section 3).

Stock projections are conducted by sampling from the posterior distribution of 1999 stock abundance estimates and adding "new fish" each year that are randomly selected from the 1981 to 1999 time series of estimates for that particular sample from the posterior. 4000 samples from the posterior are selected for each assessment region. We assume that sablefish landings in 2000 will be equal to the TAC (4000 t.), and evaluate the consequences of 2001 TAC levels of 3700 t., 4000 t., and 4500 t. The catch split (in numbers, not biomass) for the projection is 48% for the southern assessment region and 52% for the northern assessment region. This split is consistent with both the long-term (1972-1999) and short-term (1995-1999) catch split between the two regions (Table 3.1).

The expectation and the 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} percentiles of the distribution of 2002 vulnerable biomass estimates are shown in Figure 4.8. The uncertainty in stock abundance increases with each year and uncertainty in the 2002 abundance estimates is largely the result of uncertainty in "new fish" rather that uncertainty in the 1999 stock estimates.

For each of the samples from the posterior distribution, an estimate of average biomass in the absence of fishing is calculated assuming the "new fish" estimates obtained for the 1981-1999 time period are representative of average conditions for a situation with no fishery. We estimate the probability that stock abundance will drop below 25% of this "unfished" estimate in 2002, given coastwide catch levels ranging from 0 to 10,000 t. Again, we assume a 48% south and 52% north catch split. The probabilities of falling below the 25% of "unfished" level and the probabilities of stock abundance decreasing are shown in Figure 4.9. Specific management objectives for the B.C. sablefish fishery have not been specified, and our choice of 25% of unfished biomass is not intended to undermine managers' responsibility in setting management objectives. Rather, this type of analysis is often considered useful for management decisions, but requires specification of a limit reference point so we choose an *ad hoc* one.

These results suggest that harvest levels in the 3700-4500 t. range are risk-neutral in the short-term. Given above-average recruitment in 2000 considerably higher yields are potentially available.

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Table 1.1 Comparison of data used and model assumptions for the three analytical methods used to estimate B.C. sablefish abundance.

Method	Data used in Analysis				Model Structure	
	Catch	Tag		Age/sex comp.	Assumptions	Estimation
		Releases	Returns			
First-year tag returns	Trap fishery only	1991-1998 (Sept.-Dec. only)	First year	No	- no emigration - no population/ fishery dynamics - estimates vulnerable population at time of recapture	Method of moments
Multi-year tag returns	all catch	1979-1998; year round; depths<750m. fish length >68 cm. if length at release unknown, not included	All years	No	-no emigration - tagged fish have similar dynamics to vulnerable population estimates	Bayesian
Integrated Model	all catch	1979-1998; all releases; if length at release unknown, not included	First year	Yes	- no emigration, movement among depth zones - estimates vulnerable population, exploitable population, total population	Maximum Likelihood

Table 1.2 Catch (t) of sablefish in Canadian waters by gear type. (LL=longline, Other=troll, handline, sunken gillnet (1968 only) and catch incidental to the halibut longline fishery)

Year	LL[a]	%	Trawl[b]	%	Trap[c]	%	Other	%	Total[d]	Foreign[e]	Grand total
1913									1988.0		1988.0
1914									3209.0		3209.0
1915									2441.0		2441.0
1916									4312.0		4312.0
1917									5956.0		5956.0
1918									2039.0		2039.0
1919									716.0		716.0
1920									1754.0		1754.0
1921									1383.0		1383.0
1922									1293.0		1293.0
1923									1135.0		1135.0
1924									1238.0		1238.0
1925									1017.0		1017.0
1926									705.0		705.0
1927									1118.0		1118.0
1928									911.0		911.0
1929									1042.0		1042.0
1930									1124.0		1124.0
1931									397.0		397.0
1932									436.0		436.0
1933									413.0		413.0
1934									435.0		435.0
1935									659.0		659.0
1936									490.0		490.0
1937									912.0		912.0
1938									576.0		576.0
1939									617.0		617.0
1940									948.0		948.0
1941									1188.0		1188.0
1942									835.0		835.0
1943									1426.0		1426.0
1944									1519.0		1519.0
1945									1428.0		1428.0
1946									1619.0		1619.0
1947									905.0		905.0
1948									1483.0		1483.0
1949									1895.0		1895.0
1950									648.0		648.0
1951	772.8	97.04%	23.1	2.90%	0.0	0.00%	0.5	0.06%	796.4		796.4
1952	453.2	92.91%	34.0	6.97%	0.0	0.00%	0.6	0.12%	487.8		487.8
1953	335.6	97.36%	8.0	2.32%	0.0	0.00%	1.1	0.32%	344.7		344.7
1954	432.3	94.18%	26.4	5.75%	0.3	0.07%	0.0	0.00%	459.0		459.0
1955	359.0	96.12%	14.5	3.88%	0.0	0.00%	0.0	0.00%	373.5		373.5
1956	172.8	82.32%	37.1	17.68%	0.0	0.00%	0.0	0.00%	209.9		209.9
1957	465.6	90.76%	47.1	9.18%	0.3	0.06%	0.0	0.00%	513.0		513.0
1958	167.1	58.57%	117.6	41.22%	0.6	0.21%	0.0	0.00%	285.3		285.3

Year	LL[a]	%	Trawl[b]	%	Trap[c]	%	Other	%	Total[d]	Foreign[e]	Grand total
1959	298.3	83.89%	57.3	16.11%	0.0	0.00%	0.0	0.00%	355.6		355.6
1960	423.3	86.71%	64.9	13.29%	0.0	0.00%	0.0	0.00%	488.2		488.2
1961	321.3	76.63%	98.0	23.37%	0.0	0.00%	0.0	0.00%	419.3		419.3
1962	277.7	70.75%	113.7	28.97%	0.0	0.00%	1.1	0.28%	392.5		392.5
1963	222.3	77.35%	64.9	22.58%	0.0	0.00%	0.2	0.07%	287.4		287.4
1964	274.5	68.68%	125.1	31.30%	0.0	0.00%	0.1	0.03%	399.7	83.0	482.7
1965	193.2	42.42%	261.9	57.51%	0.0	0.00%	0.3	0.07%	455.4	92.0	547.4
1966	325.7	51.24%	309.7	48.73%	0.0	0.00%	0.2	0.03%	635.6	269.0	904.6
1967	252.9	64.53%	138.9	35.44%	0.0	0.00%	0.1	0.03%	391.9	1254.0	1645.9
1968	292.3	63.08%	156.0	33.66%	0.0	0.00%	15.1	3.26%	463.4	2455.0	2918.4
1969	162.3	52.17%	148.2	47.64%	0.0	0.00%	0.6	0.19%	311.1	4763.0	5074.1
1970	142.1	54.84%	116.5	44.96%	0.0	0.00%	0.5	0.19%	259.1	5246.0	5505.1
1971	123.0	39.37%	189.4	60.63%	0.0	0.00%	0.0	0.00%	312.4	3211.0	3523.4
1972	399.7	36.73%	688.5	63.27%	0.0	0.00%	0.0	0.00%	1088.2	4818.0	5906.2
1973	119.8	12.63%	82.8	8.73%	745.8	78.64%	0.0	0.00%	948.4	3032.0	3980.4
1974	41.3	8.39%	121.8	24.76%	327.1	66.48%	1.8	0.37%	492.0	4287.0	4779.0
1975	152.2	16.87%	279.8	31.01%	469.4	52.02%	0.9	0.10%	902.3	6506.0	7408.3
1976	89.4	11.58%	379.0	49.10%	303.4	39.31%	0.1	0.01%	771.9	6302.0	7073.9
1977	77.1	7.11%	786.4	72.49%	214.6	19.78%	6.8	0.63%	1084.9	3718.0	4802.9
1978	57.2	6.89%	130.5	15.72%	634.6	76.45%	7.8	0.94%	830.1	3051.0	3881.1
1979	277.0	13.58%	276.1	13.54%	1480.1	72.58%	6.0	0.29%	2039.2	2348.0	4387.2
1980	248.8	6.55%	335.3	8.83%	3210.8	84.54%	3.0	0.08%	3797.9	606.0	4403.9
1981	326.2	8.52%	228.8	5.97%	3275.4	85.51%	0.0	0.00%	3830.3		3830.3
1982	343.7	8.50%	245.9	6.08%	3437.9	84.97%	18.4	0.45%	4045.9		4045.9
1983	451.5	10.22%	274.1	6.20%	3678.0	83.23%	15.4	0.35%	4419.0		4419.0
1984	365.2	9.47%	187.0	4.85%	3275.4	84.95%	28.0	0.73%	3855.6		3855.6
1985	458.3	10.72%	233.1	5.45%	3501.3	81.89%	82.8	1.94%	4275.5		4275.5
1986	619.2	13.92%	551.8	12.40%	3277.1	73.66%	0.8	0.02%	4448.9		4448.9
1987	1133.4	24.91%	406.9	8.94%	2954.3	64.92%	56.1	1.23%	4550.7		4550.7
1988	1194.3	22.34%	638.6	11.95%	3509.7	65.65%	3.2	0.06%	5345.8		5345.8
1989	928.7	17.26%	623.4	11.59%	3828.3	71.15%	0.1	0.00%	5380.5		5380.5
1990	1372.1	27.47%	460.7	9.22%	3162.1	63.31%	0.0	0.00%	4994.9		4994.9
1991	1089.2	21.31%	438.8	8.58%	3582.0	70.08%	1.5	0.03%	5111.5		5111.5
1992	889.1	17.34%	448.4	8.74%	3789.2	73.89%	1.1	0.02%	5127.8		5127.8
1993	371.6	7.30%	543.4	10.68%	4168.4	81.93%	4.3	0.08%	5087.7		5087.7
1994	511.0	10.05%	482.4	9.49%	4090.6	80.46%	0.0	0.00%	5084.0		5084.0
1995	281.7	7.03%	406.5	10.14%	3319.0	82.83%	0.0	0.00%	4007.2		4007.2
1996	253.6	7.51%	211.0	6.24%	2914.4	86.25%	0.0	0.0%	3379.0		3379.0
1997	412.8	9.88%	285.0	6.82%	3480.2	83.30%	0.0	0.0%	4178.0		4178.0
1998	445.9	9.93%	328.0	7.30%	3718.1	82.77%	0.0	0.0%	4492.0		4492.0
1999	608.1	12.89%	399.6	8.47%	3709.4	78.64%	0.0	0.0%	4717.1		4717.1

[a] 1951-1978, 1987-1995 - DFO, B.C. Catch Statistics, Vancouver, B.C.; 1979-1986, DFO/PBS catch/effort data base; 1996-98 Archipelago Marine Research, Landing Validation data base.
[b] 1951-1991 statistics from DFO, Pacific Biological Station, Groundfish catch and effort data base; 1992-95 - DFO, B.C. Catch Statistics, Vancouver, B.C.; 1996-98 Archipelago Marine Research, Landing Validation data base
[c] 1951-1978, 1992 - DFO, B.C. Catch Stat.; 1979-1995 - DFO/PBS catch/effort data base; 1996 –98 Archipelago Marine Research, Landing Validation data base
[d] Fishery statistics of Canada. 1913-1950.
[e] McFarlane and Beamish 1983a.

Table 1.3. Estimates of the mean CPUE and the standard error of the mean (for stratified random and simple random sample design) for the Hecate Strait Inlet survey, 1995-1999.

						Stratified random		Simple random	
							Standard		Standard
year	Locality	mean	stdev	n	w	mean	error	mean	error
1995	Milbanke Sound	11.33	5.55	3	0.25				
	Gil Island	7.45	4.99	5	0.25				
	Chatham Sound	7.63	1.94	2	0.25				
	Portland Inlet	2.63	2.47	3	0.25				
						7.261	1.094	7.262	1.368
1996	Milbanke Sound	4.90	1.73	5	0.33				
	Gil Island	14.94	5.88	5	0.33				
	Chatham Sound	10.06	6.97	5	0.33				
	Portland Inlet								
						9.965	1.383	9.965	1.686
1997	Milbanke Sound	7.27	1.86	5	0.25				
	Gil Island	11.52	3.32	4	0.25				
	Chatham Sound	9.80	1.58	2	0.25				
	Portland Inlet	4.81	2.09	3	0.25				
						8.350	0.620	8.320	0.865
1998	Milbanke Sound	10.42	4.23	5					
	Gil Island								
	Chatham Sound	30.56		1					
	Portland Inlet	15.92		1					
								14.086	3.138
1999	Milbanke Sound	13.35	3.87	5	0.33				
	Gil Island	39.06	9.15	4	0.33				
	Chatham Sound								
	Portland Inlet	32.55	4.94	5	0.33				
						28.317	1.789	27.552	3.373

Table 2.1. Number of fish tagged by location and season.

	Fall			Spring	
Year	North	South	Total N&S	North	South
1991	958	1,489	2,447		
1992	1,308	2,276	3,584		
1993	2,487	4,531	7,018		
1994	1,622	1,982	3,604		
1995	7,564	5,144	12,708		
1996	3,971	5,240	9,211	7,792	7,376
1997	2,559	4,579	7,138	3,996	5,357
1998	5,058	10,897	15,955		
1999	7,906	9,087	16,993		

Table 2.2 Number of tags recovered by year of release. Trap vessel recoveries only. Tags released outside the September through December period are not included.

	Recovery year								
	1991	1992	1993	1994	1995	1996	1997	1998	1999
1991	13	70	29	18	19	9	13	13	5
1992		10	70	58	41	27	23	24	17
1993			2	261	139	44	61	68	38
1994				10	233	70	52	61	24
1995					77	867	587	375	139
1996						31	667	365	93
1997							270	823	164
1998								288	750

Table 2.3. Trap landings, total landings, and total tonnes examined for tags on board trap vessels. All units metric tonnes.

Year	trap landings	Total tonnes examined for tags on trap vessels	Total landings
1992	3,970	5,719	5,373
1993	4,186	5,997	5,109
1994	4,138	5,916	5,143
1995	3,459	4,932	4,176
1996	2,954	4,299	3,424
1997	3,404	4,979	4,087
1998	3,690	5,344	4,458
1999	3,868	4,763	4,717

Table 3.1 Sablefish landings (estimated number of fish) for Southern and Northern B.C., by depth zone. Estimates of the average weight of landed fish and the ratio of landed fish to sampled fish are based the landing selectivity and escape-ring selectivity calculations presented in Appendix C.

	Number of fish landed (1000's)								Prop. from south	Avg. wt. landed fish		Ratio landed to sampled	
	Southern B.C..				Northern B.C.								
year	shallow	mid	deep	total	shallow	mid	deep	total	south	S.	N.	S.	N.
1972	643.1	80.7	0.4	724.2	504.0	228.7	0.8	733.5	0.50	3.80	4.31		
1973	213.6	102.4	25.7	341.7	375.0	232.5	26.6	634.0	0.35	3.76	4.26		
1974	505.9	122.0	12.2	640.0	354.0	185.0	11.5	550.5	0.54	3.78	4.29		
1975	726.8	126.5	3.7	856.9	603.6	341.0	29.3	973.9	0.47	3.79	4.28		
1976	630.4	109.1	4.0	743.5	651.2	328.1	18.0	997.2	0.43	3.79	4.29		
1977	566.4	76.0	5.3	647.7	328.4	163.4	10.1	501.9	0.56	3.79	4.29		
1978	439.1	87.8	17.5	544.4	233.3	167.6	26.6	427.5	0.56	3.78	4.24		
1979	501.2	116.5	29.7	647.4	162.9	230.4	71.1	464.4	0.58	3.78	4.16	1.79	1.43
1980	137.5	356.6	99.7	593.8	92.3	211.7	85.8	389.8	0.60	3.69	4.11	2.05	1.44
1981	153.8	170.3	58.2	382.3	174.9	241.9	164.4	581.2	0.40	3.72	4.14	1.98	1.42
1982	183.2	188.7	81.8	453.7	116.0	291.3	163.0	570.3	0.44	3.72	4.10	2.00	1.43
1983	199.5	170.6	116.6	486.7	101.8	292.1	240.0	633.9	0.43	3.73	4.08	2.04	1.42
1984	187.8	243.4	66.8	498.1	100.0	238.4	143.6	482.0	0.51	3.72	4.10	1.98	1.43
1985	204.7	303.2	70.4	578.3	118.7	298.2	81.1	498.0	0.54	3.71	4.11	1.98	1.44
1986	284.2	243.6	57.0	584.9	173.8	257.2	115.1	546.2	0.52	3.73	4.15	1.92	1.43
1987	304.7	295.5	57.1	657.3	153.6	223.2	138.4	515.2	0.56	3.73	4.14	1.92	1.42
1988	490.0	211.1	51.2	752.3	137.2	306.3	203.2	646.7	0.54	3.76	4.10	1.84	1.42
1989	359.1	289.1	118.4	766.5	177.0	290.9	168.8	636.8	0.55	3.73	4.13	1.96	1.42
1990	319.6	252.2	49.1	620.9	307.8	274.1	81.5	663.4	0.48	3.74	4.21	1.90	1.42
1991	198.7	137.5	29.7	366.0	281.1	559.1	152.3	992.6	0.27	3.74	4.13	1.89	1.44
1992	174.6	69.5	26.3	270.4	221.6	621.4	219.6	1062.6	0.20	3.76	4.10	1.86	1.44
1993	157.4	266.3	52.9	476.6	134.8	443.4	240.7	818.9	0.37	3.70	4.08	1.98	1.43
1994	181.4	302.8	50.3	534.4	181.8	389.4	197.7	768.9	0.41	3.71	4.11	1.96	1.43
1995	137.6	247.9	119.4	504.8	99.6	278.9	185.3	563.8	0.47	3.70	4.09	2.08	1.43
1996	153.4	192.2	13.5	359.0	60.9	361.7	92.2	514.8	0.41	3.72	4.06	1.90	1.46
1997	200.1	201.4	85.6	487.1	66.9	420.5	72.8	560.2	0.47	3.72	4.06	1.99	1.46
1998	274.0	330.4	100.7	705.1	135.6	273.7	34.6	443.8	0.61	3.72	4.14	1.98	1.45
1999	237.5	209.5	57.7	504.7	146.0	401.2	79.3	626.5	0.45	3.96	4.34	1.48	1.23
Avg. 1972-1999									0.47				
Avg. 1995-1999									0.48				

Table 3.2. The number of fish aged and number of samples (in brackets) that are used in the Integrated Model analyses.

	Southern B.C.			Northern B.C.		
year	shallow	mid-depth	deep	shallow	mid-depth	deep
1980	0 (0)	0 (0)	358 (7)	0 (0)	559 (8)	882 (15)
1981	0 (0)	0 (0)	0 (0)	772 (3)	494 (2)	0 (0)
1982	537 (2)	636 (3)	0 (0)	670 (5)	377 (5)	150 (3)
1983	0 (0)	710 (5)	0 (0)	343 (2)	631 (6)	99 (2)
1984	310 (2)	1034 (9)	0 (0)	445 (4)	299 (6)	0 (0)
1985	139 (2)	1567 (5)	0 (0)	150 (3)	926 (4)	0 (0)
1986	384 (4)	293 (3)	334 (2)	404 (4)	803 (4)	125 (1)
1987	300 (1)	0 (0)	0 (0)	0 (0)	1065 (4)	0 (0)
1988	311 (2)	1347 (6)	100 (2)	294 (1)	414 (6)	0 (0)
1989	260 (2)	729 (4)	583 (3)	720 (5)	1207 (7)	375 (2)
1990	152 (8)	299 (6)	355 (7)	0 (0)	100 (2)	0 (0)
1991	0 (0)	331 (8)	249 (6)	146 (3)	581 (13)	266 (6)
1992	199 (4)	399 (8)	405 (8)	95 (3)	610 (13)	486 (9)
1993	200 (4)	795 (16)	372 (8)	69 (2)	874 (20)	353 (8)
1994	247 (4)	676 (10)	368 (7)	156 (9)	553 (23)	395 (11)
1995	234 (7)	616 (14)	193 (9)	500 (13)	1173 (27)	143 (7)
1996	60 (1)	385 (7)	70 (1)	94 (4)	706 (15)	186 (6)

Table 3.3 Total tag releases (Rel), the proportion of recoveries with full information (P), the number of recoveries during year of tagging (R1), and the adjusted number of tag releases, by depth stratum for Southern and Northern B.C. The adjusted number of tag releases are used in the Integrated Model analyses.

	Shallow depth				Mid-depth				Deep			
Year	Rel.	P	R1	Adj.	Rel.	P	R1	Adj.	Rel.	P	R1	Adj.
Southern B.C.												
1979	302	0.68	10	195.4	7605	0.658	152	4852.1	1189	0.775	41	880.5
1980	128	0.524	1	66.1	4758	0.687	272	2996.7	325	0.603	9	187.0
1982	1801	0.366	0	659.2	1205	0.348	0	419.3				
1991					525	0.642	1	336.1	959	0.846	1	810.3
1992	326	0.767	1	249.0	1030	0.619	1	636.6	919	0.776	1	712.1
1993	529	0.693	0	366.6	2044	0.675	0	1379.7	1954	0.673	0	1315.0
1994	602	0.789	0	475.0	617	0.75	2	460.8	755	0.743	0	561.0
1995	1921	0.832	6	1592.3	2252	0.839	15	1874.4	963	0.811	0	781.0
1996	1825	0.848	29	1518.6	10454	0.872	153	8962.9	312	0.9	0	280.8
1997	1822	0.871	146	1441.0	7822	0.896	636	6372.5	273	0.692	0	188.9
1998	816	0.937	39	725.6	8562	0.84	178	7014.1	1486	0.71	6	1049.1
Northern B.C.												
1979	34	0.833	0	28.3	6328	0.614	253	3632.4	247	0.577	0	142.5
1980	227	0.583	3	129.3	3808	0.603	55	2241.2	2172	0.576	54	1197.1
1981	1370	0.55	4	749.5	8497	0.614	177	5040.2	546	0.667	6	358.2
1982	524	0.486	0	254.7	2482	0.518	0	1285.7				
1991					553	0.705	10	379.9	401	0.717	1	286.5
1992	45	0.75	0	33.8	754	0.636	7	472.5	507	0.557	2	280.4
1993	170	0.5	0	85.0	1549	0.612	3	945.0	764	0.52	0	397.3
1994	155	0.676	0	104.8	732	0.791	3	576.0	734	0.678	2	495.7
1995	212	0.756	2	158.3	7054	0.782	44	5472.2	256	0.804	0	205.8
1996	147	0.971	0	142.7	11324	0.911	134	10182.2	276	0.938	0	258.9
1997	362	0.902	6	320.5	5796	0.933	310	5097.7	389	0.942	30	336.4
1998	104	0.813	5	79.6	4645	0.907	57	4156.0	303	0.952	6	282.5

Table 3.4. Estimates of sablefish recruitment (1000's of 2 year-olds) from Integrated Model analyses with either a low (1) or high (100) penalty weight on the 1997 to 1999 estimates.

	Southern B.C.		Northern B.C.	
year	Low Pwt	High Pwt	Low Pwt	High Pwt
1972	4944	4888	3008	2936
1973	3699	3699	1198	1211
1974	2644	2572	792	806
1975	2327	2292	730	749
1976	1091	1060	784	784
1977	940	941	916	888
1978	1672	1712	1685	1613
1979	4473	4795	4233	4198
1980	3222	3428	3460	3419
1981	3026	3246	3959	4030
1982	2898	3165	3840	3852
1983	2052	2236	3467	3472
1984	1558	1724	2807	2837
1985	1474	1632	2508	2495
1986	1722	1915	2228	2210
1987	2235	2522	1910	1893
1988	2322	2665	1229	1196
1989	1623	1885	1033	1002
1990	1088	1281	775	762
1991	1775	2100	1229	1214
1992	2151	2611	2597	2569
1993	828	1018	1997	2171
1994	159	174	482	414
1995	173	196	599	89
1996	651	6437	687	20417
1997	14340	2436	62392	2134
1998	2652	2424	2792	2132
1999	2445	2417	2740	2131

Table 4.1. Summary of number of tags released, number recaptured, and recapture rates by tagging year for all releases and releases <750 m.

	All releases			Released <750 m			Ratio of recapture rates
year	Number released	Number recaptured	Recapture Rate	Number released	Number recaptured	Recapture Rate	
Southern B.C.							
79	9096	1969	0.216	7907	1658	0.210	0.969
80	5211	1030	0.198	4886	962	0.197	0.996
82	3006	603	0.201	3006	603	0.201	1.000
91	1484	105	0.071	258	49	0.190	2.684
92	2275	240	0.105	1356	182	0.134	1.272
93	4527	546	0.121	2421	377	0.156	1.291
94	1974	305	0.155	1114	217	0.195	1.261
95	5136	983	0.191	4099	873	0.213	1.113
96	12591	2244	0.178	12118	2190	0.181	1.014
97	9917	2208	0.223	9417	2150	0.228	1.025
98	10864	979	0.090	9378	917	0.098	1.085
Northern B.C.							
79	6602	1851	0.280	6362	1825	0.287	1.023
80	6207	1021	0.164	3580	607	0.170	1.031
81	10413	1261	0.121	9801	1219	0.124	1.027
82	3006	605	0.201	3006	605	0.201	1.000
91	954	182	0.191	553	129	0.233	1.223
92	1306	201	0.154	739	130	0.176	1.143
93	2483	432	0.174	1515	292	0.193	1.108
94	1621	303	0.187	887	216	0.244	1.303
95	7522	1598	0.212	7061	1487	0.211	0.991
96	11747	1774	0.151	10568	1564	0.148	0.980
97	6547	1618	0.247	5617	1415	0.252	1.019
98	5052	361	0.071	4634	316	0.068	0.954

Table 4.2. Summary of the number of tags released, number recaptured during calendar year of tagging plus the following year, and recapture rates for all releases < 750 m. Estimates presented for fish <68 cm at release and for fish > 68 cm at release.

	Fish > 68 cm at release			Fish< 68 cm at release			Ratio of recapature rates
year	Number released	Number recaptured	Repcapture Rate	Number released	Number recaptured	Repcapture Rate	
Southern B.C.							
79	1640	257	0.157	6267	551	0.088	1.782
80	1801	304	0.169	3085	277	0.090	1.880
82	1214	155	0.128	1792	138	0.077	1.658
91	21	4	0.190	237	7	0.030	6.449
92	411	14	0.034	945	38	0.040	0.847
93	482	44	0.091	1939	134	0.069	1.321
94	228	16	0.070	886	67	0.076	0.928
95	1013	79	0.078	3086	238	0.077	1.011
96	3716	348	0.094	8402	871	0.104	0.903
97	2735	480	0.176	6682	1392	0.208	0.842
98	2016	243	0.121	7362	674	0.092	1.317
Northern B.C.							
79	2443	456	0.187	3919	601	0.153	1.217
80	1438	190	0.132	2142	138	0.064	2.051
81	3209	368	0.115	6592	257	0.039	2.941
82	790	138	0.175	2216	191	0.086	2.027
91	295	40	0.136	258	37	0.143	0.945
92	340	26	0.076	399	26	0.065	1.174
93	667	77	0.115	848	83	0.098	1.179
94	392	57	0.145	495	91	0.184	0.791
95	2196	234	0.107	4865	578	0.119	0.897
96	3171	301	0.095	7397	762	0.103	0.921
97	1718	325	0.189	3899	868	0.223	0.850
98	1598	138	0.086	3036	178	0.059	1.473

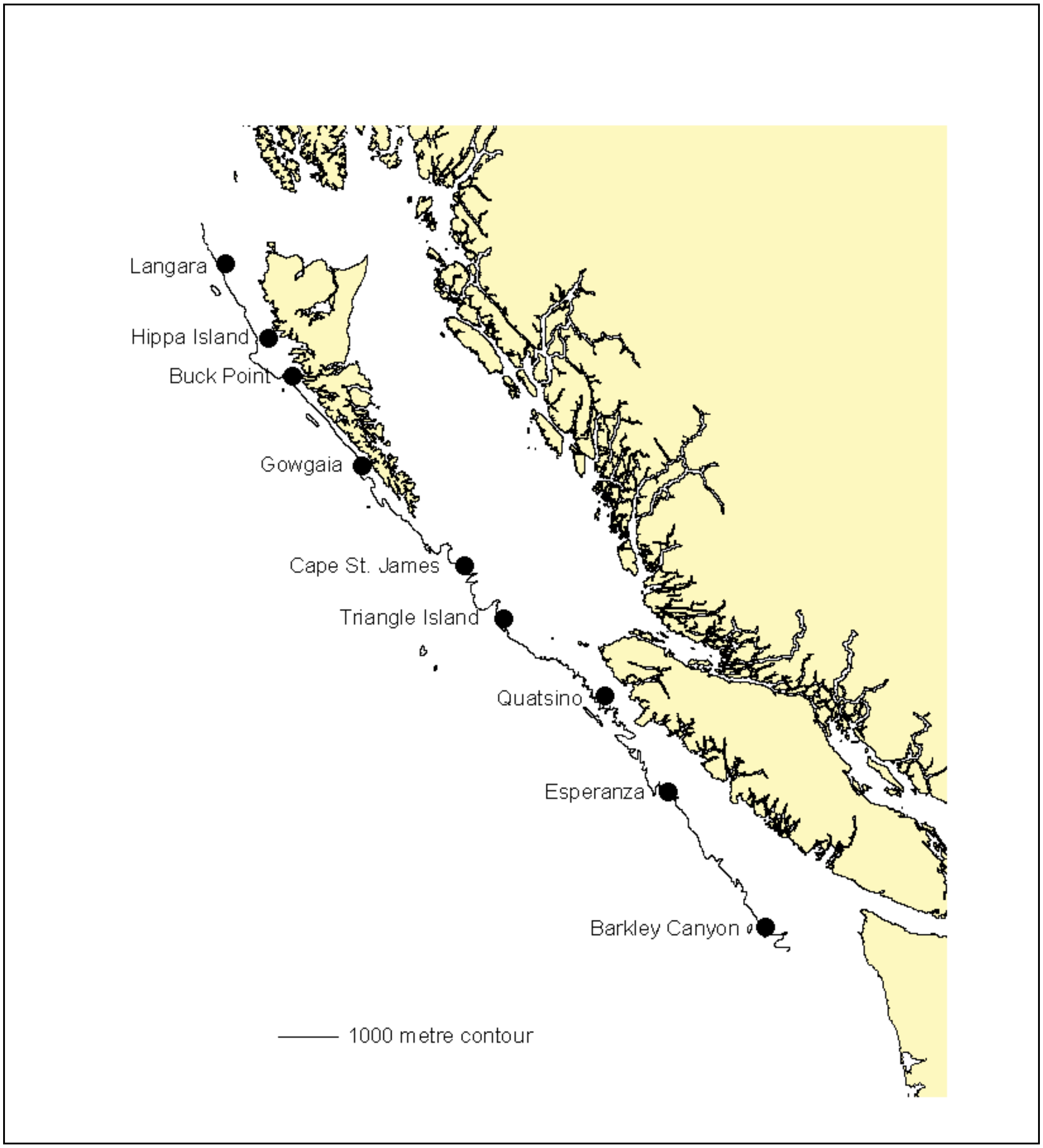


Figure 1.1 Sablefish survey sites off the west coast of Canada.

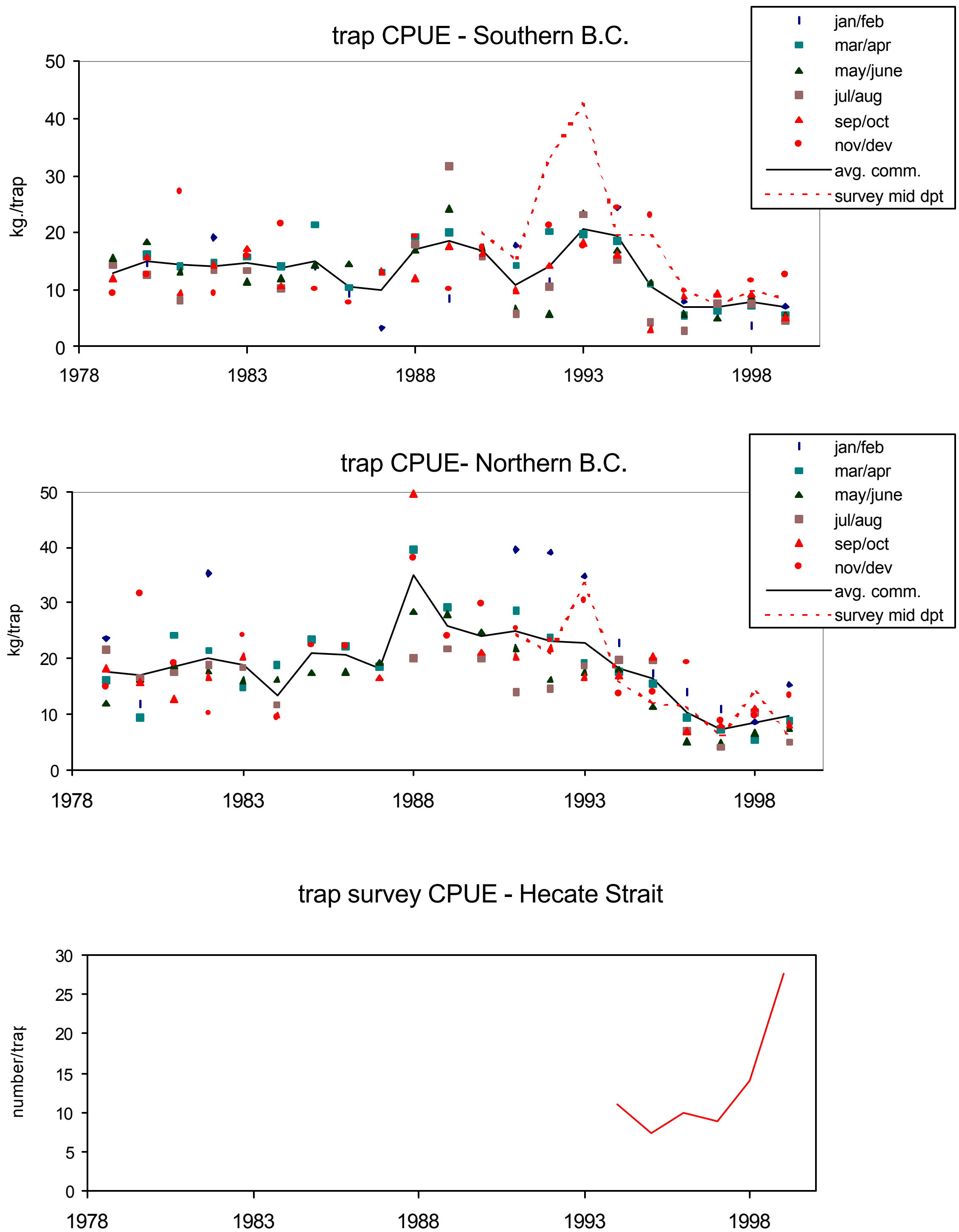


Figure 1.2. Trap fishery CPUE (kg/trap) for 2 month periods, average annual fishery CPUE and annual survey CPUE for Southern and Northern B.C. sablefish regions. The lower panel shows trap survey CPUE (number/trap) for Hecate Strait, 1994-1999.

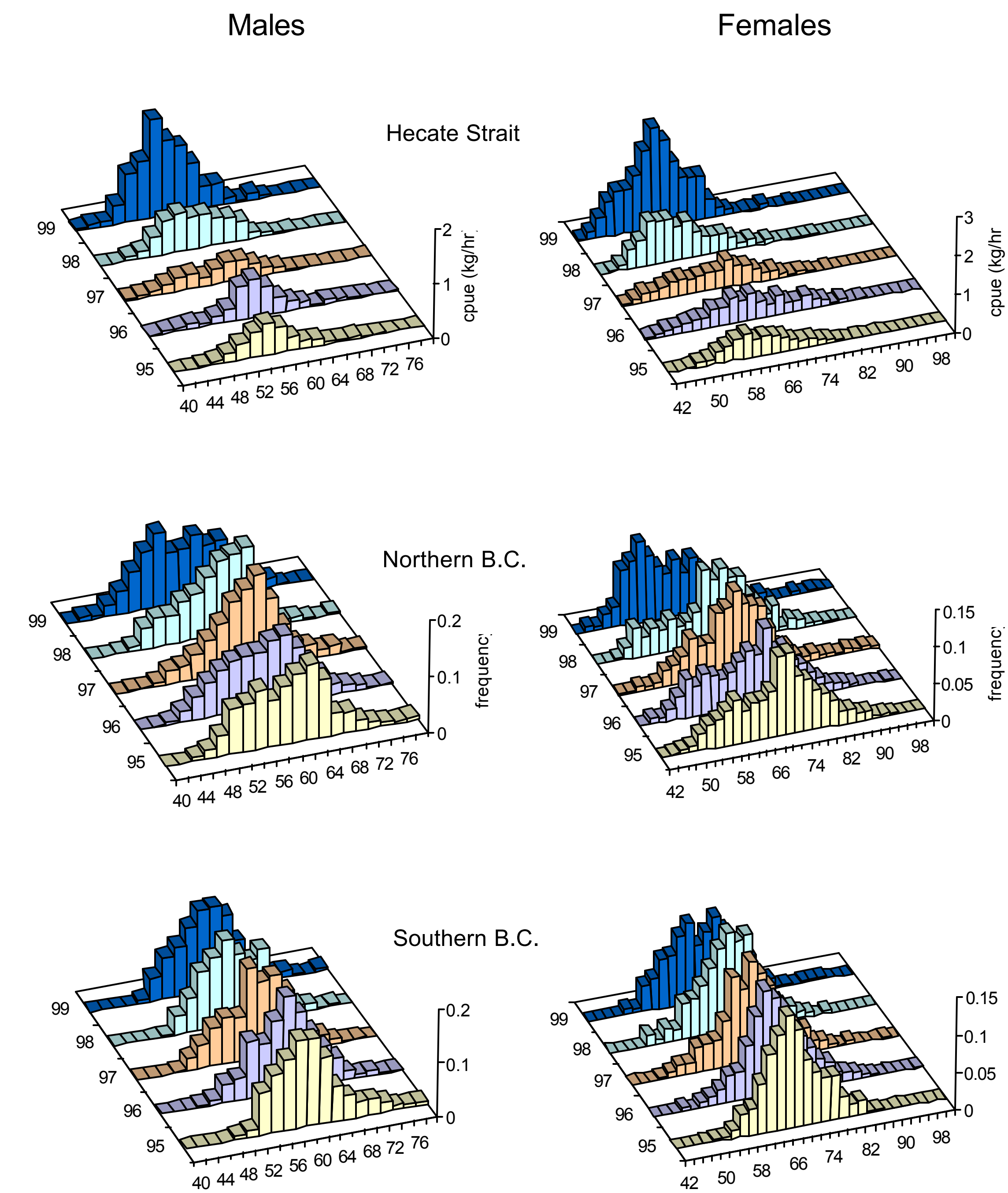


Figure 1.3. Distribution of sablefish length (cm) by sex and region. For Hecate Strait the data are scaled by survey catch rates (i.e. CPUE by length category); for the other regions data are relative frequencies. Data are all sablefish caught in surveys at depths ≤ 800 m.

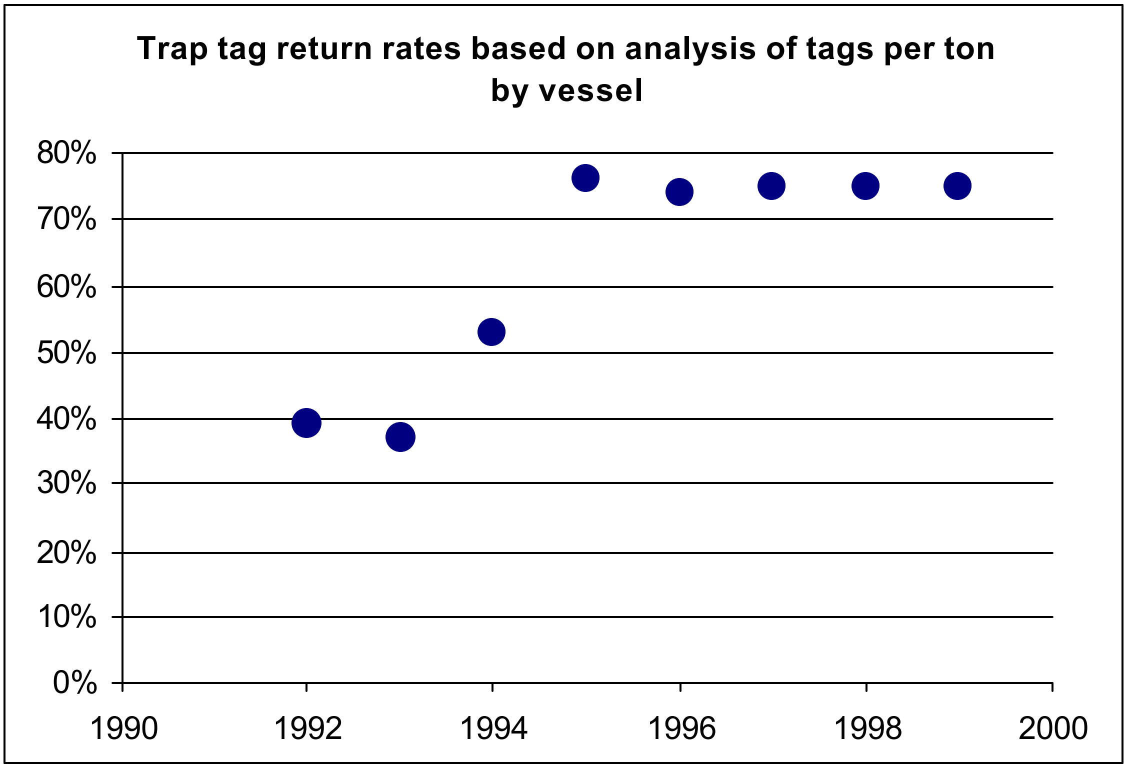


Figure 2.1. Estimates of tag return rate based on analysis of vessel to vessel differences in tag return rates.

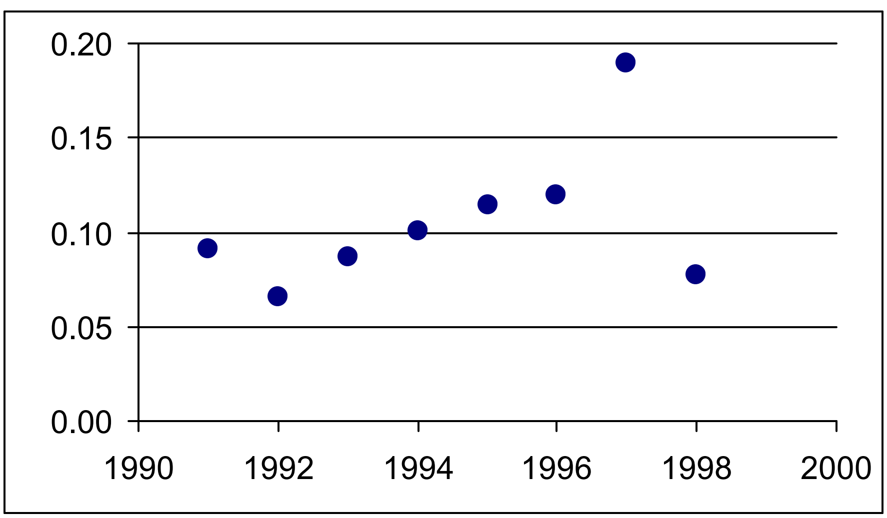


Figure 2.2. Estimated proportion of tags captured in the calendar year fo llowing release.

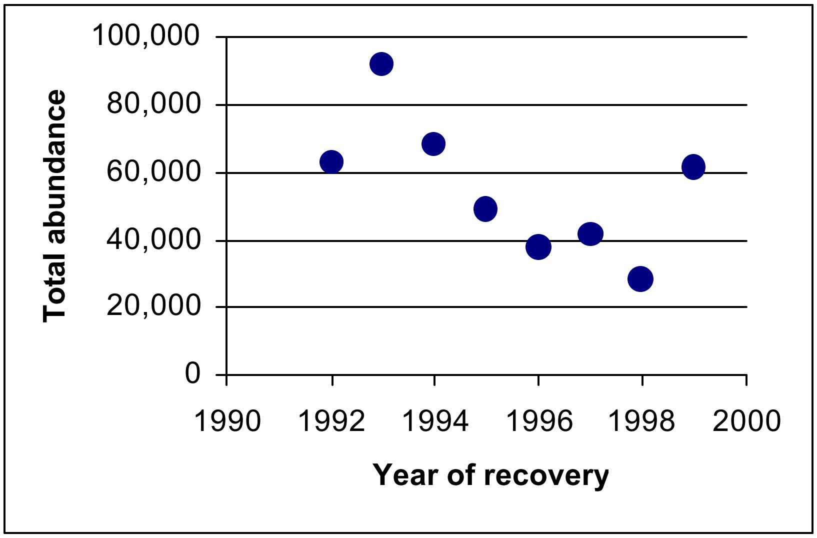


Figure 2.3. Estimated total abundance of the sable fish stock.

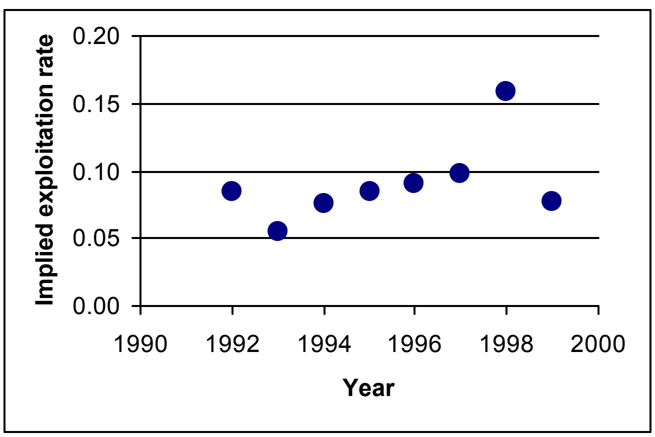


Figure 2.4. Estimated total exploitation rate on the sablefish stock.

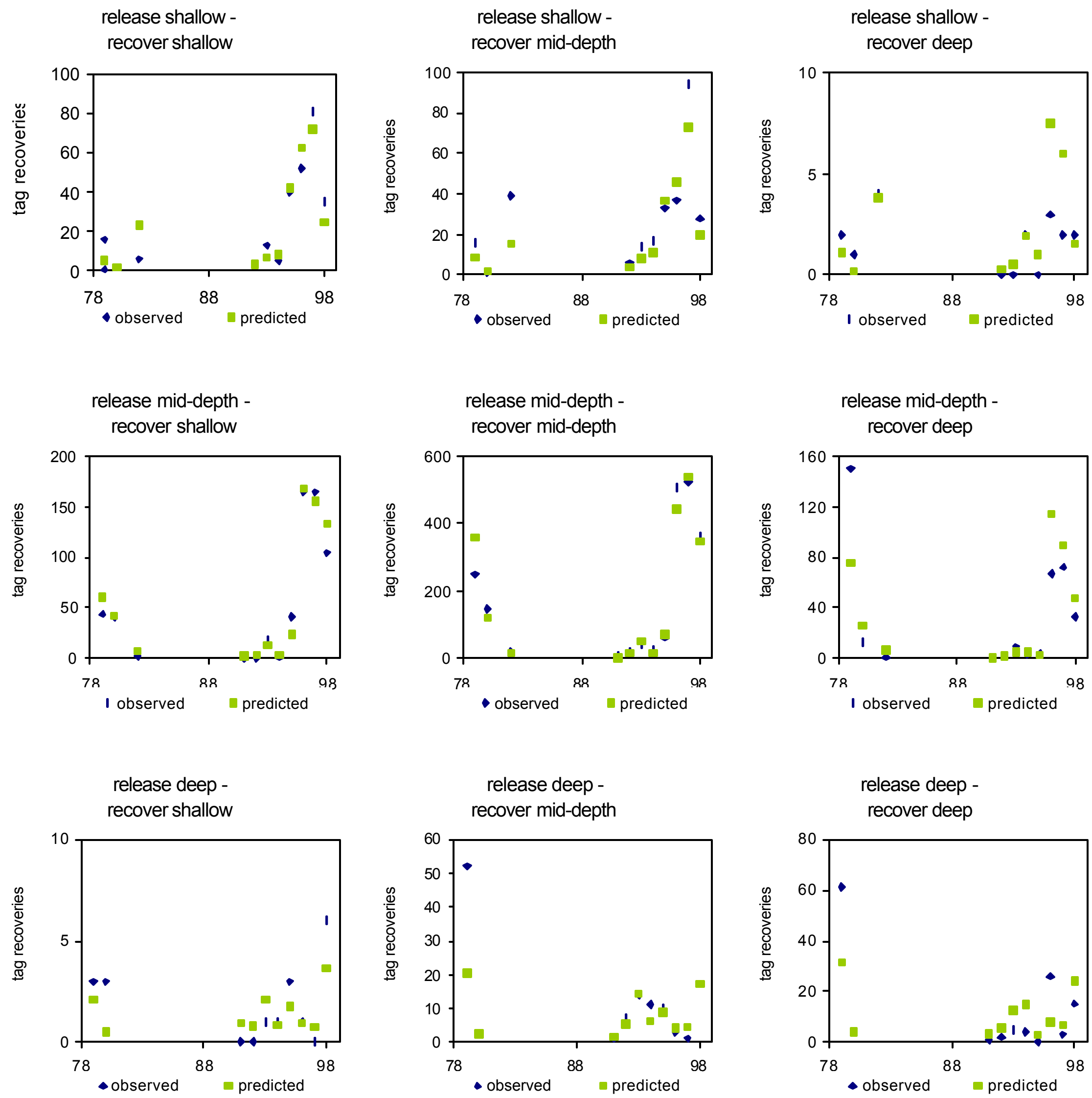


Figure 3.1. Observed and predicted number of tag recoveries in the year following release from integrated model fits to Southern B.C. tag data by release region and year and recovery regions. The years on the x axis reflect the year of release.

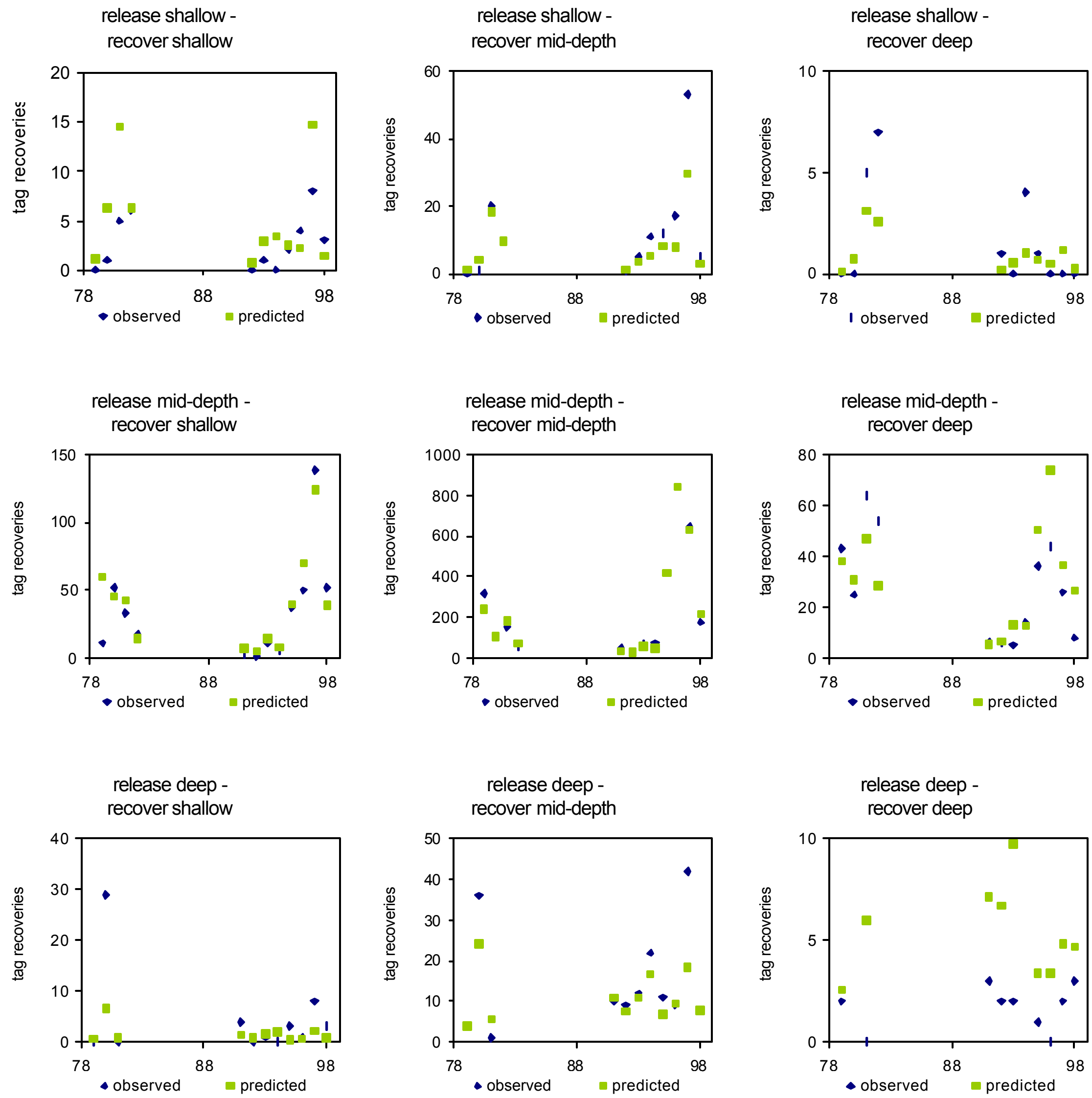


Figure 3.2. Observed and predicted number of tag recoveries in the year following release from integrated model fits to Northern B.C. tag data by release region and year and recovery regions. The years on the x axis reflect the year of release.

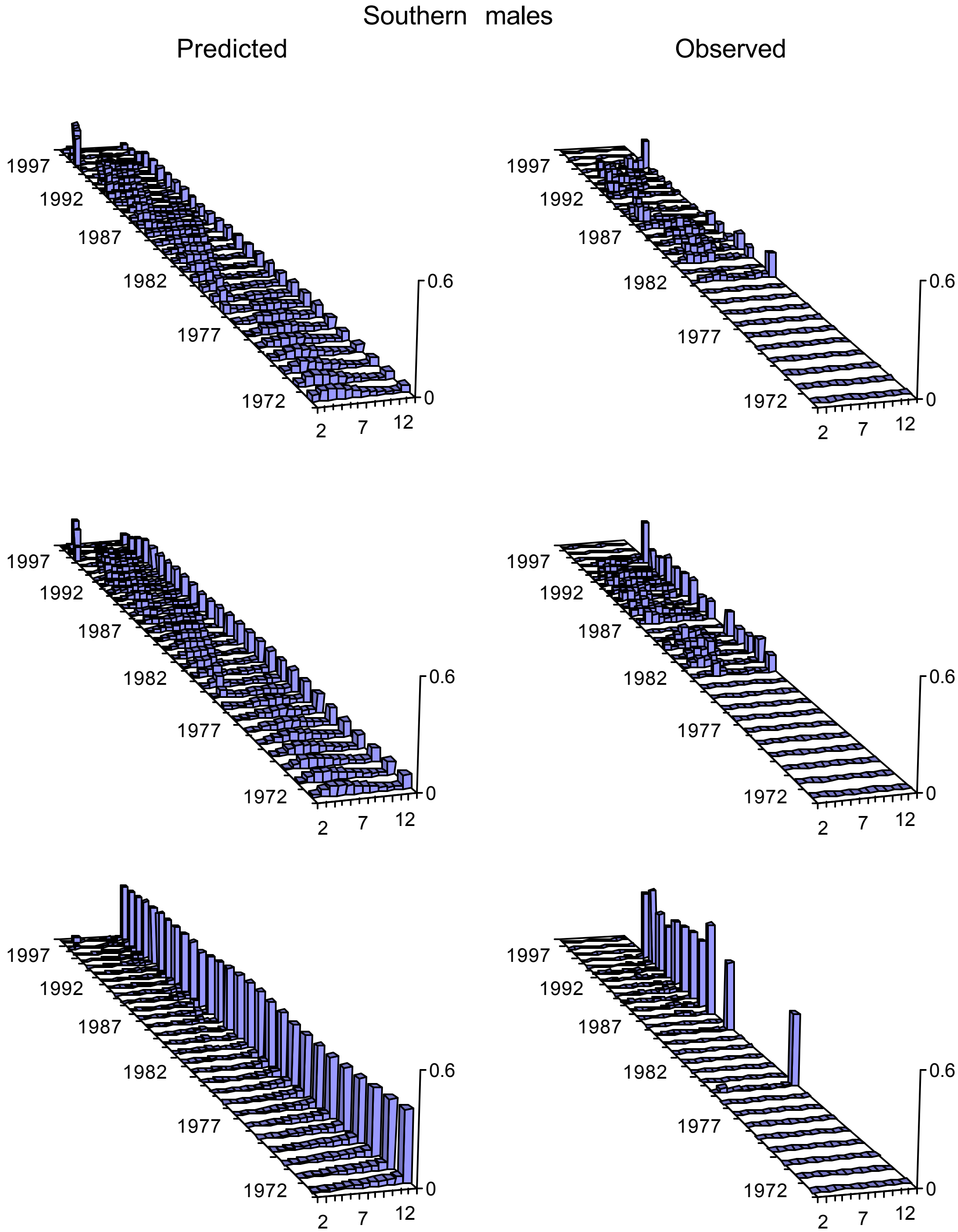


Figure 3.3. Observed and predicted proportion-at-age/sex for Southern B.C. males by depth zone (shallow depth on top, mid-depth in middle and deep on bottom). Note that within a depth zone the proportion-at-age for males and females sums to 1.

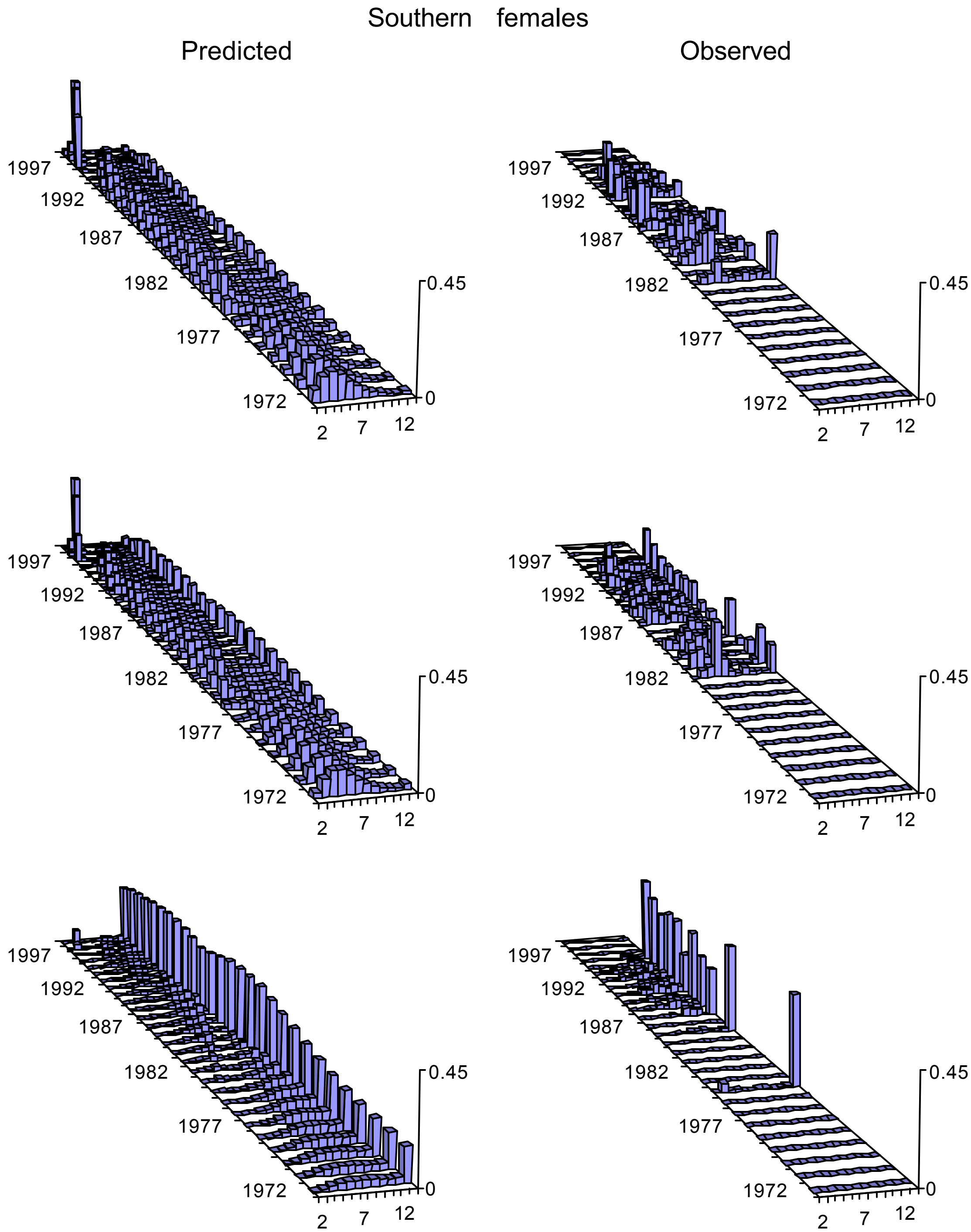


Figure 3.4. Observed and predicted proportion-at-age/sex for Southern B.C. females by depth zone (shallow depth on top, mid-depth in middle and deep on bottom). Note that within a depth zone the proportion-at-age for males and females sums to 1.

Northern males

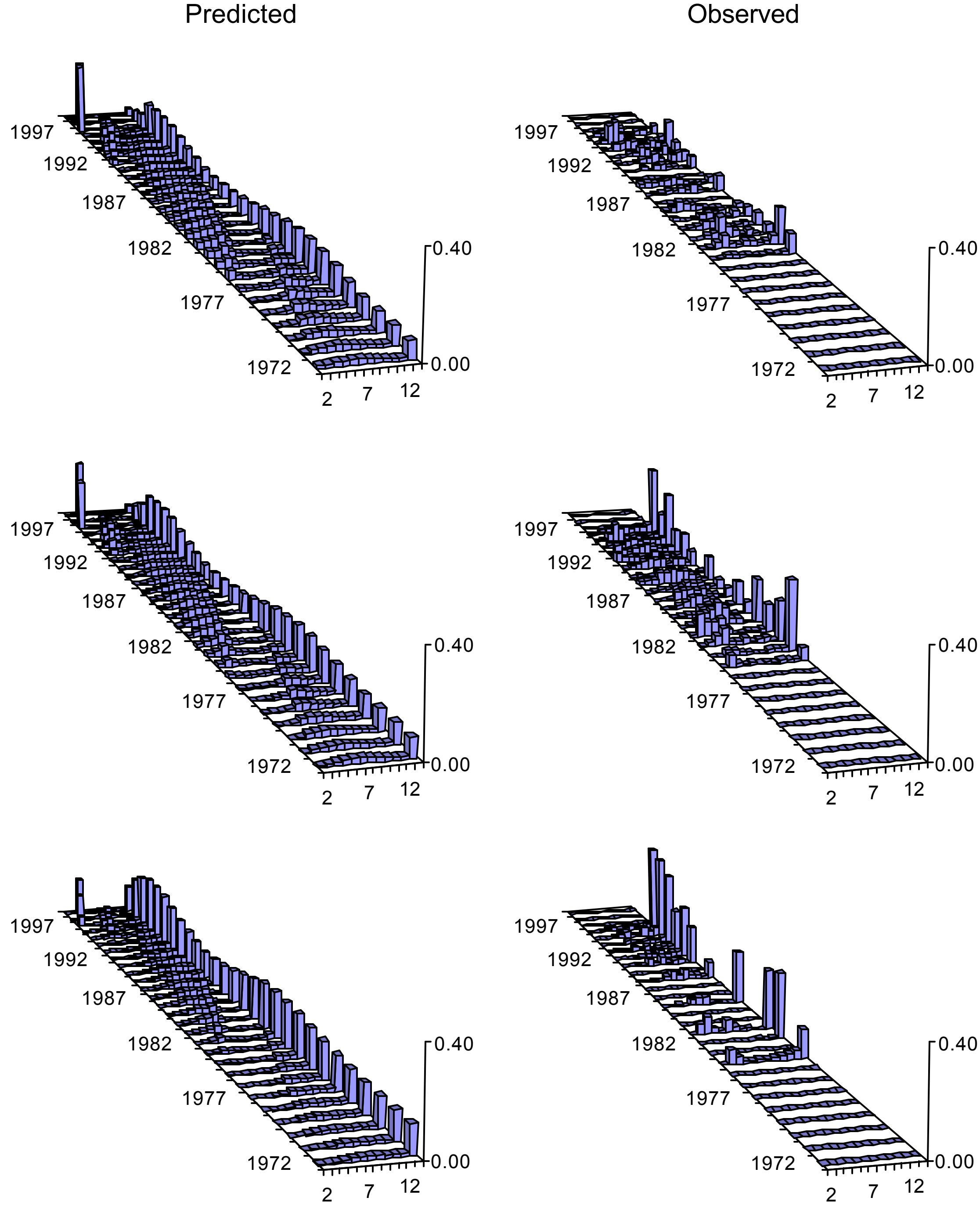


Figure 3.5. Observed and predicted proportion-at-age/sex for Northern B.C. males by depth zone (shallow depth on top, mid-depth in middle and deep on bottom). Note that within a depth zone the proportion-at-age for males and females sums to 1.

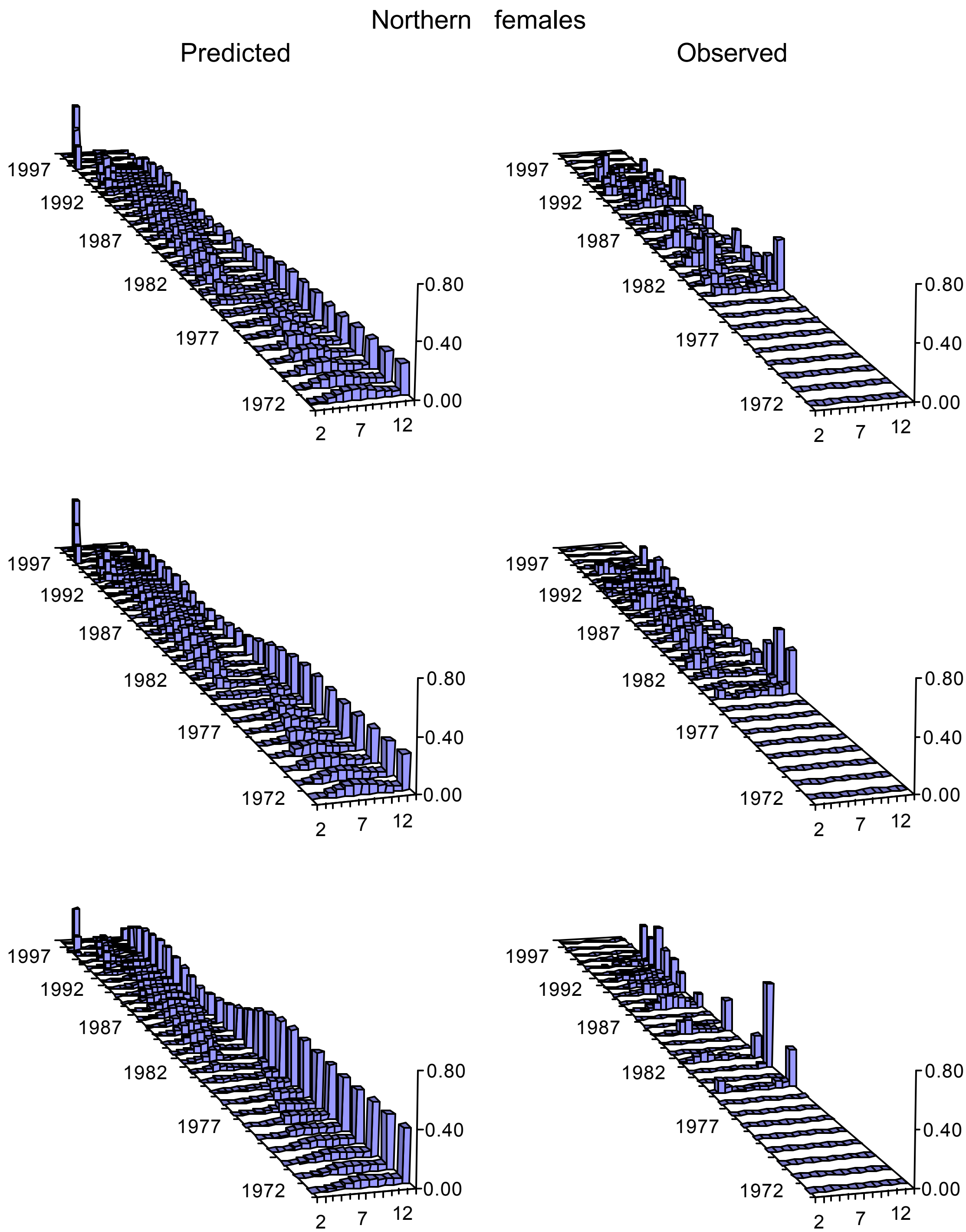
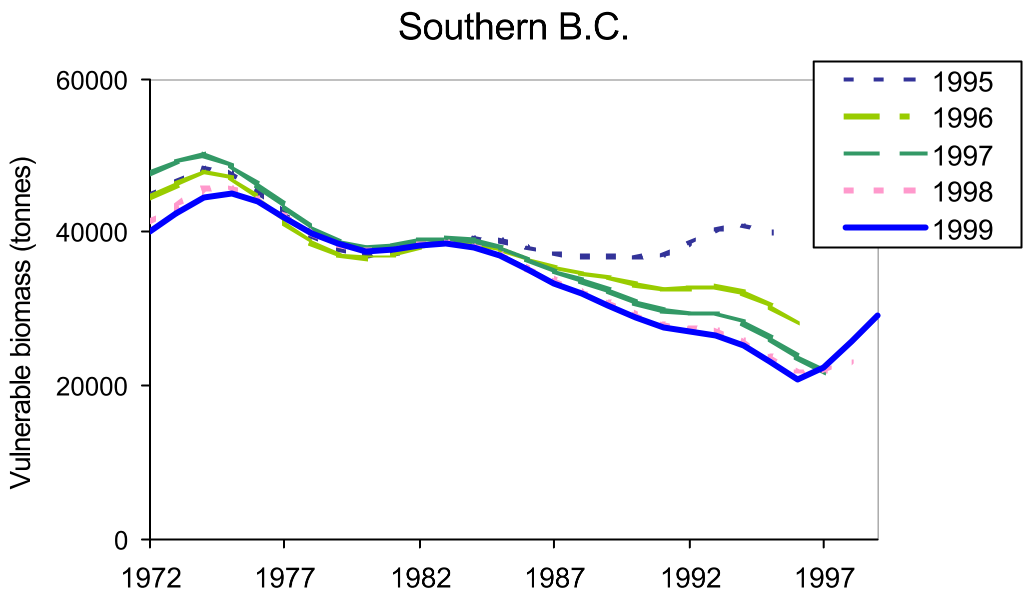


Figure 3.6. Observed and predicted proportion-at-age/sex for Northern B.C. females by depth zone (shallow depth on top, mid-depth in middle and deep on bottom). Note that within a depth zone the proportion-at-age for males and females sums to 1.



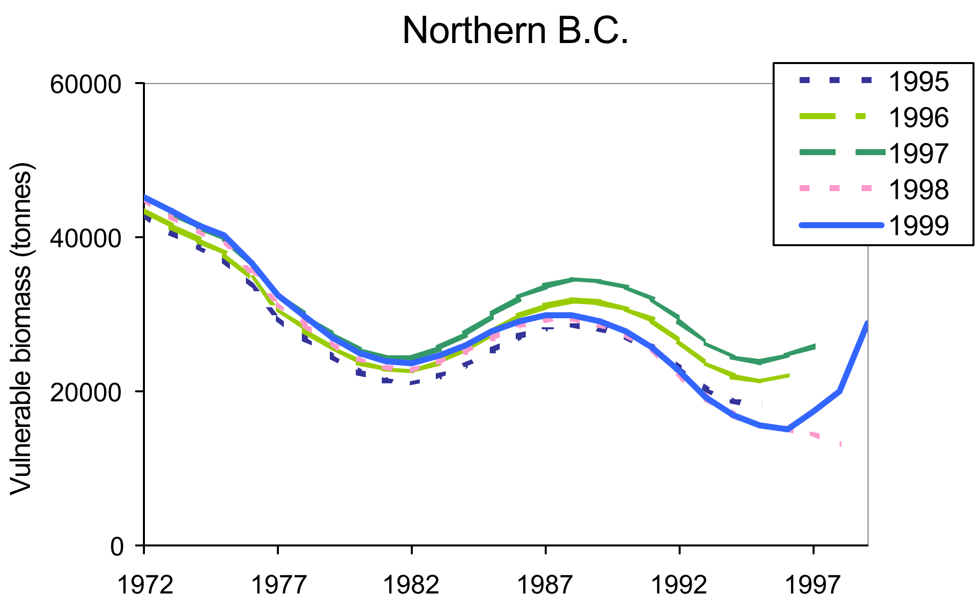


Figure 3.7. Retrospective analyses (data series ending in 1995 through 1999) from Integrated Model fits to Southern and Northern B.C. sablefish data.

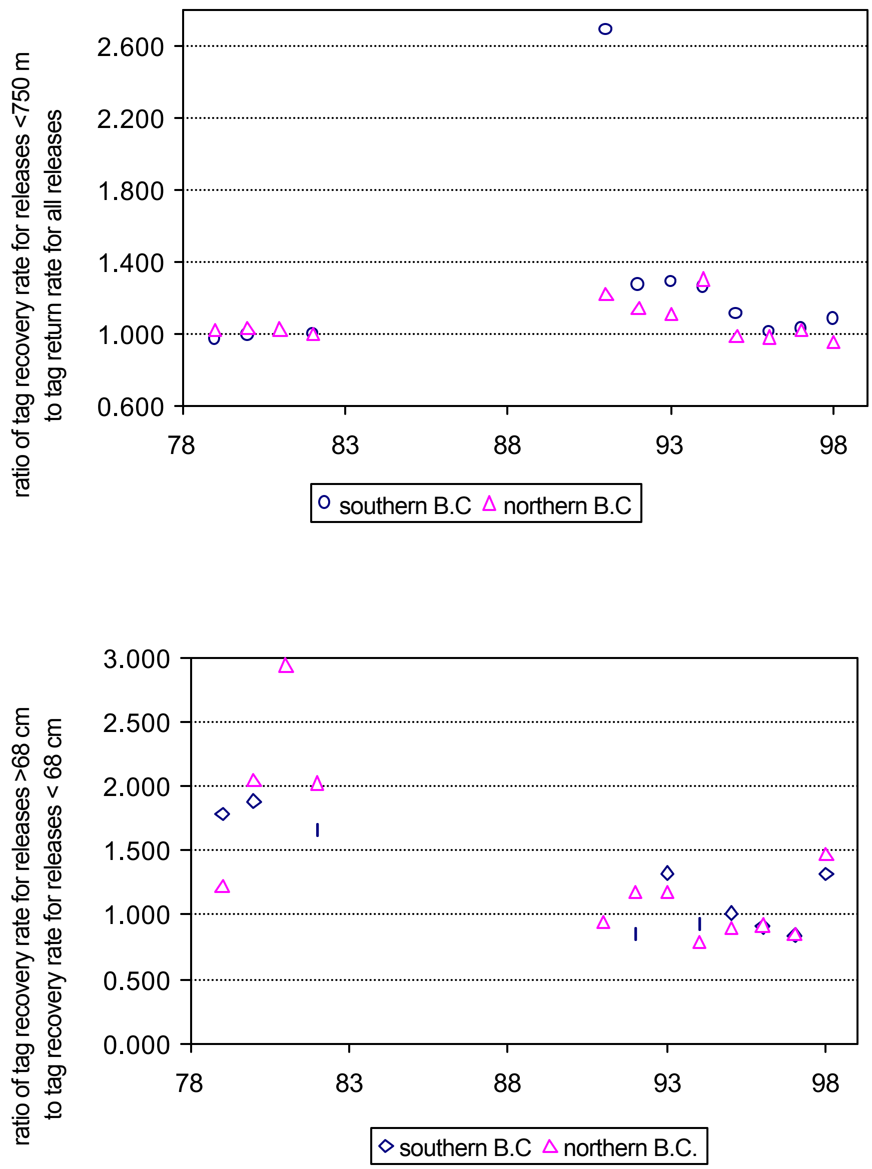


Figure 4.1. The ratio of tag recovery rate (all recoveries divided by releases) for releases of fish caught at depths < 750 m. to the tag recovery rate for all releases (top panel). The ratio of tag recovery rate (recoveries during year of tagging and the following year divided by releases) for fish > 68 cm at release to the recovery rate for fish < 68 cm at release (bottom panel).

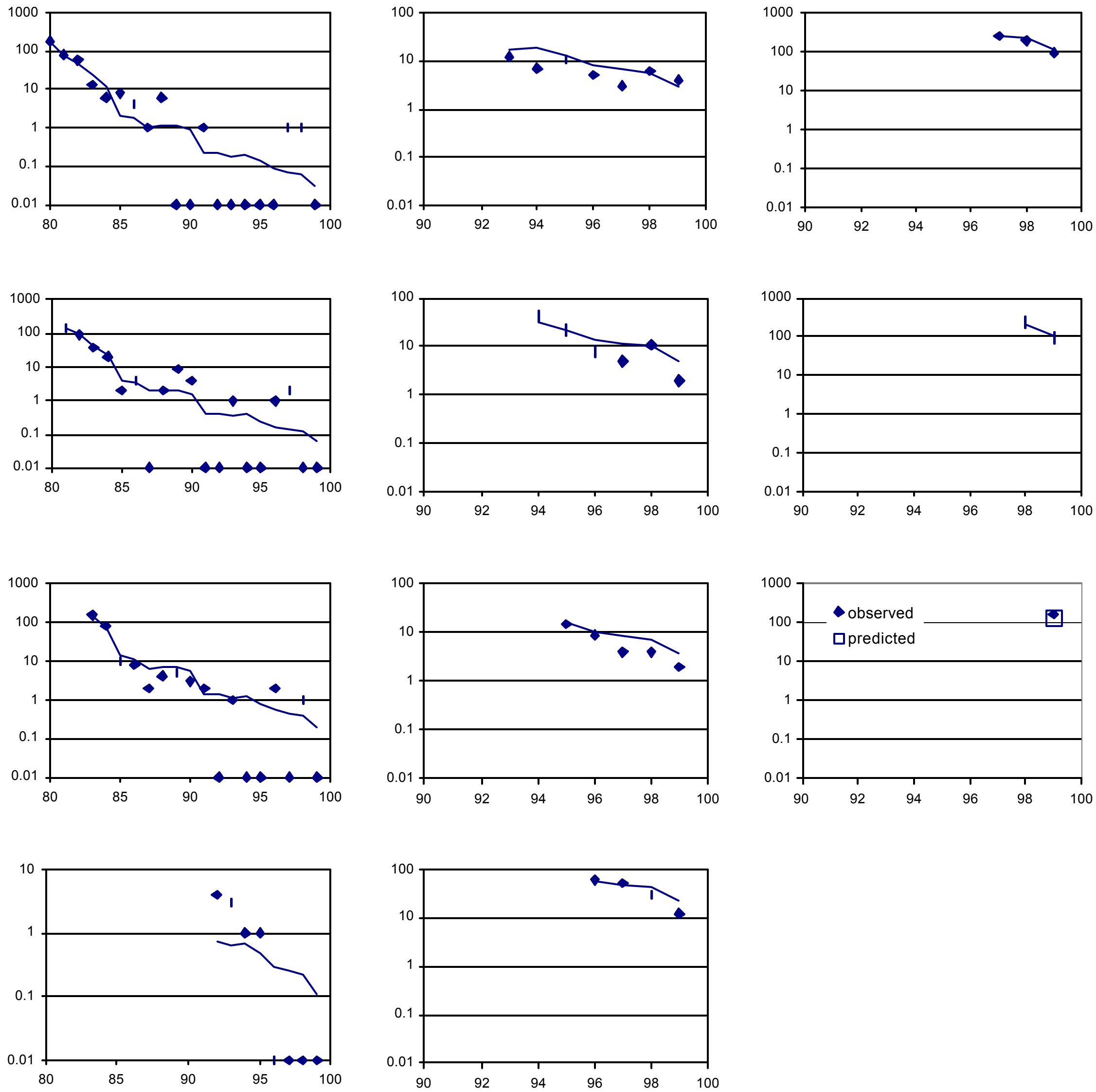


Figure 4.2. Predicted (lines) and observed (points) number of tag recoveries by release group (1979 through 1998, each in separate plots) and recovery year for the mark-recapture model fit to Southern B.C. sablefish tagging data. Predicted values are from the maximum of the posterior distribution.

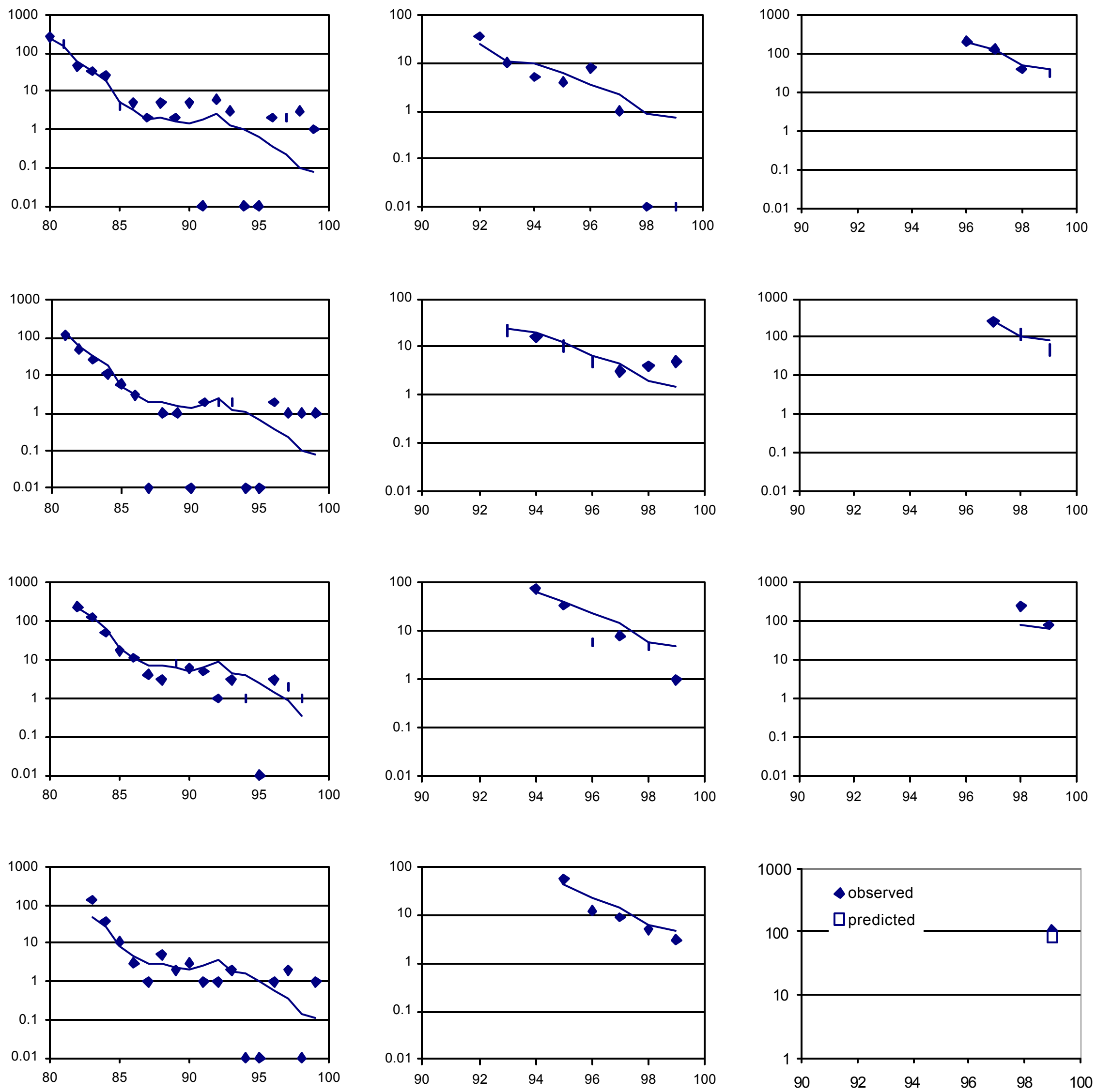


Figure 4.3. Predicted (lines) and observed (points) number of tag recoveries by release group (1979 through 1998, each in separate plots) and recovery year for the mark-recapture model fit to the Northern B.C. sablefish tagging data. Predicted values are from the maximum of the posterior distribution.

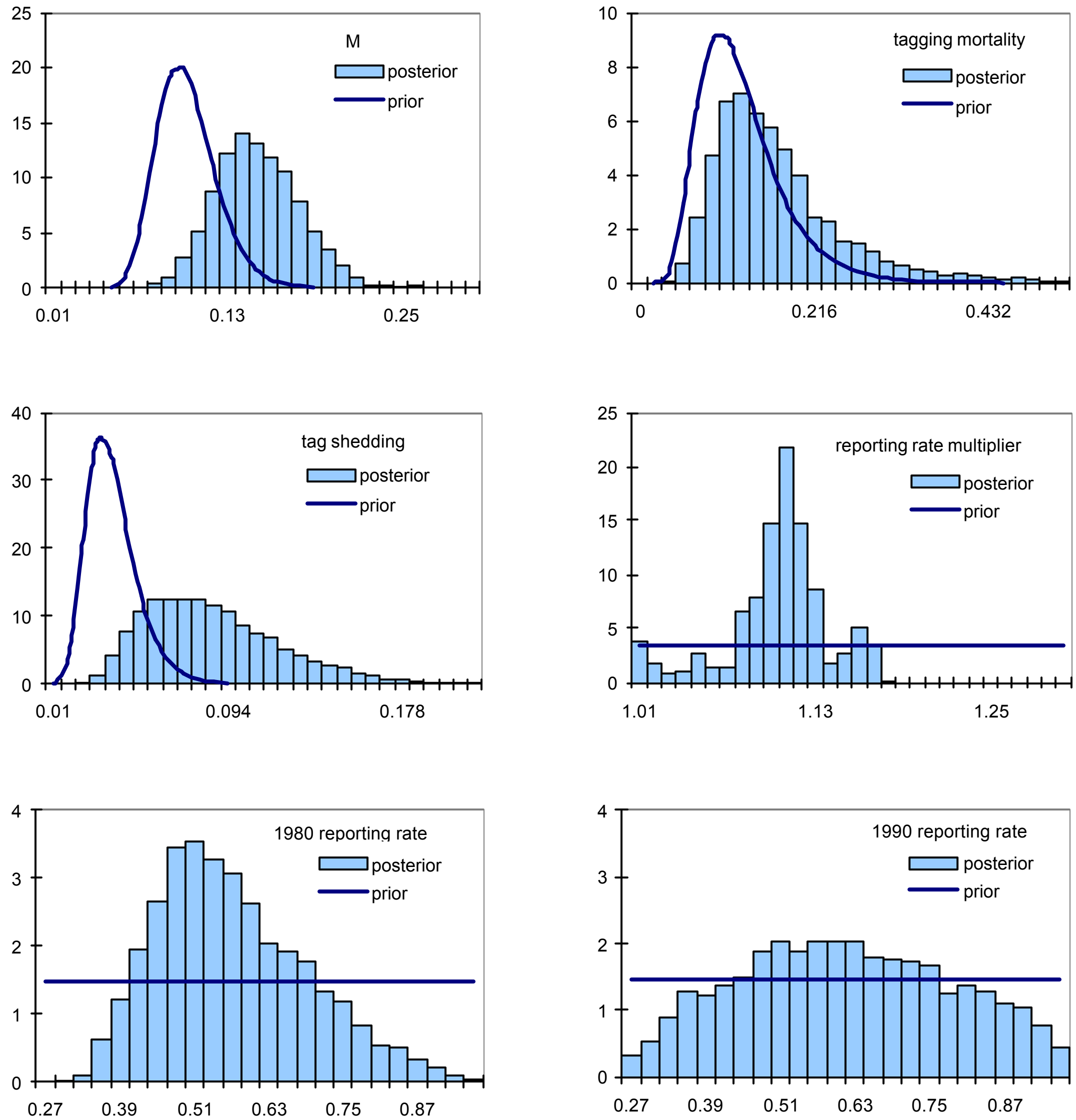


Figure 4.4. The Bayesian prior and posterior probability distributions (pdf) of mark-recapture model parameters for the Southern B.C. sablefish stock.

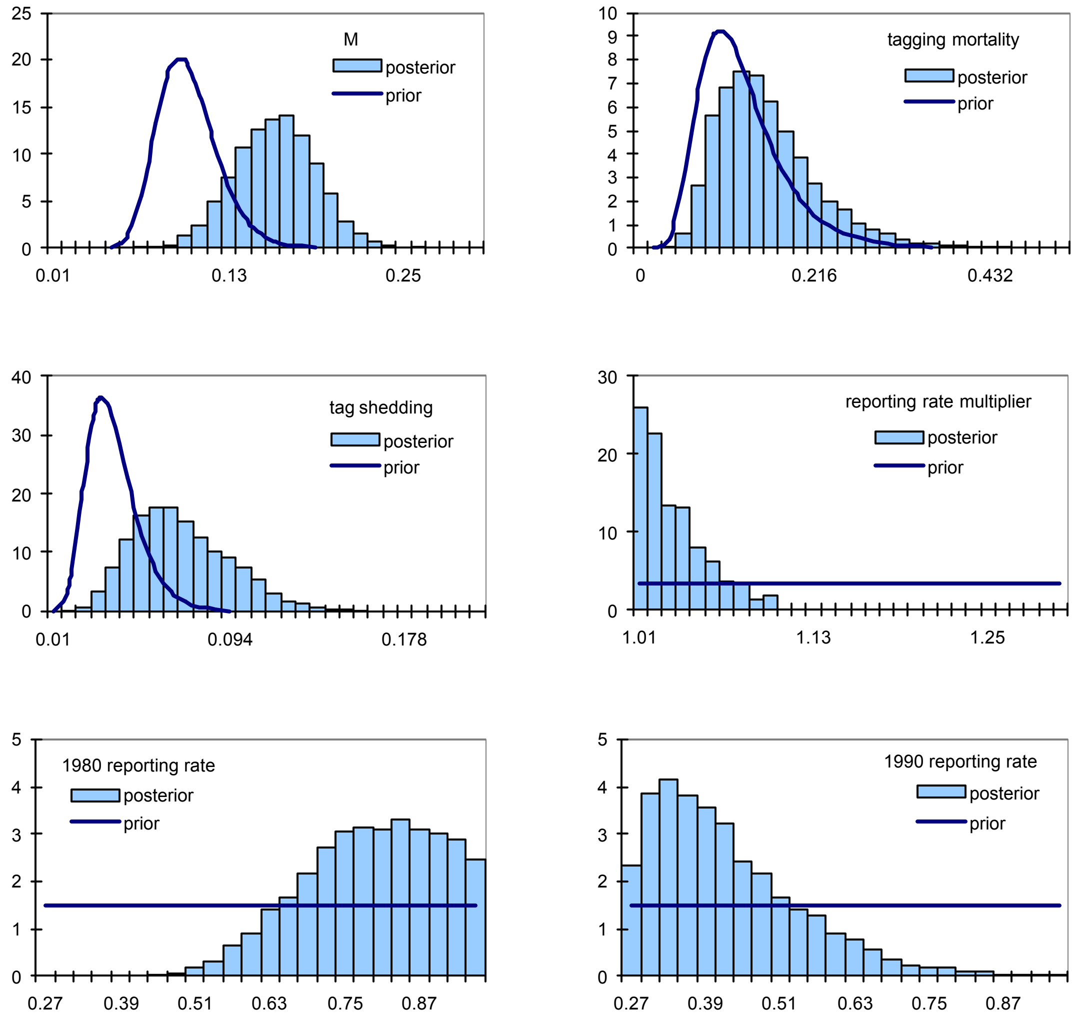


Figure 4.5. The Bayesian prior and posterior probability distributions (pdf) of mark-recapture model parameters for the Northern B.C. sablefish stock.

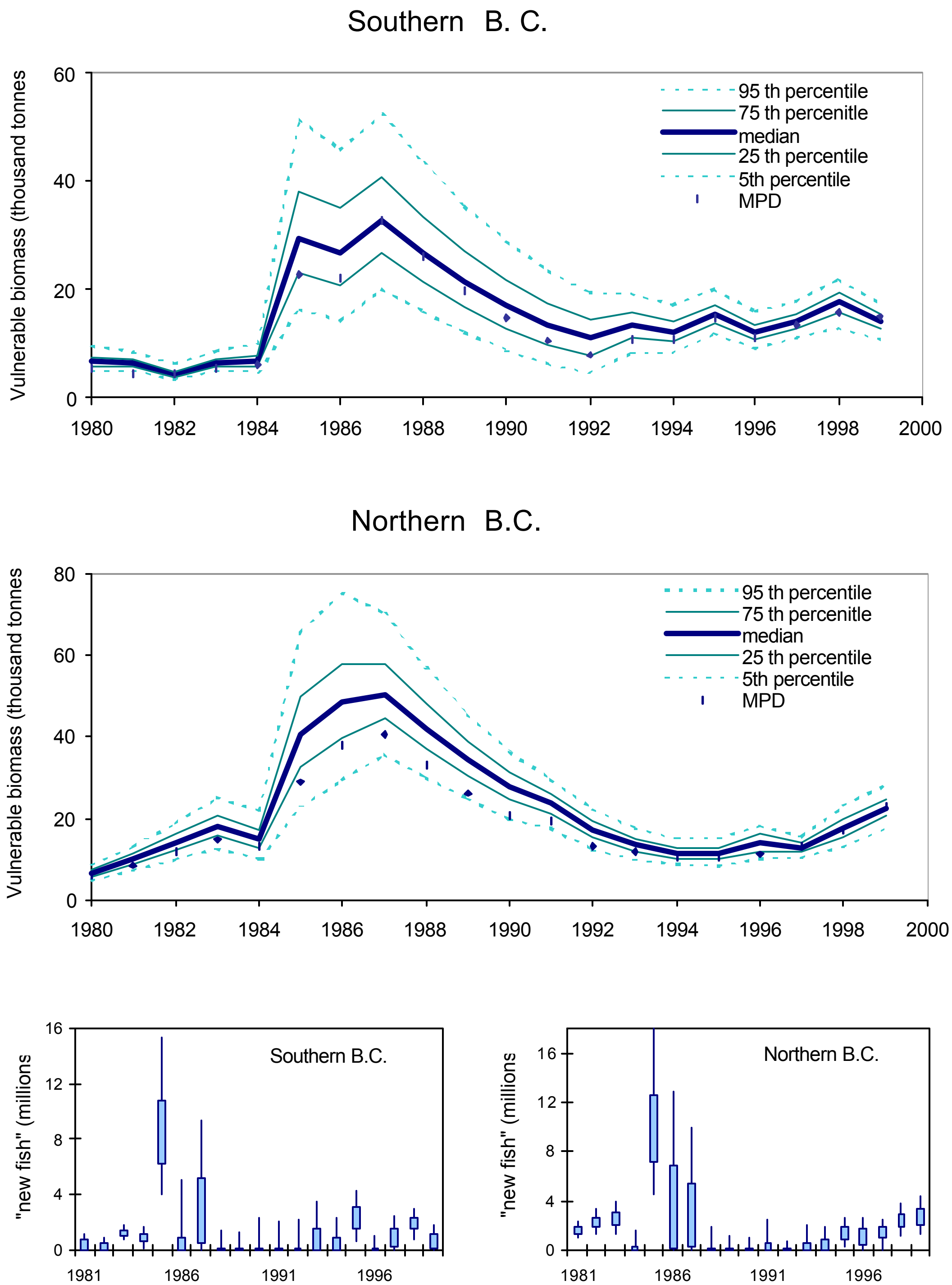


Figure 4.6. Percentiles of the posterior distribution and the maximum of the posterior distribution (MPD) of vulnerable biomass from mark-recapture model fits to the Southern B.C. and Northern B.C. sablefish data. Bottom panels show the inter-quartile range (bars) and 5th to 95th percentiles of the probability distribution (lines) of “new fish” estimates.

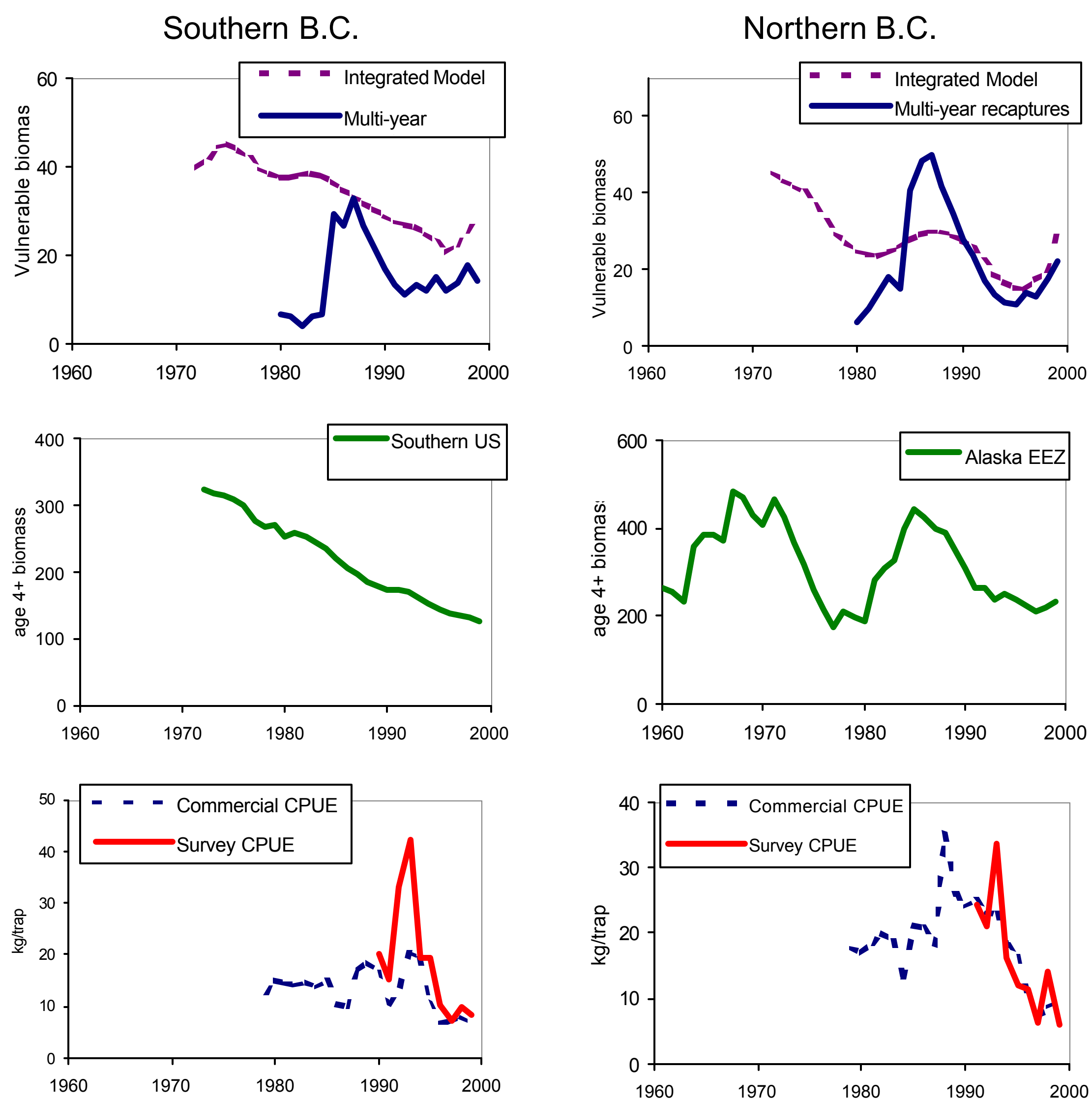
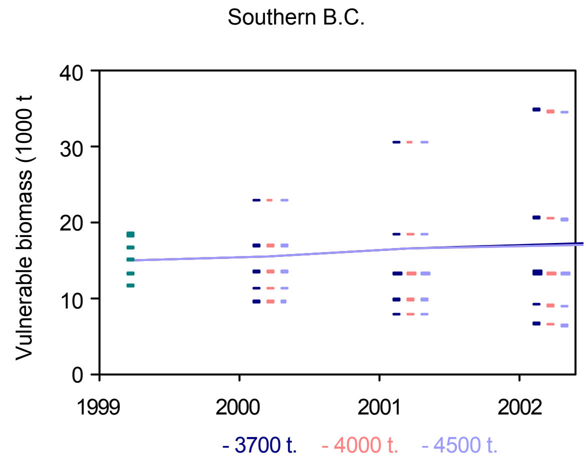


Figure 4.7. Estimates of vulnerable biomass obtained from analyses presented in this document, age 4+ biomass from US sablefish assessments, and CPUE indices.



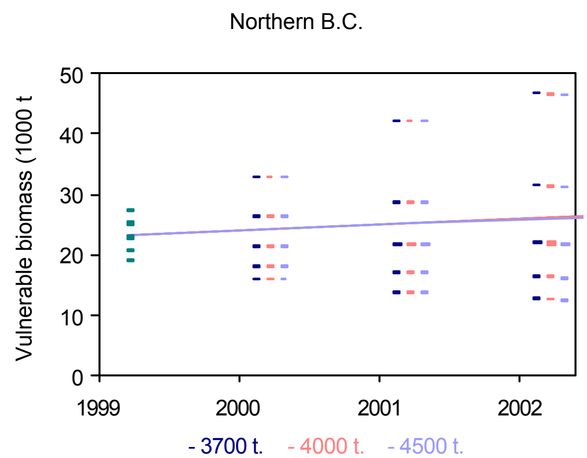
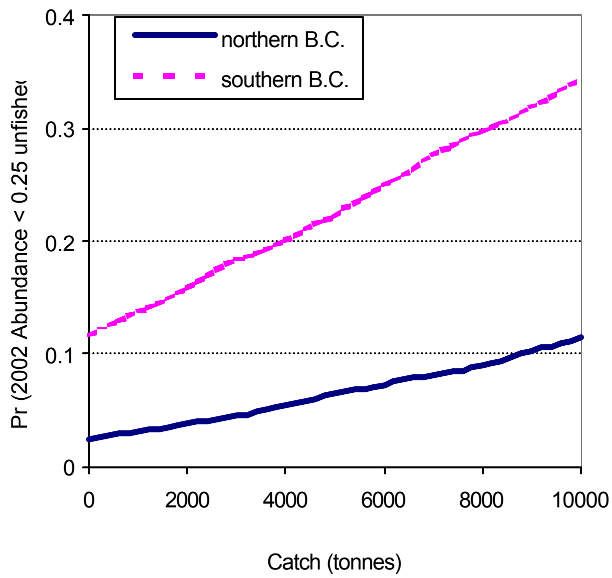


Figure 4.8. The projected stock trajectories at coastwide harvest levels of 3700t, 4000t, and 4500 t. The solid lines show the expected values. The points show the 10th, 25th, 50th 75th, and 90th percentiles of the distributions.



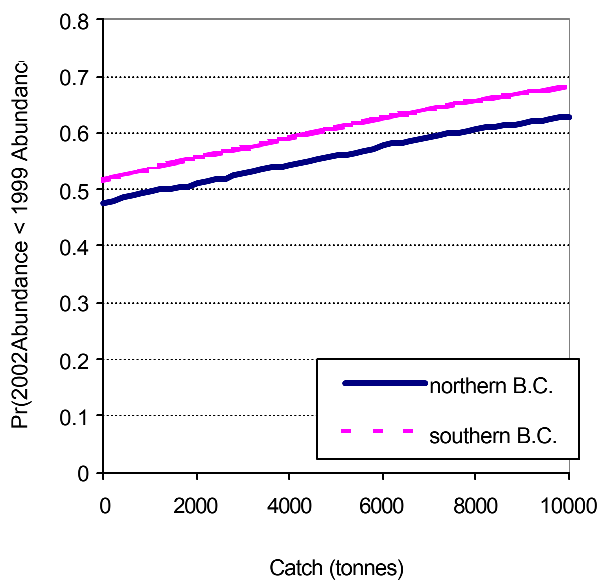


Figure 4.9. The estimated probabilities that vulnerable biomass in 2002 will be less than 25% of the unfished level (top figures) and the estimated probability that vulnerable biomass in 2002 will be less than in 1999 for alternative coast-wide harvest levels. The coast-wide catch is split 48% to Southern B.C. and 52% to Northern B.C.

APPENDIX A

Description of the Integrated Catch-Age Mark-Recapture Model

The Integrated Model is a spatially and sexually disaggregated age-structured model. Spatial disaggregation involves both bathymetric strata and geographic regions. The main inputs to the model include estimates of the age and sex structure of the survey catch by region and year, estimates of the total fisheries catch by region and year and tag return data.

The model is formulated to deal with the specific data available for the B.C. sablefish stocks. For example, the commercial catch is not sampled for age and sex composition. We assume that the age and sex structure of the commercial catch is the same as that from the annual surveys which may be reasonable given the survey uses similar gear and fishes in similar locations as the commercial fishery. This assumption if modified to include the effect of escape-rings that are used in commercial fishery traps beginning in 1999. Additionally, we assume that not all sablefish that are caught are landed, but that smaller (not tagged) fish are released. Estimation of “landing” selectivity and “escape-ring” selectivity parameters is described in Appendix C.

Definitions for the symbols and notation we use in describing the model are given in the following list:

r indexes the regions,
i indexes the years,
j indexes the age classes,
s indexes the sexes,
t indexes the tag groups,
N_R is the number of regions,
N_I is the number of years of fishing,
N_J is the number of age classes in the population,
i_t the year in which the tag group was tagged,
r_t the region in which the tag group was tagged.

The fundamental model parameters (i.e. those estimated through minimization):

$\overline{R}$ the average total recruitment for each sex,
$\boldsymbol{h}_{ri}$ the log-normal deviations from average recruitment for region r in year i,
$\boldsymbol{g}$ scaling parameter for historic recruitment level,
a_{rsj} is the proportion of the age j and sex s fish in the population in region r that are available to the fishery at the beginning of each year,
$\boldsymbol{e}_{ri}$ determines the level of the fishing mortality rate in region r in year i,
M is the instantaneous natural mortality rate,

q_r is the catchability in region r,
$d_{rr'1}$ determines the proportion of fish moving from region r to region r',
$d_{rr'2}$ determines age-dependent movement of fish from region r to region r',
$\boldsymbol{r}_{ri}$ is the proportion of the tagged fish caught in region r in year i that are reported,
s_r^T is the survival rate from tagging in region r,

Model parameters that are functions of the fundamental parameters:

R_{rsi} the recruitment of sex s fish to region r in year i,
$\widetilde{N}_{rsij}$ is the total number of age class j fish of sex s in the population in region r at the beginning of year i before movement,
N_{rsij} is the total number of age class j fish of sex s in the population in region r at the beginning of year i after movement,
A_{rsij} is the number of age class j fish of sex s in the population in region r at the beginning of year i which are available to the fishery,
A_{ri} is the total number of fish in the population in region r at the beginning of year i which are available to the fishery,
C_{rsij} is the catch of age class j fish of sex s in the population in region r during year i,
C_{ri} is the total catch in region r for year i,
p_{rsij} is the proportion of the survey catch of sex s fish in region r during year i which consists of age class j fish,
C_{tri}^T is the total catch of tag group t fish in region r for year i,
F_{rsij} is the instantaneous fishing mortality rate of age class j fish of sex s in region r for year i,
F_{rsij}^T is the instantaneous fishing mortality rate for tagged fish of age class j and sex s in region r for year i,
Z_{rsij} is the instantaneous total mortality rate of age class j fish of sex s in region r for year i,
S_{rsij} is the survival rate of age class j fish of sex s in region r for year i,
S_{rsij}^T is the survival rate of tagged fish of age class j and sex s in region r for year i,

$\boldsymbol{l}_{jrr'}$ are the coefficients of the matrix of transition rates between regions r' and r for age class j fish.

Data inputs to the model:

$\widehat{C}_{ri}$ is the observed total catch in region r for year i,
$\widehat{p}_{rsij}$ is the observed proportion of the survey catch of sex s fish in region r during year i which consists of age class j fish,
I_t the number of fish tagged in tag group t,

$\widehat{C}^{T}_{tri}$ is the observed total catch of tag group t fish in region r for year i.

v_{rsj} is the estimated proportion of the catch of age class j fish of sex s in region r that are landed.

r_{rsj} is the estimated escape-ring retention selectivity for fish of age class j and sex s in region r.

We employ a form of the catch equations that assumes the population in each region is comprised of available and unavailable fish. Our rationale for using an availablity parameterization is that it allows us to assume similar dynamics for the tagged and the untagged components of the population. Portions of the younger age-classes reside in areas that are not commercially fished, and thus are not available to the fisheries. This includes areas such as the inlets of Hecate Strait. Fish are tagged during sablefish surveys that employ commercial trap gear and fish in commercial fishing locations. Hence, we assume that all tagged fish are fully available to the fisheries. Note that this assumption is modified for the 1999 fishery, when the commercial fishery began to use escape-rings in the traps. The sablefish surveys continue to use unmodified gear (no escape-rings).

We parameterize availability is a function of age and sex. Until 1999, all available fish are assumed to be equally vulnerable to the fisheries, however, not all fish that are caught are landed. The instantaneous fishing mortality rates are parameterized as functions of the sex- and age-specific landing selectivity. The landing selectivities are estimated independently, and are fixed quantities in the estimation procedure. For 1999 an alternate fishing mortality function that accounts for escape-ring retention selectivity is used.

Note that the only fishery-related quantities fit in the analyses are the total fisheries catches in each region and year. We assume that all available fish are equally vulnerable to the annual sablefish survey, and fit the model to the survey sex- and age-composition data. The instantaneous fishing mortality rates relate the quantities C_{rsij}, N_{rsij}, and A_{rsij} via the catch equations. The form of the catch equations used in this paper is given by

$$F_{rsij} = q_r v_{rsj} \exp\left(\boldsymbol{e}_{ri}\right) \qquad \text{for } i \le 1998$$

$$F_{rsij} = q_r v_{rsj} r_{rsj} \exp\left(\boldsymbol{e}_{ri}\right) \qquad \text{for } i \ge 1999$$

$$Z_{rsij} = F_{rsij} + M$$

$$S_{rsij} = \exp\left(-Z_{rsij}\right)$$

$$A_{rsij} = a_{rsj} N_{rsij}$$

$$C_{rsij} = \frac{F_{rsij}}{Z_{rsij}}\left(1 - S_{rsij}\right) A_{rsij} \qquad \text{for } 1 \le i \le N_I \quad 1 \le j \le N_J$$

$$C_{ri} = \sum_{sj} C_{rsij}$$

$$R_{rsi} = \exp\left(\boldsymbol{h}_{ri}\right)\bar{R} \qquad\qquad \text{where } \sum\nolimits_{ri} \boldsymbol{h}_{ri} = 0$$

$$\tilde{N}_{rsi1} = R_{rsi}$$

$$\tilde{N}_{rs,i+1,j+1} = S_{rsij}A_{rsij} + \exp\left(-M\right)\left(N_{rsij} - A_{rsij}\right)$$

$$\begin{aligned}\tilde{N}_{rs,i+1,N_j} = {} & S_{rsi,N_j-1}A_{rsi,N_j-1} + \exp\left(-M\right)\left(N_{rsi,N_j-1} - A_{rsi,N_j-1}\right) + \\ & S_{rsiN_j}A_{rsiN_j} + \exp\left(-M\right)\left(N_{rsiN_j} - A_{rsiN_j}\right)\end{aligned}$$

$$N_{rsij} = \sum_{r'} \boldsymbol{l}_{jrr'}\tilde{N}_{r'sij}$$

$$p_{rsij} = A_{rsij} \Big/ \sum_{sj} A_{rsij}$$

We assume that tagged fish have the same dynamics as the available component of the untagged population. Further, we assume that the sex and age composition of fish tagged in region r in year i is the same as the sex and age composition of the suvey in region r in year i. The symbols used to describe the dynamics of the tag groups are the same as those used to describe the population as a whole, with the addition of a superscript "T" and a subscript "t" to index the tag groups. For example N^T_{trsij} is the number of fish from tag group t of sex s and age class j in region r at the beginning of year i. With this convention in mind the equations used to describe the tag group dynamics are:

$$\tilde{N}^T_{tr_tsi_tj} = p_{r_tsi_tj}\, s^T_r I_t$$

$$\tilde{N}^T_{trsi_tj} = 0 \qquad \text{for } r \neq r_t \text{ or } i < i_t$$

$$F^T_{rsij} = q_r \exp\left(\boldsymbol{e}_{ij}\right) \qquad \text{for } i \leq 1998$$

$$F^T_{rsij} = q_r r_{rsj} \exp\left(\boldsymbol{e}_{ij}\right) \qquad \text{for } i \leq 1998$$

$$S^T_{rsij} = \exp\left(-F^T_{rsij} - M\right)$$

$$C^T_{trsij} = \frac{F^T_{rsij}}{Z_{rsij}}\left(1 - S^T_{rsij}\right) N^T_{trsij} \qquad \text{for } i_t \leq i \leq N_I \quad 1 \leq j \leq N_J$$

$$\tilde{N}^T_{trs,i+1,j+1} = S^T_{rsij} N^T_{trsij}$$

$$\tilde{N}^T_{trs,i+1,N_j} = S^T_{rsij,N_j-1} N^T_{trsi,N_j-1} + S^T_{rsiN_j} N^T_{trsiN_j} \qquad \text{for } 1 \leq i \leq N_I$$

$$N^T_{trsij} = \sum_{r'} \boldsymbol{l}_{jrr'} \tilde{N}^T_{tr'sij}$$

$$C^T_{tri} = \sum_{sj} C^T_{trsij}$$

We assume that not all tagged fish that are caught are reported each year, and estimate annual tag reporting rates by region. Let $\boldsymbol{r}_{ri}$ be the proportion of tags recaptured in region r in year i that were reported and i_M be the first year that tag recovery observations are fit in the tag recovery likelihood function (i.e. $i_M = \min_t(i_t + 1)$). Then, $\boldsymbol{r}_{ri} C^T_{tri}$ is the predicted number of tag group t returns in year i and region r.

Modeling the movement of fish between the regions

Define the age specific movement parameters $\boldsymbol{l}_{rr'j}$ by

$$\boldsymbol{l}_{rr'j} = d_{rr'1} \exp\Big(d_{rr'2}\big(-1+2(j-1)/(N_J-1)\big)\Big)$$

where $\boldsymbol{l}_{rr'j}$ determines the amount of movement of age j fish between region r and region r'. The parameters $d_{rr'}$ are only estimated for those regions that are contiguous. However due to the implicit form of the movement equations we have employed it is still possible for fish to move to noncontiguous regions in one time period.

To simplify the discussion of the equations for moving the fish between regions we shall suppress indices reflecting the dependence on age. With this simplification in mind the equations for moving the fish between regions are based on the following system of ordinary differential equations.

$$\frac{dN_r}{dt} = -\left(\sum_{r'\neq r} \boldsymbol{l}_{r'r}\right) N_r + \sum_{r'\neq r} \boldsymbol{l}_{rr'} N_{r'} \qquad \text{for } 1 \le r \le N_R$$

The standard *explicit* finite-difference approximation to this differential equation over a one year period is given by

$$N_r = N'_r - \left(\sum_{r'\neq r} \boldsymbol{l}_{r'r}\right) N'_r + \sum_{r'\neq r} \boldsymbol{l}_{rr'} N'_{r'} \qquad \text{for } 1 \le r \le N_R$$

where the N'_r denote the number of fish at the beginning of the period. The explicit solution has some undesirable properties. If $\sum_{k\neq j} \boldsymbol{l}_{kj} > 1$ then it is possible to get negative solutions to the finite difference equations. To ovecome these difficulties we have employed the *implicit* form of the difference equations.

$$N_r = N'_r - \left(\sum_{r'\neq r} \boldsymbol{l}_{r'r}\right) N_r + \sum_{r'\neq r} \boldsymbol{l}_{rr'} N_{r'} \qquad \text{for } 1 \le r \le N_R$$

This version is called implict because the N_r are implicity defined via the relationship. We use the implicit form because it has better properties for large values of the parameters $\boldsymbol{l}_{rr'}$. To solve the equations for the N_r transpose all the terms involving the N_r to the left hand side of the equation

$$N_r + \left(\sum_{r' \neq r} \boldsymbol{l}_{r'r} \right) N_r - \sum_{r' \neq r} \boldsymbol{l}_{rr'} N_{r'} = N'_r \qquad \text{for } 1 \leq r \leq N_R$$

This is a linear system which can be solved by standard matrix techniques. Let $N = \left(N_1, \ldots, N_{N_R} \right)$ and $N' = \left(N'_1, \ldots, N'_{N_R} \right)$. Let B be the matrix,

$$B = \begin{pmatrix} 1 + \sum_{k \neq 1} \boldsymbol{l}_{k1} & -\boldsymbol{l}_{12} & \cdots & -\boldsymbol{l}_{1N_R} \\ -\boldsymbol{l}_{21} & 1 + \sum_{k \neq 2} \boldsymbol{l}_{k2} & \cdots & -\boldsymbol{l}_{2N_R} \\ \vdots & \vdots & \ddots & \vdots \\ -\boldsymbol{l}_{N_R 1} & -\boldsymbol{l}_{N_R 2} & \cdots & 1 + \sum_{k \neq N_R} \boldsymbol{l}_{kN_R} \end{pmatrix}$$

then

$$N = B^{-1} N'.$$

Recalling that the $\boldsymbol{l}_{rr'}$ actually depend on the age class j**,** the B will be denoted by B_j.

Calculating the initial age structure and population size from stationary conditions

The age-structured model requires $2N_R N_J$ parameters to specify the initial population by sex in the regions. This can be a large number of parameters whose values are often not well determined by the available data. Allowing these parameters to be free (i.e. independent variables) may introduce undesirable transient effects into the model. An alternative approach is to restrict the values of these parameters by imposing stationary conditions on the model.

Assume that the recruitment rate and survival rates have been constant for a long time before the first year for which we have data. The numbers at age will approach a stationary distribution that remains constant over time. Given the survival rates and the movement parameters, it is possible to use the stationary conditions to express the number at age in terms of the recruitment. This reduces the number of free parameters from $2N_R N_J$ to $2N_R$ (the numbers of fish of each sex recruiting to each region). Since we have assumed that the sex ratio at recruitment is 1:1 this is further reduced to N_R parameters.

Let N_j be the N_R dimensional vector of numbers at age (ignoring sex for notational simplicity). Let S_j be the N_R by N_R diagonal matrix of stationary survival rates for age class j fish. Let B_j be the age dependent movement matrix. The stationary conditions are:

$$N_{j+1} = B_j^{-1} S_j N_j \qquad \text{for } 1 < j < N_J - 1$$

$$N_{N_J} = B_{N_{J-1}}^{-1} S_{N_{J-1}} N_{N_{J-1}} + B_{N_J}^{-1} S_{N_J} N_{N_J}$$

Solving for N_{N_J} we get

$$N_{N_J} = \left(I - B_{N_J}^{-1} S_{N_J} \right)^{-1} B_{N_{J-1}}^{-1} S_{N_{J-1}} N_{N_{J-1}}$$

where I is the identity matrix.

For the B.C. sablefish stocks it appears reasonable to assume that recruitment is restricted to the shallow depth regions. Further, we assume that the recruitment for the years prior to the first year for which we have data is proportional to the average relative recruitment for the years when we do have data. The number of parameters required to define the population in the first year is then reduced from N_J to 1. The parameter $\boldsymbol{g}$ is a scaler between the average recruitment rate estimated for the period of the data analysis and the rate for the prior period.

$$N_{rs1} = \boldsymbol{g} \exp(\boldsymbol{h}_r) \overline{R} \qquad \text{where } \boldsymbol{h}_r = \sum_i \boldsymbol{h}_{ri}$$

It is necessary to pick suitable values for the stationary survival rates. Several possible candidates for the survival rates used in the calculations are the unexploited survival rate (death is only from natural mortality), the average survival rate for the first few years (perhaps only the first year) of fishing, or the average annual survival rate over the entire history of the fishery. For the current analyses we assume that the stationary survival rate for each region is equal to the product of a stationary survival rate parameter and the average survival rate estimated for the region over the time-period of the analysis.

Bayesian formulation of the model

In some formulations of age-structured models for fisheries some aspects of the model such as the availability coefficients a_{rsj} are given parametric forms that depend on a (relatively) small number of parameters. If the particular parametric form is inappropriate its use can lead to biased estimates in the model. We prefer to use a nonparametric form where the availabilites are (almost) free parameters. To leave them completely free would lead to an over-parameterized model. Using a Bayesian approach it is possible to put regularizing penalties on the parameters such as penalizing their vectors of second differences (i.e.if we assume a linear trend, then 2nd differences will be zero if trend is linear). The size of the penalty can be varied to produce availability curves of the desired smoothness without the necessity for specifying its parametric form. This approach has been followed here for the availability coefficients as well as the time-dependent tag reporting rates, $\boldsymbol{r}_{ri}$. Computationally these assumptions appear as penalty terms that form a part of the Bayesian prior distribution.

Fitting the model to data and hypothesis testing

Fitting the model to the data observations requires assumptions about the form of the observation error structures. For the fits described in this document, we assume a poisson distribution of the tag return observations, log-normal distributions for the total catch and survey index observations, and a robustified normal distribution (Fournier et. al 1990) for the proportion-at-age observations. The objective function $f = f_1 + f_2$ where f_1 is the frequentist component which is the negative logarithm of the probability density of the observations and f_2, the Bayesian contribution, which is the negative logarithm of the prior probability distribution put on the parameters is

$$
\begin{aligned}
f_1 = & \sum_{tri} \left(\boldsymbol{r}_{ri} C^T_{tri} - \widehat{C}^T_{tri} \ln\left(\boldsymbol{r}_{ri} C^T_{tri} \right) \right) \\
& + \sum_{rsij} 100 \left(p_{rsij} - \widehat{p}_{rsij} \right)^2 \Big/ \left(0.02 + p_{rsij} \right) \\
& + \sum_{ri} 1000 \left(\log\left(1.0 + C_{ri}\right) - \log\left(1.0 + \widehat{C}_{ri}\right) \right)^2
\end{aligned}
$$

$$
\begin{aligned}
f_2 = \ & 10 \sum_{r=1, i=i_M}^{N_R, N_I - 1} \left(\log(\boldsymbol{r}_{ri}) - \log\left(\boldsymbol{r}_{r,i+1}\right) \right)^2 \\
& + \sum_{r=1, j=1}^{N_R, N_I - 2} \left(a_{rsj} - 2a_{rs,j+1} + a_{rs,j+2} \right)^2 \\
& + 10 \left(\log \boldsymbol{r}_{1N_J} \right)^2 \\
& - 0.001 \sum_{r=1, i=1}^{N_R, N_I} \log\left(0.95 \exp\left(-10.0 \boldsymbol{e}^2_{ri}\right) + 0.05 \left(\exp\left(-2.0 \boldsymbol{e}^2_{ri}\right) \right) \right) \\
& + pwt \sum_{i=N_{I-2}}^{N_I} \boldsymbol{h}_{ri}
\end{aligned}
$$

where for simplicity we have indicated that the sums take place over all regions and years. In fact the sum only occurs for those regions and years for which the corresponding data have been gathered. We added the final term in f_2 for the current analysis to stabilize estimates of recruitment for the period 1996-1999, years for which there is no age-composition data. Values of pwt were either 1 (low) or 100 (high).

In the Bayesian context we are employing, this objective function is viewed as the posterior distribution for the parameters given the observed data. Bayesian hypothesis testing or model selection is carried out by using Bayes Factors. We have employed the posterior Bayes factors introduced by Aitken (1991).

Following Aitkin we have employed the maximum values of the objective function for each model hypothesis (the mode of the posterior distribution) for the calculation of posterior Bayes factors. Let $g_1(\boldsymbol{q}_1)$ and $g_2(\boldsymbol{q}_2)$ denote the two posterior distributions corresponding to two different model hypotheses for the two set of parameters $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$ and let $\hat{\boldsymbol{q}}_1$ and $\hat{\boldsymbol{q}}_2$ be the values of those parameters which maximize the posterior distributions. Then the asymptotic form of the posterior Bayes factor (Aitken 1991, pg 116) takes the form of a penalized likelihood ratio

$$2^{d/2}\, g_1\left(\hat{\boldsymbol{q}}_1\right) \Big/ g_2\left(\hat{\boldsymbol{q}}_2\right)$$

where *d* is equal to the number of parameters in model 1 minus the number of parameters in model 2. Following Aitken (1991) we consider a value < 1/1000 for the posterior Bayes factor as providing 'overwhelming' evidence for the validity of model 2 over model 1.

For the 1998 sablefish stock assessment (Haist et al. 1999a), the posterior Bayes factor hypothesis testing procedure, as outlined above, was used to test numerous alternative model structures. The hypotheses that significantly improved the model fits were:

1) a different average recruitment level prior to 1966 than for 1966-1997 (i.e. $g \neq 1$)
2) annual reporting rates different than 1.0, but the same for all regions

3) annual reporting rates in US region different than in B.C. regions
4) initial survival of fish tagged in "deep" regions less than in shallower regions
5) age-dependent movement of sablefish among regions

For the 2000 sablefish stock assessment these hypothesis are components of the *base case* model formulation.

APPENDIX B

Mark-Recapture Model

We implement a mark-recapture model that estimates the survival of tagged fish “cohorts” over time. The total vulnerable population, which shares parameters with the tag “cohorts” (fishing and natural mortality), is also modeled. In addition to fishing and natural mortality, tag “cohorts” are assumed to have additional losses due to tagging mortality (immediately upon tagging) and due to on-going tag shedding (see Appendix D). The actual number of tags released are adjusted for the tagging-induced mortality and for recaptures that occur during the calendar year of tagging. Tag reporting rates, estimated for the 1991-1998 period are incorporated in the analysis. We estimate two additional reporting rates, one for 1980 and one for 1990, and assume there is a linear trend over the time interval. The model is implemented as a Bayesian analysis, therefore requiring specification of priors for all model parameters.

Model Description

The fundamental model parameters, that is, those estimated directly through the analysis, and their prior distributions are shown in the following table:

Fundamental model parameter	Prior	Description
$\ln\left(N_{1980}\right)$	$U\left[0,\infty\right]$	Log of initial population size
$\ln\left(A_t\right), \quad 1981 \le t \le 1999$	$U\left[0,\infty\right]$	Log of new fish entering population in year *t* (recruits, immigration, etc.)
r_{1980}, r_{1990}	$U\left[0.25,0.95\right]$	Reporting rates for 1980 and 1990
$\ln(M)$	$N\left[-2.3,0.2^2\right]$	Log of instantaneous natural mortality rate
$\ln\left(m\right)$	$N\left[-2.15,0.4^2\right]$	Log of tagging mortality rate
$\ln\left(s\right)$	$N\left[-3.307,0.312^2\right]$	Log of instantaneous tag shedding rate
u	$U\left[1.0,1.3\right]$	reporting rate multiplier

Data inputs to the model are:

Model data	Description
$\tilde{C}_t$	Number of fish in catch in year t
$\tilde{T}^G$	Number of tagged fish in release group G
t^G	Index for year that tagging group G is released
$\tilde{R}_t^G$	Number of tag recoveries in year t from release group G
$\tilde{a}^G$	Proportion of tags recovered from release group G with full recovery information (i.e. year of recovery)
$\tilde{r}_t,\ 1991 \le t \le 1999$	Tag reporting rate estimates (Appendix B, Haist et al 1999)
$\tilde{c}_t$	Ratio of number of fish sampled for tags to the number of fish landed (see Appendix C)

The following table shows the relationships that depend on fundamental model parameters and/or data:

Relationships depending on fundamental parameters	description
$T_{t^G+1}^G = \tilde{T}^G \tilde{a}^G (1-m) - \tilde{R}_{t^G}^G / r_{t^G}$	Initial conditions for tag groups
$r_t = r_{1979} + (r_{1990} - r_{1979}) \dfrac{t-1979}{1990-1979}$; $1979 \le t \le 1990$	Linear trend in reporting rate between 1979 and 1990
$r_t = u\,\tilde{r}_t$ for $1991 \le t \le 1999$	Multiplier for 1991-1999 reporting rate estimates
$Z_t = F_t + M$	Total morality for untagged fish
$F_t^T = F_t \tilde{c}_t$	Note: $\tilde{c}_t$ is 1 for all analyses presented here
$Z_t^T = F_t^T + M + s$	Total mortality for tagged fish

We employ the standard Baronov catch equations to describe the relationships among catch, fishing and total mortality, and population size for the untagged population:

$$\tilde{C}_t = \frac{F_t}{Z_t}\left(1 - \exp(-Z_t)\right) N_t$$

$$N_{t+1} = \exp(-Z_t) N_t + A_{t+1}$$

We assume that the total catch ($\tilde{C}_t$) estimates are without error, and solutions for F_t are obtained using an iterative Newton-Raphson algorithm. Tagged fish are assumed to follow similar dynamics to the untagged population, but with additional losses due to tag shedding and no additions after tagging:

$$C_t^G = \frac{F_t^T}{Z_t^T}\left(1-\exp\left(-Z_t^T\right)\right)T_t^G$$

$$T_{t+1}^G = \exp(-Z_t^T)T_t^G$$

The predicted number of tag returns is the product of the number caught and the reporting rate:

$$R_t^G = r_t C_t^G$$

Parameter Estimation

Parameter estimation is conducted using a Bayesian method. Bayes rule, specifies the posterior density for a parameter set, $\boldsymbol{q}$, given data y as

$$p(\boldsymbol{q} \mid y) = \frac{p(\boldsymbol{q})L(y \mid \boldsymbol{q})}{\int_q p(\boldsymbol{q})L(y \mid \boldsymbol{q})}$$

where $p(\boldsymbol{q})$ is the prior probability of $\boldsymbol{q}$ and $L(y \mid \boldsymbol{q})$ is the likelihood pf data y given parameter set $\boldsymbol{q}$. Posterior probability densities can be approximated using Markov chain Monte Carlo (MCMC) algorithms (Gelman 1996). We use the MCMC algorithm implemented in ADModel Builder software (Otter Software). This algorithm initiates the chain at the maximum of the posterior distribution and uses the variance-covariance matrix to determine steps in the chain. The ADMB software requires specification of the negative log of the numerator of the above function (i.e. $-\ln\left(p(\boldsymbol{q})\right) - \ln(L(y \mid \boldsymbol{q})$).

We assume a poisson distribution for the tag recovery observations. Ignoring constant terms, the negative log-likelihood of the data observations given parameter estimates ($\boldsymbol{q}_i$) is

$$\ln\left(L\left(\tilde{R}_t^G \mid \boldsymbol{q}_i\right)\right) = \boldsymbol{f}\sum_G \sum_{t=t^G+1}^{1999} R_t^G - \tilde{R}_t^G \ln\left(R_t^G\right)$$

The parameter $\boldsymbol{f}$ is a dispersion parameter to account for the over-dispersion of the residuals. $\boldsymbol{q}$ was fixed at a value close to its expected value (such that twice the deviance at the maximum of the posterior density was approximately equal to the number of degrees of freedom).

Given the assumptions regarding the distributions of model parameters and ignoring constant terms,

$$-\ln\left(p(\boldsymbol{q})\right) = \frac{\left(\ln(M) - \ln\left(M^P\right)\right)^2}{2\boldsymbol{s}_M^2} + \frac{\left(\ln(m) - \ln\left(m^P\right)\right)^2}{2\boldsymbol{s}_m^2} + \frac{\left(\ln(s) - \ln\left(s^P\right)\right)^2}{2\boldsymbol{s}_s^2}$$

where the values of $\ln\left(M^P\right), \ln\left(m^P\right), \ln\left(s^P\right), \sigma_M^2, \sigma_m^2, \sigma_s^2$ are given in the table specifying the priors. Note that parameters with uniform priors do not appear explicitly in the above function. The AdModel Builder software automatically sets $p(\theta)=0$ for parameters that are outside of specified bounds.

To ensure convergence of the MCMC algorithm, and hence a representative sample from the posterior distribution, chains of 100 million were run. The chains were thinned to 4000 for presentation and stock projections.

For both assessment regions 26 parameters are estimated in fitting the mark-recapture model. The number of tag recovery data points fit in the estimation is 108 for the northern region and 98 for the southern region.

APPENDIX C

Analysis of escape-ring study

At the initiative of industry, a study to evaluate the effect of escape-rings in sablefish traps was undertaken in 1997. The objective of the study was to determine an appropriate escape-ring size that would allow small sablefish to leave the traps with minimal loss of the larger, more valuable sablefish. Four escape-ring sizes, ranging from 3 ½ inch to 4 ½ inch, as well as control traps with no escape-ring were used in the study. Results of a preliminary analysis of the data (Saunders and Surry 1998) led to a fishery regulation in 1999 requiring escape-rings (minimum size 3 ½ inches) in all commercial traps. The preliminary analysis did not attempt to estimate escape-ring retention selectivity or other parameters that would be required for future stock assessments as a result of the escape-rings.

Data

A description of the study design is presented by Saunders and Surry (1998). Briefly, six strings of traps were set in two locations, one inshore and one offshore. The six strings were further stratified to 3 strings set for 24 hours and 3 for 48 hours. Each string contained 11 replicates each of the control trap and traps with the four escape-ring sizes. Five "guard" traps were placed at each end of the string.

Data from the escape-ring study were obtained from Mark Saunders (file "escape97.xls"). The data were checked for errors, corrections made where reasonable, and remaining problem data removed from the data set. I decided that all "reasonable" data should be included in the analysis, including that from malfunctioning traps and traps with fish stuck in the escape-rings. The rationale for this is that we are trying to estimate the performance of escape-ring traps in the fishery, and not all traps will function perfectly in the fishery. However, as fishermen gain experience with the escape-ring traps, it is possible that the traps will function better than they did in the study.

The analyses presented here are limited to evaluating the impact of 3 ½ and 3 7/8 inch escape-rings, as larger size rings have not yet been used in the fishery.

<u>Model for estimating escape-ring selectivity</u>

The objective here is to estimate the length-specific selectivity of escape-ring traps (for a given escape ring size) relative to control traps. The analysis conforms to the original study design, that is 4 blocks encompassing the inshore and offshore strings and the 24 hour and 48 hour soak times.

The initial analysis (Saunders and Surry, 1998) observed that higher catches (in numbers) occurred in the traps with small escape-rings than in the control traps. Therefore a model to estimate selectivity must account for potential differences in the probability that a fish will enter an escape-ring trap versus a control trap. The model used for this analysis follows that proposed by Gagnon (1992), which allows for differences in efficiency (or the relative attraction, in the case of traps) of the two gear types. Unlike Gagnon (1992), the model used here does not allow size-specific relative efficiencies of the two gear types. The study is comprised of an equal number of control traps and escape-ring traps (for a specified escape-ring size), so the data can be aggregated by strata without adjustment for sample size differences.

For a fish to be caught in a trap, it must both enter the trap and be retained in the trap. If these two events are independent, this can be expressed as the product of the probability of entering the trap and the probability of being retained in the trap. Assuming the probability of entering a control trap and the probability of entering an escape-ring trap is independent of fish size, and the probability of being retained in a control trap is one, then, given that a fish of length l is caught and retained in one of the traps, the probability that it is an escape-ring trap ($\boldsymbol{f}_l$) is

$$\boldsymbol{f}_l = \frac{P^e P_l^r}{P^e P_l^r + P^c}$$

where

P^e is the probability that a fish enters an escape-ring trap
P^c is the probability that a fish enters a control trap
P_l^r is the probability that a fish of length l is retained in an escape-ring trap

Defining $\boldsymbol{d}$ as the relative probability of entering a control trap, $\boldsymbol{d} = \frac{P^c}{P^e}$, then,

$$\boldsymbol{f}_l = \frac{P_l^r}{P_l^r + \boldsymbol{d}}$$

Gear selectivity is often modeled using a logistic function. However this function may be restrictive so we use a 3 parameter function that encompasses the logistic:

$$P_l^r = \frac{1}{1 + \exp(\boldsymbol{a} - \boldsymbol{b}l)^{1/g}}$$

Data from the escape-ring comparison experiment consists of two sets of fish sizes S^e and S^c. The set S^e contains the sizes of the n^e fish that were caught by the escape-ring traps and S^c the n^c sizes caught by the control traps. Assuming that the fish behave independently, the log-likelihood of the data is

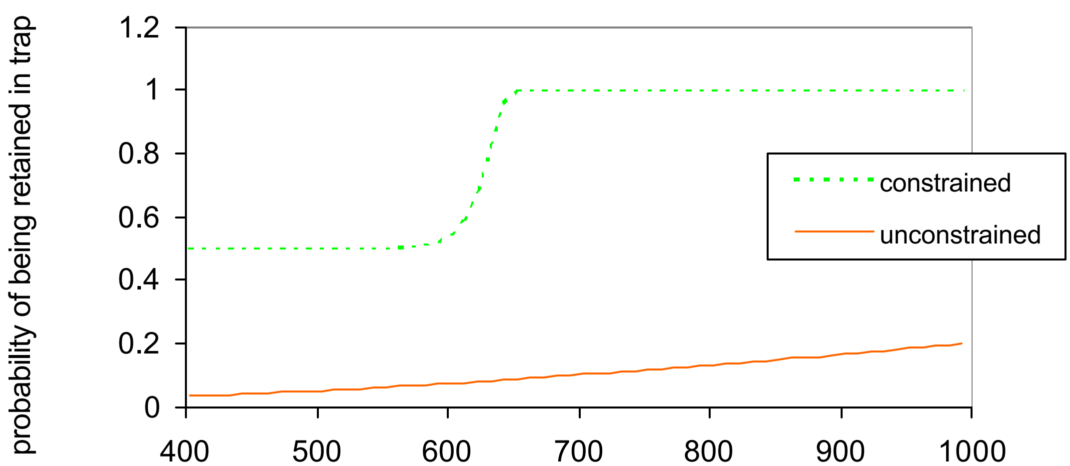
$$l = \sum_{x_i \in S^e} \log(\boldsymbol{f}_l) + \sum_{x_j \in S^c} \log(1 - \boldsymbol{f}_l)$$

The function $\boldsymbol{f}_l$ has four estimable parameters, $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{g}$, and $\boldsymbol{d}$, of which the first three describe the trap retention selectivity. The parameter $\boldsymbol{d}$, a nuisance parameter, accounts for a possible difference in the attraction of fish to escape-ring and control traps. Note that while this is a nuisance parameter from the perspective of estimating escape-ring selectivity, it is a key parameter if attempts are made to standardize commercial CPUE data.

Parameter Estimates

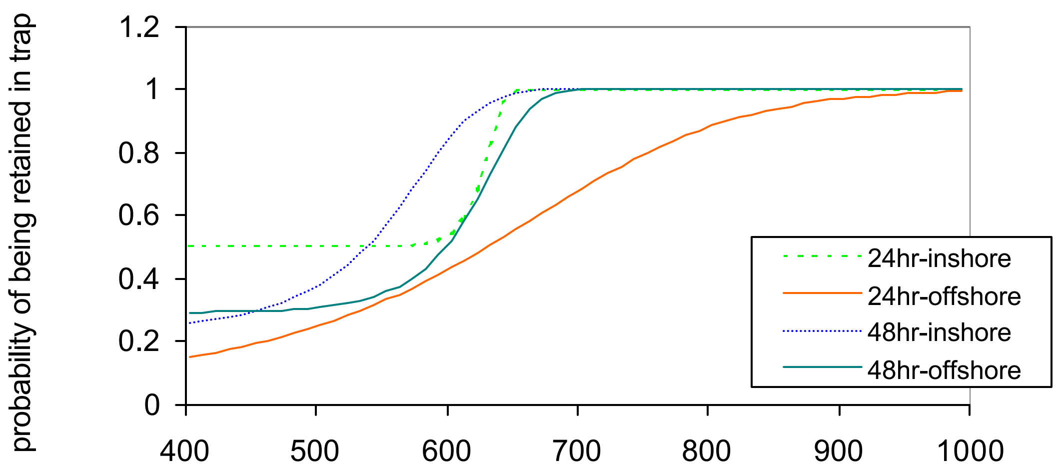
The escape-ring selectivity model was fit to both the 3 ½” and 3 7/8” escape-ring data, for each of the design blocks (inshore 24 hour, inshore 48 hour, offshore 24 hour, offshore 48 hr). In two instances parameter estimation was problematic because of confounding. That is, similar estimates of $\boldsymbol{f}_l$ can be obtained with very different combinations of $\boldsymbol{d}$ and P_l^r. This led to some unrealistic estimates of the size at which 100% of the sablefish were retained. To avoid this problem an Ad Hoc lower bound (0.60) was placed on the parameter specifying the relative probability of entering escape-ring and control traps. The following figure shows the effect of this bound on the analysis of the 3 7/8” escape-ring data for the inshore, 24 hour block.

3 7/8 escape ring - 24 hr inshore



Differences among the retention selectivity curves for the four blocks were not significant at the 0.05 level (likelihood ratio tests comparing fits to aggregated data to fits for individual blocks). If sample sizes had been larger, significant differences would probably have been detected because the retention curves differ substantially among the blocks, as shown in the following figure.

3 7/8 escape ring

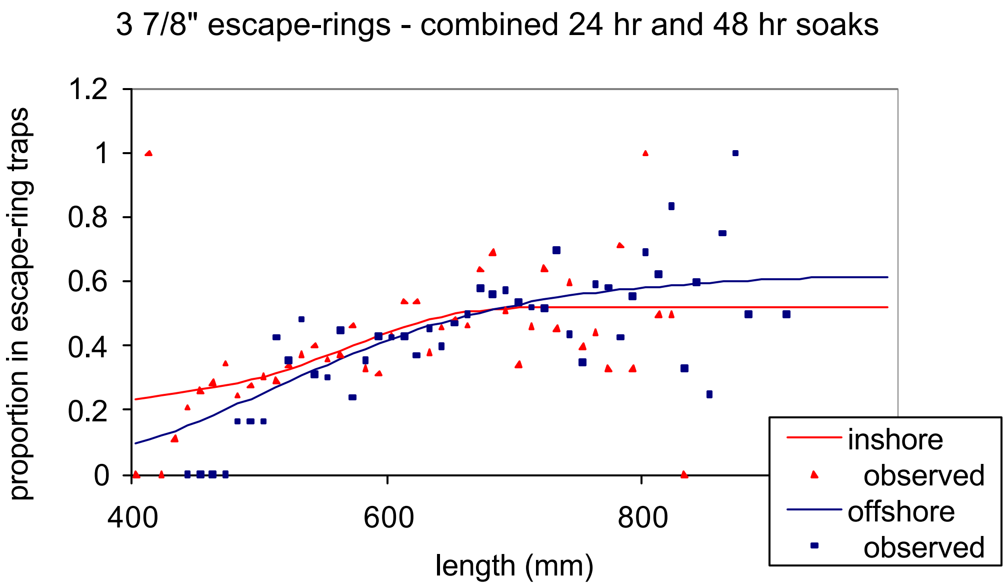


The estimated values for the relative probability of entering control traps (d) for the four survey blocks is shown below:

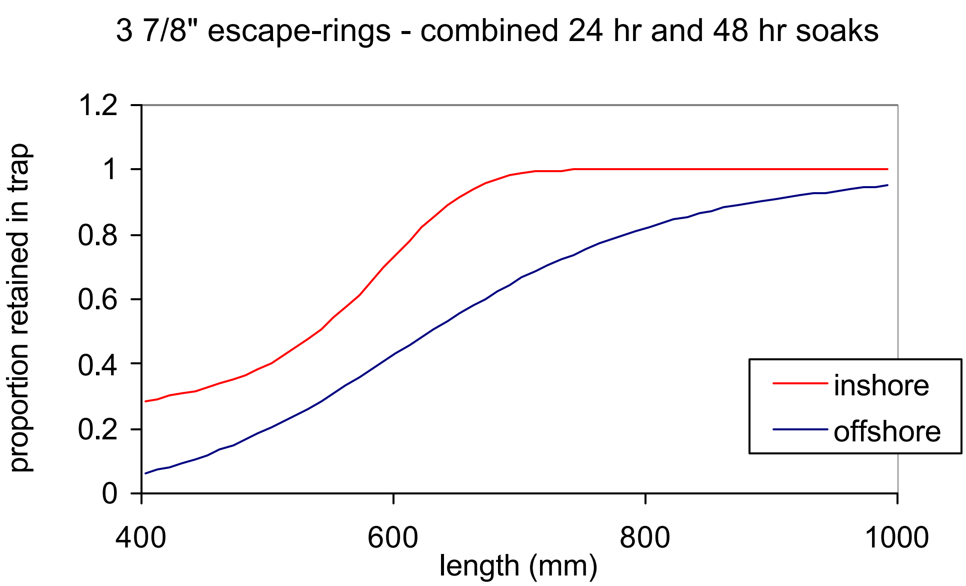
	inshore		offshore	
ring-size	24 hrs	48 hrs	24 hrs	48 hrs
3 7/8"	1.21	0.81	0.60*	0.84
3 ½"	1.00	0.60*	0.70	0.68

* - constrained

During the 1999 sablefish trap fishery the proportion of the landed catch taken with 3 7/8", 3 ¾", and 3 ½" escape-rings was 0.64, 0.19, and 0.16, respectively. Historically, the median soak time for the commercial trap fishery is 36 hours (25th and 75th percentiles at 24 and 51 hours). Therefore the most appropriate retention selectivity model to use for stock assessment purposes is one based on the 3 7/8" escape-ring data from the offshore strings for the combined 24 hour and 48 hour soak times. The following figure shows the fit to the data observations, grouped by 10 mm intervals for presentation purposes, when the 24 hour and 48 hour soak time strings are combined.



The estimated retention selectivity curve is shown in the following figure.



The estimated values for the relative probability of entering control traps when the 24 hour and 48 hour soak time strings are combined are 0.92 and 0.59 for the inshore and the offshore data respectively. These are not constrained solutions.

Impact of escape-rings on sablefish assessment

The primary impact that use of escape-rings in the commercial trap fishery will have on the B.C. sablefish assessment is through their effect on the number of fish that are sampled for tags. Secondarily, they will affect the average weight of landed fish (and hence, the conversion of tonnes landed to number landed) and trap-fishery based CPUE indices.

Estimating the number of fish sampled for tags in the commercial fishery

For the previous stock assessment (Haist et al 1999b) it was assumed that tagged small fish, which would normally be released because of their size, are retained and their tags returned. Therefore the number of fish sampled for tags is greater than the number landed as described below.

$$\textit{number sampled} = \textit{number landed} + \textit{number caught and released}$$

$$\textit{number sampled} = \frac{\textit{tonnes landed}}{\textit{average weight}}\left(1+\frac{\textit{number caught and released}}{\textit{number landed}}\right)$$

$$\frac{\textit{number sampled}}{\textit{tonne landed}} = \frac{1}{\textit{average weight}}\left(1+\frac{\textit{number caught and released}}{\textit{number landed}}\right)$$

For notational ease, the following quantities are defined:

i index for stratum (strata used in the assessment are: northern shallow, northern mid-depth, northern deep, southern shallow, southern mid-depth, southern deep)

N_{il} the number of fish of length l in stratum i (bio-data from sablefish surveys)
w_l the estimated average weight of fish of length l (Table 5.6, Saunders et al 1996, $w_l = 2.4419\left(10^{-9}\right)l^{3.346942}$)
P_l^r the probability that a fish of length l that enters a trap will remain in the trap (as estimated in previous section)
P_l^v the probability that a fish of length l that is caught in a trap is landed (shown below)
$\hat{W}_i$ the average weight of landed fish from stratum i
$\hat{R}_i$ the ratio of the number of fish caught and released to the number of fish caught and landed for stratum i
$\hat{S}_i$ the number of fish sampled for tags per tonne of fish landed in stratum i

Then, as defined above

$$\hat{S}_i = \frac{1}{\hat{W}_i}\left(1 + \hat{R}_i\right)$$

Prior to escape-rings, only the probability of landing small fish affected the estimates $\hat{W}_i$ and $\hat{R}_i$,

$$\hat{W}_i = \frac{\sum_l N_{il} w_l P_l^v}{\sum_l N_{il} P_l^v}$$

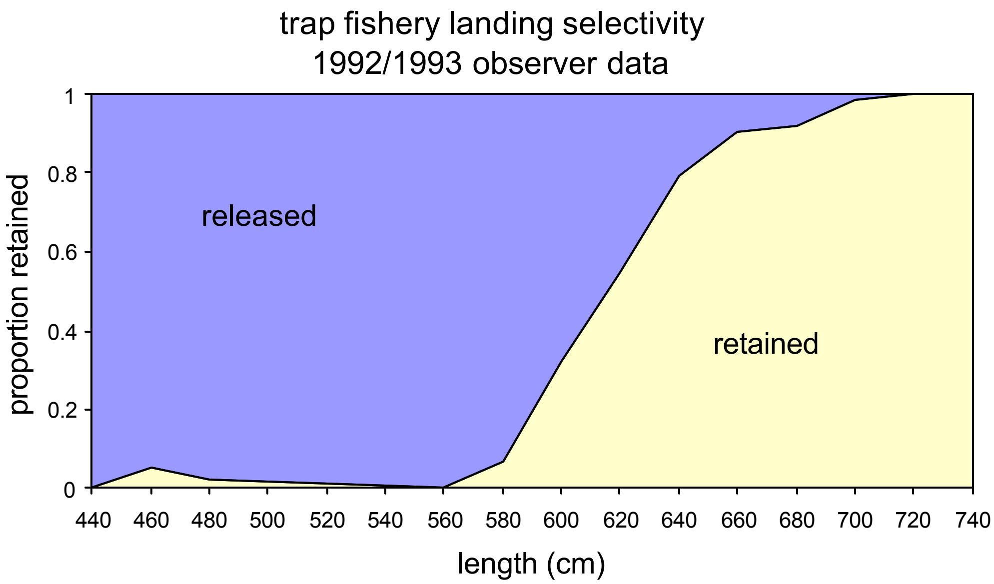
$$\hat{R}_i = \frac{\sum_l N_{il}\left(1 - P_l^v\right)}{\sum_l N_{il} P_l^v}$$

With escape-rings both the probability of retention in the traps and the probability of landing small fish impacts the estimates $\hat{W}_i$ and $\hat{R}_i$,

$$\hat{W}_i = \frac{\sum_l N_{il} w_l P_l^r P_l^v}{\sum_l N_{il} P_l^r P_l^v}$$

$$\hat{R}_i = \frac{\sum_l N_{il}\left(1 - P_l^v\right) P_l^r}{\sum_l N_{il} P_l^r P_l^v}$$

The probability that a fish of length *l* will be landed (rather than released) was estimated from observer data collected in 1992 and 1993 (Haist et al 1999b), and is shown in the following figure.



The following table shows estimates of the parameters $\hat{W}_i$ and $\hat{R}_i$, based on the escape-ring retention curves estimated by fitting data from all offshore strings (i.e. combined 24 and 48 hr soaks), the landing selectivity curve shown above, and strata-specific length frequency data (from surveys 1980-1996)

Stratum	$\hat{W}_i$			$\hat{R}_i$	
	All fish	Landed fish		Landed fish	
		no ring	3 7/8" ring	no ring	3 7/8" ring
south-shallow	3.01	3.81	4.06	0.68	0.36
south-mid	2.68	3.63	3.85	1.02	0.52
south-deep	2.45	3.72	3.95	1.67	0.83
north-shallow	3.75	4.44	4.72	0.38	0.20
north-mid	3.27	4.00	4.22	0.50	0.25
north-deep	3.47	4.03	4.23	0.35	0.18

These results suggest that escape-rings have only a small effect on the average weight of landed fish (approximately a 7% decrease for 3 7/8" escape-ring traps). The impact on the ratio of released to landed fish is much greater with an approximate decrease of 50% for 3 7/8" escape-rings.

The following table shows the impact of the escape-rings on the number of fish landed per tonne, the number of fish sampled per tonne, and the probability that a fish caught in an escape-ring trap will be retained in the trap.

stratum	# fish/tonne landed		# fish sampled/tonne landed		Proportion caught retained in trap
	no ring	3 7/8” ring	no ring	3 7/8” ring	3 7/8” ring
south-shallow	262	246	440	336	0.52
south-mid	275	260	555	396	0.47
south-deep	269	253	719	463	0.43
north-shallow	225	212	310	254	0.60
north-mid	250	237	374	297	0.56
north-deep	248	236	334	279	0.59

The estimated effects of escape-rings shown in the tables above are calculated for the entire vulnerable population in each region. For analyses using the Integrated Model, estimated are required for each sex and age. The probability that a fish of age *j* and sex *s* is retained in a trap is estimated by:

$$r_{isj} = \sum_l P_l^r N_{ilsj} \Big/ \sum_l N_{ilsj}$$

where N_{ilsj} is the number of fish in region *r* of age *j* , sex *j*, and length *l*. The probability that a fish (not tagged) that is caught is landed is:

$$v_{isj} = \sum_l P_l^v N_{ilsj} \Big/ \sum_l N_{ilsj}$$

APPENDIX D

Tag-shedding rate estimation

A total of 654 fish were double-tagged with two Floy anchor tags during the period 1977-1998 (primarily in 1982). Of these releases, 162 were later recaptured. (Note: more fish were double-tagged with one floy and one "suture" tag, but recoveries from these were not available for this analysis). A model is fit to this data to estimate the annual tag-shedding rate.

Let s_1 be the probability that a fish retains a tag immediately after release, and let s_2 be the instantaneous rate of long-term tag-shedding. Then the probability that a fish retains a tag to time t (r_t) is $r_t = s_1 \exp(-s_2 t)$, and the probability that it sheds a tag is $1 - r_t$. Assuming that for double-tagged fish the probability of loosing the first tag is the same as the probability of loosing the second tag, and that these two events are independent, the probabilities of retaining 0, 1, and 2 tags at time t is:

Number of tags	Probability of event
0	$p(0) = (1 - r_t)^2$
1	$p(1) = r_t(1 - r_t)$
2	$p(2) = (r_t)^2$

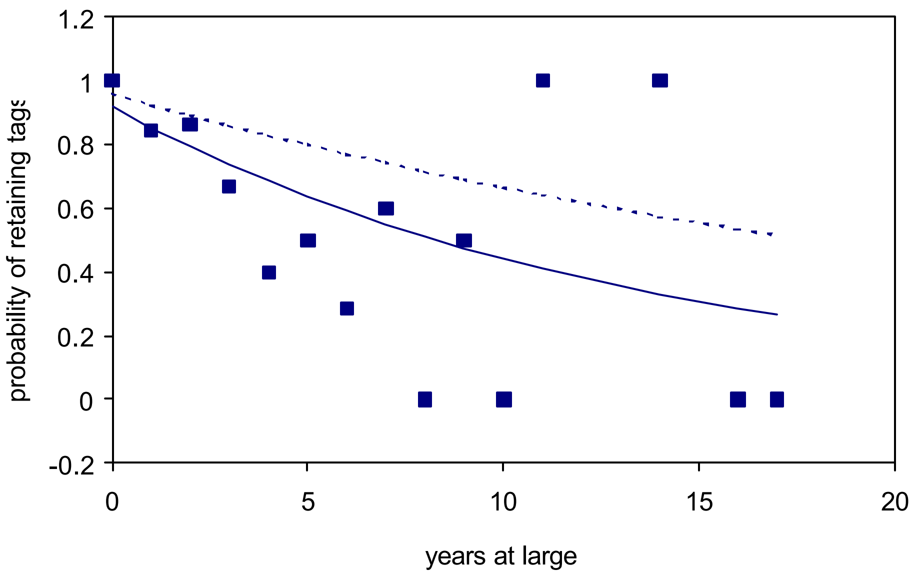
Of course, fish that have shed both tags can not be observed. The data conform to a binomial distribution with one unobserved category. Let N_{1j} equal 1 if the *j*th fish is recaptured with one tag, otherwise 0. Let N_{2j} equal 1 if the *j*th fish is recaptured with two tags, otherwise 0. Then the log-likelihood of the data observations, given parameters s_1 and s_2, is:

$$\ln(L) = \sum_j N_{1j} \ln(p(1)) + N_{2j}(p(2))$$

Maximum-likelihood estimation, fitting the above model to the data from recaptured double-tagged fish yielded the following parameter estimates with associated standard deviations (Delta method) of the estimates.

parameter	MLE	St. dev.
s_1	0.9584	0.0261
s_2	0.0366	0.0117
$\ln(s_2)$	-3.3075	0.3196

The predicted relationship between the probability of retaining two tags (solid line) and the number of years-at-large and the data observations (proportion of double-tagged fish recaptured with two tags), grouped over 1 year intervals for presentation purposes) are shown in the following figure.



The dashed line shows the probability that a single-tagged fish will retain its tag. The total number of recoveries ob double-tagged fish are shown in the following table (grouped by one year intervals).

	Years at large														
	0	1	2	3	4	5	6	7	8	9	10	11	14	16	17
# recovered	6	83	36	6	5	2	7	5	2	4	1	1	2	1	1

Beamish and McFarlane (1988) analyzed the data for double-tagged fish released in B.C. between 1977 and 1982. Their data included the recoveries of fish released with one anchor tag and one suture tag that were not available for this analysis, but did not include double-tagged recoveries past 1985. They assumed that the proportion of fish recaptured with one tag was proportional to the tag loss rate, and estimated tag loss over the first year at 10% and subsequent loss at 2% per year. The values obtained here differ from those obtained by Beamish and McFarlane (1988) (5% initial loss and 3.6% per year), suggesting it would be prudent to analyze the full data set. Analysis of the enlarged data set would also reduce the standard error of the estimates.

Lenarz and Shaw (1997) analyze U.S. recovery data from double-tagged sablefish. In that study each fish was tagged with two Floy anchor tags, one placed below the anterior end and the other the posterior end of the first dorsal fin. They estimated an initial tag retention rate of 0.95, and instantaneous tag shedding rates of 0.030 and 0.069 for the anterior and posterior tags, respectively. Their estimates are similar to those obtained here.