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Sablefish Stock Assessment for 1999 and Recommended Yield Options for 2000 and 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 10-11% from 1991 to 1997, but rose to 14% in 1998.

Analytical stock assessments are conducted using an integrated catch-age mark-recapture model. The stock reconstructions suggest that from 1972 to 1998 the available biomass of sablefish decreased by 50% in northern B.C. and by 48% in southern B.C. The 1998 female spawning stock biomass (SSB) is estimated at 50-67% of the virgin level for the southern B.C. stock, and from 38-48% of the virgin level for the northern B.C. stock. These SSB levels are well above “high risk” levels, hence, there are no short-term conservation concerns for these stocks.

Deterministic stock projections are conducted for the 2000 to 2008 period at three levels of fixed harvest. Stock projections suggest that current removals in the north are not sustainable, and that in the next 8 years considerable reduction in removals from the north may be required if recruitment does not increase. Recent reductions in trawl by-catch and reduced mortality of small sablefish from escape rings may result in increased recruitment.

Résumé

Ce document présente les résultats d’une importante évaluation de la morue charbonnière de la Colombie-Britannique. La principale source de données sur les tendances d’abondance provient du programme de marquage, plus particulièrement du pourcentage d’étiquettes retournées au cours de l’année suivant le marquage. À la grandeur de la côte, ce pourcentage est demeuré stable à 10-11 % de 1991 à 1997 avant de s’accroître à 14 % en 1998.

Les évaluations analytiques des stocks sont réalisées par modèle intégré de captures selon l’âge et de marquage-recapture. Les reconstructions du stock indiquent que, de 1972 à 1998, la biomasse disponible de morue charbonnière a diminué de 50 % dans le nord de la C.-B. et de 48 % dans le sud. La biomasse du stock reproducteur (« SSB ») de 1998 est estimée à de 50 à 67 % de la valeur d’avant exploitation pour le stock du sud de la C.-B. et à 38-48 % pour le stock du nord. Ces valeurs sont nettement supérieures à celles correspondant à un « risque élevé » et il n’y a donc pas lieu de s’inquiéter à court terme de la conservation de ces stocks.

Des prévisions déterministes sont effectuées pour la période allant de 2000 à 2008, à trois niveaux de récolte fixes. Les prévisions indiquent que les prélèvements actuellement effectués dans le nord ne sont pas durables et que, à moins qu’il n’y ait augmentation du recrutement, il pourra s’avérer nécessaire de réduire considérablement les prélèvements au cours des huit prochaines années. Les réductions récentes des prises accidentelles des chalutiers et de la réduction de la mortalité des morues charbonnières de petite taille dans les anneaux de sortie pourraient donner lieu à une augmentation du recrutement.

Introduction

This assessment document is organized in three sections. The first section describes the history of the B.C. sablefish fishery and updates pertinent fisheries statistics. In the second section, analyses of the B.C. sablefish mark-recapture data are presented. The final section describes results of analyses applying an integrated catch-age mark-recapture model to the B.C. sablefish data and presents results of stock projections using this model.

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 5956 t were realised during the 1910's, however landings remained modest from 1920 to 1965, ranging between 210 t and 1895 t (Table 1.1).

Foreign fishery

Exploitation increased in the late 1960's with the arrival of foreign longline fleets from Japan, the U.S., the USSR and the Republic of Korea (Table 1.1). The largest annual catches of sablefish occurred during this period with a peak 7408 t removed in 1975 (Table 1.1; Figure 1.1). Unrestricted foreign fishing ceased in 1977 with declaration of the Canadian 200 mile Economic Exclusive Zone (EEZ). Some foreign fishing was allowed between 1977 and 1980 to utilise yield declared surplus to Canadian domestic fleet needs (Table 1.1).

Domestic fishery

Canadian landings since 1951 have been caught with longline, trawl, and trap gear (Table 1.1). Since 1976, Canadian annual catches have averaged 4062 t and ranged from 830 t in 1978 to 5381 t in 1989 (Table 1.1). Fisheries have been managed under quotas allocated to “T” licence (trawl gear) and “K” licence (longline and trap gear) fleets. Additional sablefish are caught as by-catch in the halibut fishery and there are small allocations to research charters and to First Nations food fisheries (Table 1.2).

The trawl component of the catch has always been the smallest. Since 1977, the percentage has ranged from 5-16% (Table1.1). Since 1981, trawl landings have been limited by a quota allocation based on the historic average catch (8.75% of the commercial TAC).

Longline was the dominant gear type in most years prior to 1973 (Table 1.1). In 1973, the trap fishery began to develop in earnest, thereby reducing the dominance of longline gear. Since then, the percentage of longline-caught fish in the total catch has fluctuated between 6.6% (1980) and 27.2% (1990) (Table 1.1). Over the period 1977-1998 longline landings averaged 550 t/y (Table 1.1).

The trap fishery for sablefish began in 1973 and averaged 449 t over the first six years (Table 1.1). Since 1978, trap landings have ranged between 1480 t (1979) and 4168 t (1993) (Table 1).

Fisheries Management

In 1981 the Department introduced a limited entry (48 licences) "K" tab licence under which fishers could land sablefish using either longlined hooks or traps. The management history, including dates and quotas by year, is presented in Tables 1.2 and 1.3. While the management approach has consistently been based on catch quotas, the method chosen to manage the quotas has varied considerably. During the period 1981-1984 fishing was unrestricted until the quota was taken. The total number of days to take the quota declined from 245 days to 181 days. From 1985-1987 the fishery was split into two openings with provision for a third if quota remained. However, with increasing fleet efficiency and participation in the fishery, it was difficult for managers to predict the duration of the fishery.

In 1988 and 1989, fishers were given their choice of one of five openings. They were allowed to choose an opening they felt to be optimal regarding market conditions and conflicts with other available fisheries (i.e. herring, halibut, etc.). It was however, difficult for DFO to determine the number of days required to take the quota, again because of variable participation and increasing fleet efficiency. As a consequence, total quota overruns increased to 29.8% and 21.6% in 1988 and 1989, respectively (Table 1.2).

In 1990, Individual Vessel Quota's (IVQ) were introduced and remain in effect through 1999. Vessels were allocated proportional quota shares based on historical catch and overall vessel length.

IVQ Fishery

During the period 1990-93, the first three years of Individual Vessel Quota (IVQ) management, the proportion of catch attributed to longline was high (17-27%) but has dropped to below 10 percent over the 1993-98 period. The initial increase was due to large vessels developing longline operations for other groundfish species which included their sablefish quota. In this way the vessels could fish most of the year. The subsequent decline was due to a movement away from the multispecies longline approach in favour of dedicated trap fishing with transferred quota. The transferred quota allows the vessels to fish sablefish most of the year and traps were chosen as the most effective gear.

The impact of IVQ's on the distribution of trap effort was considerable. There was an abrupt shift in trap effort from the south (Major areas 3C, 3D, and 5A) to the north (Major areas 5B and 5E) in 1991 (Figure 1.2 and Figure 1.3) as fishers under the IVQ program were attracted by higher catch rates and larger fish in the north. The percentage of total trap catch taken from the north increased to 84% and 92% in 1991 and 1992, respectively from an average of 55% over the period 1977-1990. In recent years there has been a shift back to the south as the percentage of catch in the north has dropped to 44% in 1998 (Figures 1.2 and Figure 1.3). The shift is due in part to declining CPUE in the north and in part to a direct request to the industry to balance the effort rather than having to implement area-specific quotas.

The sablefish trap fishery extends from approximately 300-1300 m (150-650 fm) although over 85% of the fishing effort has been expended between 500-900 m (250-450 fm) (Fig. 1.4). Additional fishing effort was expended in deeper water from 1979-1983 in both northern and southern waters, and during 1990-1992 in the south, but this deepwater fishing averaged only ~20% of the total fishing effort for those periods. In recent years there has been an increase in shallow effort coastwide and increased deep effort in the south

1.2 Commercial Trap fishery - CPUE

Catch data were obtained from sales slips and landing validation logs. Nominal effort data were captured from logbooks (interviewed effort), accounting for an average of 84% of the total catch between 1979-1992 (Saunders *et al*. 1994). Nominal CPUE for each stock was calculated as the sum of the catch over the sum of the effort. Total fishing effort for each stock was estimated by dividing the nominal CPUE into total catch for the stock.

Because CPUE during the January-March period is generally higher than other periods and this period has been fished during only a small proportion of the years in the data series, we chose the April-December period and the 250-450 fm depth range as that which would provide data most consistently reflecting stock conditions, for the calculation of nominal CPUE. We note a similar conclusion on data segregation by depth for a recent U.S. assessment of the Washington-California sablefish stock (Methot *et al*. 1994).

Nominal CPUE values have been slightly higher in northern waters over the entire time series and CPUE was relatively stable from 1979-1987 in both areas (Fig. 1.5 and Table 1.4). In 1988 and 1989, CPUE increased dramatically in both the north and south (Fig. 1.5). There is considerable evidence, the majority of which is difficult to quantify, which suggests that the period prior to 1988 is not comparable to the years following. Specifically, some combination of the following factors is likely responsible for the increase:

1. The management strategy shifted from fixed to harvester-chosen openings in 1988 (Table 1.3). In this management framework, some vessel masters

(presumably the most efficient) fished on several different vessels for the different openings

2. Hake in combination with squid began to be used as bait in the trap fishery. A bait loading experiment conducted during 1996 (B. Leaman, unpublished data) has confirmed that the combination of hake and squid results in higher catch rates and that CPUE increases linearly with increased weight of hake bait.

3. Fishers have noted that during 1988 and 1989 most were fishing to maximise yield at whatever the cost, given speculation that IVQ's would be awarded on the basis of the vessels landing history. With that in mind some reported reduced high-grading and increased bait loading. Vessel logs were modified in 1995 to capture these data, but are not available for the earlier period.

Since the peak in 1988, CPUE in the north has declined continuously through 1997. Although the comparability of CPUE values over the entire time series is questionable, the continuing decline since 1991 (Figure 1.5), a relatively stable period in the fishery from a management perspective, is a cause for concern. The southern stock CPUE showed a similar rapid increase in 1989 followed by a more rapid decline during 1990 and 1991. A second peak occurred in 1993/94 and the CPUE has declined through 1995 and 1996 and has increased slightly in 1997 and 1998 (Fig 1.5 and Table 1.4).

The introduction of mandatory escape rings in 1999 will disrupt the time series of CPUE again as selectivity of the traps is changed. This will require some standardization if the series is to be continued in the future.

1.3 General Biological Information

<u>Trap surveys</u>

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 1.6). 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.

2. Sablefish Tagging Analysis

Since 1977 over 250,000 sablefish have been tagged as part of ongoing studies by DFO in cooperation with the Pacific Blackcod Fishermen's Association. Table 2.1 shows the annual number of fish tagged by area. This includes all tagged sablefish, including juvenile fish and fish that were tagged in mainland inlets. Tagging methods have been described elsewhere (Murie et al. 1995a and Smith et al. 1996). In short, fish are captured in traps during the annual surveys, and tagged with spaghetti tags.

2.1 Tagging Mortality, Tag Shedding, and Tag Return Rate

We used the same assumptions as Murie et al. (1995b) of tagging mortality of 0.1 and tag shedding of 0.1. These rates are reasonably consistent with other sablefish tagging studies. A tag loss rate of 10% in the first year and 2% in subsequent years was found by Saunders et al. (1990). Heifetz and Fujioka (1991) used a value of 10% tag shedding but do not seem to have assumed any tagging mortality.

An analysis of tag returns per ton of fish landed by vessel was conducted to determine the percentage of tags being returned (Appendix B). The analysis indicates that in the early 1990s many vessels were not returning tags, but that by 1995 all vessels were consistently returning tags. The table below shows the estimated tag return rates on the assumption that the tags per ton of fish landed is proportional to the proportion of tags returned, and the vessels with the highest tags/ton landed have 100% tag returns.

Estimated tag return rate by year:

	Recovery Year						
	91	92	93	94	95	96	97
Tag return rate	29%	39%	37%	53%	76%	74%	75%

Table 2.2 shows the number of tags returned by year of release and year of recovery. The two primary characteristics of these data are the rapid decline in number of tags returned in the first few years after tagging, and the slower rate of decline after the first five years.

2.2 Estimates of Total Mortality Rate

Figure 2.1 shows the number of tags returned as a function of the number of years since release for tags released between 1977 and 1985. By plotting this on a log scale, the slope of the decline is equal to minus the total instantaneous mortality rate (Z). We can see here that there is a much more rapid decline in the first few years after release than in later years. This is seen more clearly in Figure 2.2, where the estimated rate of change between years is plotted [$\log(N_{t+1}/N_t)$]. Again tags released between 1977 and 1985 are included.

The log scale figure shows more clearly the high rate of disappearance in the first five years after release, and then the much lower disappearance rate in later years. The solid lines (Figure 2.2) represent the averages from 1-5 years following release and from 6-20 years following release. Note that this analysis assumes constant exploitation rates, and constant tag return rates, but since we are averaging across many years this will hopefully average out.

2.3 Depth and Area Mixing

Table 2.3 shows the relationship between area of release and area of recovery. There is a slight tendency for fish tagged in middle depths (250-400 f.) to be caught in middle depths more commonly than fish tagged in deeper locations, but clearly there is considerable mixing between deep and middle depths. The fish released in shallow depths are much more likely to be caught in shallow water, and this is presumably because so many of the fish tagged in shallow water were the juveniles in the Hecate Strait tagging.

In addition to significant depth movement there is movement between areas. Table 2.4 shows the proportion of fish tagged in each area that are recovered in other areas. Fish from the north are predominantly recovered in the north, and fish from the south largely in the south. There is significant movement from the north and Hecate Strait to Alaska.

Figure 2.3 shows the gradual movement of fish to Alaska, taking roughly 8 years before the proportion seems to stabilize.

2.5 Analysis of Long Term Returns - Where Do They Come From

The change in disappearance rate from the first five years to later periods suggests that the fish are moving into an area with lower exploitation rate, and then gradually moving back. It could be that fish move into an area that is unfished, such as offshore mid-water, and then gradually move back. The pattern of tag returns from fish tagged in the 1970s and

1980s suggest this might be the case.   The following table shows the number of tags returned from fish released in the 1977-1987 period:

Year of return	Number returned
90	254
91	236
92	246
93	150
94	26
95	6
96	102
97	110
98	113

Note that the number of recoveries has stayed high, except for the low recoveries in 1994 and 1995. There are three possible explanations for this:

- Tag return rates in 1994 and 1995 were poor. The pattern of returns from both B.C. and Alaska is similar and it seems most unlikely that there was some consistency in behavior between B.C. and Alaskan fishermen.

- The data system "lost" tag returns for 1994 and 1995. This is a possibility that needs to be investigated.

- The vulnerability of the fish is determined by environmental factors, and in 1994 and 1995 the fish were very invulnerable. If there is a large population of older fish in a relatively invulnerable location and something in 1994 and 1995 kept these fish away from the area of fishing.

2.6 Short Term Tag Return Rates

We can calculate the percentage of tags returned in each year (correcting for the estimated tag return rate), to look for temporal patterns in tag returns, particularly in the first year after release (Table 2.5). We generally ignore the year of release because the releases are usually done in the fall (except 1996 and 1997 where there were both spring and fall releases). We see that in general 10%-11% of the tags are returned in the year following release. The major exception to this is the 1997 release year, which had unusually high returns in the year of release, and then also high returns in the year following recovery. In part, the high return rate in 1997 results from the spring-release component of the 1997 tag group that would have been been more vulnerable to the 1997 fishery. The increased return of the 1997 release group in 1998 (14.6%) may indicate that the exploitation rate has increased.

2.7 Summary of Tagging Analyses

This exploratory analysis of the tagging data provides the following conclusions:

- Tag disappearance in the first years after release are high (z=0.5) but decline considerably after 5 years (Z=0.2). This is most consistent with the fish moving into a less vulnerable state, either an unfished area, or reduced vulnerability, in the first few years after tagging

- The large number of fish returned from the 1977-1985 releases in the 1990s suggest that the total mortality rate on the stock must have been reasonably low.

- The dramatic change in number of tags returned in 1994 and 1995 suggest that there exists a reserve of long lived fish that may or may not be vulnerable to the fishery, depending upon environmental conditions.

- The long persistence of tags and the other factors discussed above suggest that the total fishing mortality rate on black cod has remained within the target range of 10-15% and could be lower.

3. Integrated Catch-Age Mark-Recapture Analyses

The development of catch-age models for the assessment of B.C. sablefish has 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. For the 1998 sablefish stock assessment a model that integrates catch-age and mark-recapture analysis was developed (Haist et al. 1999). The model is a spatially and sexually disaggregated age-structured model that simultaneously fits to catch, age-composition, and tag recovery data.

There were some inconsistencies in the 1998 stock assessment model fits, obtained with the Integrated Model that suggested the model structure did not capture all the pertinent features of the sablefish population dynamics. The stock abundance trajectories, obtained when fitting to the full tag release data series, 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 (Section 2), the model moved fish to, and accumulated them in, regions of low fishing mortality. These regions were the southern B.C. deep region and the U.S. region.

In this section we describe modifications to the Integrated Model and data structures from last years assessment, present results of stock reconstructions for both a *base case* and for a number of sensitivity runs, and present results of stock projections based on deterministic harvest levels and recruitment levels.

3.1 Integrated Model Structure

A number of modifications have been made to the Integrated Model analyses for the current assessment. 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 those used previously (Haist et al. 1999). Major changes include alternative assumptions regarding the migration process and the inclusion of fishery selectivity parameters.

Migration Structure

The structure of the Integrated Model used for last years assessment explicitly modeled emigration out of B.C., but did not model immigration into B.C waters. The reason for not modeling immigration is that we have no data (i.e. mark-recapture, age-composition, catch) from which to estimate movement parameters. However, if there is significant immigration into B.C. waters that is not accounted for in the model structure, the stock reconstuctions will be biased.

A hypothetical example of this process is shown in Figure 3.1. This example compares the trend over three years in the ratio of tagged to untagged fish in two populations – one with both immigration and emigration and one with only emigration. The example is a simplified version of a real population in that there is no recruitment, natural mortality, or fishing mortality. Given the hypothetical immigration and emigration used in the example, the tagged to untagged ratios in the two populations differ by a factor of two after 3 years. Clearly, a model that ignores immigration can lead to highly biased stock estimates, if there is in fact significant movement into the population.

Given that we do not have data to explicitly estimate immigration of sablefish into B.C. waters, there is an alternative framework for analyzing the tag return data if we adopt the following assumptions:

1) Annually, the number of fish that migrate out of B.C. waters is equal to the number of fish that migrate in.
2) Annual fishing mortality rates and tag reporting rates for Canadian tagged sablefish in the US zone (i.e. for fish that have emigrated out of B.C.) are the same as those in the B.C. zone.

We can then treat US tag recoveries of Canadian tagged sablefish as if they were recovered in B.C., and conduct the analyses allowing only movement among the B.C. regions. However, if the two assumptions are not met exactly, stock abundance estimates will also be biased for analyses conducted with this model/data formulation.

Bias as a result of deviations from the two assumptions will be minimized if tag return data for only the first year following release is used in the fitting procedure. For this time interval, the effects of immigration and emigration on the ratio of tagged to untagged fish in the population will be small relative to the effects over a longer time period. We term analyses conducted using this model/data formulation as the *no-emigration, first-year recoveries* option. This formulation is used in the *base case* assessments because we believe it will be the least biased of the three migration formulations we consider. Sensitivity analyses using the explicit emigration-no immigration formulation (*emigration* runs) and the no-emigration formulation and fitting to all tag recovery data (*no emigration, all recoveries*) are explored.

<u>Trap Fishery Retention Selectivity</u>

Age composition data used in the B. C. sablefish stock assessment is primarily from research surveys. The surveys use commercial fishing gear and are often conducted from commercial fishing vessels. They occur in areas where the fishing fleet operates. Previous catch-age analyses were based on the assumption that the age composition of the fisheries was the same as that of the surveys. In terms of the age composition of fish caught in the fisheries, this is probably not an unreasonable assumption. However, not all fish that are captured are retained and landed. Fisheries regulations mandate a minimum 55cm. size limit, and additionally there is some grading for larger fish due to market demands.

The analyses for the current stock assessment explicitly separate the survey and fishery data. The survey is assumed to sample all available fish and the model is fit to the survey sex- and age-composition data. The commercial fishery is modeled with sex- and age-specific selectivity to account for fish retention. All released fish are assumed to survive. The sex- and age-specific selectivity parameters are not estimated through the analysis, but are fixed quantities as described below. For the commercial fishery, the model is fit only to total catch data.

Discussions with fishermen inform us that most smaller fish that would generally be released due to their size are retained if they are tagged. If this is the case, there is an inconsistency between the model formulation that assumes the age- and sex-specific fishing mortality rates for the population are the same as those for tagged cohorts. The model structure should be revised to account for these different fishing mortality rates, but this was not done for the current assessment. Rather, we use selectivity ogives that are intermediate between those estimated for the retention of caught fish and ones where all available fish are retained.

Data collected by observers in 1992 and 1993, where random samples of both retained and released fish were measured, provide estimates of the proportion of fish retained by length category (Figure 3.2). The data indicate that a significant proportion of fish that are between the 55 cm size limit and 65 cm are released. Rather than using these estimates of fish retention we assume there is knife-edge selection at 55 cm. On the basis of this assumption we estimate sex- and age-specific retention selectivities (proportion retained) from the length/age distribution data from the research surveys. The estimated sex- and age-specific retention selectivities (the data parameters, r_{rsj}, in Appendix 1) are shown in Figure 3.2.

Other Changes

The number of age classes in the analysis is 12 (age 2 through a 13+ group), and the first year for the analysis is 1972. Previously, 15 age-classes were used and the analysis began in 1966. The rationale for this is that preliminary analyses indicated some problems with obtaining local minima solutions. The problem appeared to be related to parameters that affected the initial population size and distribution. Fewer age-classes and fewer years where only catch data was fit in the analysis appear to have resolved the local minima problem.

We assume that there is no mortality (fishing and natural) of tagged fish in the year they are tagged. The rationale for this is that most of the tagging episodes occurred in November so only a small fraction of the year remains after the tags are applied. Note that we do include some spring-release tag data, so the assumption of no fishing and natural mortality in the year of tagging is not completely appropriate.

An option was included in the model code to group tag return data after a specified number of years-at-large. Under this option, the tag return data (returns by year, region, and depth stratum) for each tag cohort is attributed to the aggregate tag cohort after the specified number of years-at-large. For example, if the specified number of years-at-large is 4 and the tag cohort was tagged in 1991, tag cohort specific data is fit for the 1992 through 1995 tag returns. The tag return data for 1996 and later is attributed to the aggregate group, maintaining the information on tag recovery year and region. The primary reason for including this option was to miminize the amount of computer memory required to run the program. This option was only used for the analyses using tag release data from 1979 onward.

An optional penalty function that penalizes for the terminal year tag reporting rate parameter deviating from a value of 1 was added to the objective function. Unlike previous analyses where the value of this parameter was generally close to 1 (Haist et al. 1999, Haist et al. 1998), unrealistically low values were obtained for some of the stock reconstructions.

The tag return data is assumed to be Poisson distributed. Previously, a robust Chi-square measure was used for the tag return data fits. The robust Chi-square objective function leads to predicted tag return numbers that are generally higher than those observed. The Poisson distribution is commonly assumed in fitting mark-recapture data (Hilborn 1990).

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). A seventh region, to accommodate tag returns from the U.S., is modeled for the *emigration* model formulation. Data used in the current stock assessment is similar to that used previously (Haist et al. 1999) with data updated through 1998 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. The anticipated 1999 sablefish catch by region, which is used in the stock projections, is based on the 1999 coastwide quota (4500 t.) and the observed 1999 catch distribution through September.

The age-composition data have been updated to include data from the 1996 research survey. Additionally, depth information was retrieved for commercial catch samples collected between 1991 and 1995, and the age data from these samples have been included in the age-composition summaries (Table 3.2). The commercial fishery data are all from random, ungraded (i.e. caught, not retained) samples.

We do not fit the survey abundance indices (Section 1.3) the current analyses, however the survey indices are compared to model predicted values. Annual relative abundance indices are calculated from survey CPUE (catch in numbers/trap) data for each of the B.C. regions. The mean annual survey CPUE is assumed to index fish density and these estimates are weighted by the relative size of each region (Saunders and McFarlane 1993, Table 5.6) to generate relative abundance estimates by region. The regions for which area measurements were calculated are somewhat different than those used in the current analyses, so the abundance indices may not provide accurate information on the relative abundance by region.

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 analysis consists of the tag releases between 1979 and 1982 that covered a broad geographic area, and those from 1991 through 1997 that followed the systematic design (Table 3.3). Additionally, for the earlier period, release groups were restricted to those that occurred within the general areas utilized by the commercial fishery.

Tag recovery information is available for 18,957 recoveries from the release groups we include in the analysis. For some tag recoveries (34%), the information is incomplete (e.g. recovery year, recovery area, or recovery depth missing). Rather than loose the partial information available for many of these tags, we allocate tags to recovery regions based on the partial information available, and the distribution of recoveries with more complete information. Tags with missing year of recovery were excluded from the analysis (421 recoveries). An additional 201 tags were not included because they had incomplete information and there was no basis on which to allocate them to a recovery stratum (i.e. no recoveries for the release group and recovery year with more complete information).

3.3 Integrated Model Analyses

Numerous fits of the Integrated Model to the B.C. sablefish data have been conducted to explore the stability of results under alternative assumptions. Through this process a model structure that appears to have reasonable properties was developed. In part, this structure relates to assumptions made regarding the biology of sablefish and how this interacts with the fishing process. Additionally, this structure constrains the values of parameters where the available data is uninformative. A number of hypothesis tests to evaluate alternate model assumptions were conducted for the 1998 stock assessment (Haist et al. 1999). The model assumptions that significantly improved the model fits are now considered part of the basic model structure. Features of the basic model structure are summarized in Tables 3.4 and 3.5.

For the current assessment we conducted a number of analyses using alternative model and data formulations. A summary of the model formulations, run number, and some of the key parameter estimates for these analyses is presented in Table 3.6. The analyses include a *base case,* that is, a model and data formulation that we believe provides the least biased parameter estimates. Additional analyses were conducted to investigate sensitivity of results to alternative assumptions. Features of the *base case* assessments (Runs 1.3 and 2.3) are:

- separate northern and southern B.C. analyses
- fit tag release and recovery data from 1991 onward
- no explicit emigration and fit only first year tag returns
- penalty function for terminal year reporting rate parameter deviating from 1.

Sensitivity runs were conducted to explore the following:

- coastwide analyses
- tag release and recovery data from 1979 onward
- explicit emigration
- no explicit emigration and fit tag recoveries for all years
- no penalty function for terminal year reporting rate parameter

Base Case Stock Reconstructions

Stock abundance estimates from the *base case* stock reconstructions (Runs 1.3 and 2.3) are shown in Figure 3.3. For the southern stock, biomass has declined steadily from 1972 through 1998. The northern stock also shows a significant decline in abundance over this period, however stock abundance increased in the mid 1980's due to a period of above average recruitment.

Estimates of availability-at-age suggest that females are fully available to the survey at age 7 in southern B.C. and at age 8 in northern B.C. (Figure 3.3). In southern B.C., 82% of males in the oldest age-classes are estimated as available to the survey and the fishery. This estimate is, of course, dependent on the assumption that females in the oldest age-classes are fully available. In northern B.C., only 23% of males in the oldest age-classes are estimated as available to the survey and the fishery. The low estimates of availability for northern B.C. males raised some concern during the 1998 sablefish stock assessment review. A potential explanation was that the survey did not extend seaward enough to capture the full sablefish distribution, in particular the male distribution. The maximum depth fished in the survey is 1200m and off the west coast of the Queen Charlotte Islands this depth occurs inshore of a poorly charted submarine ridge that runs parallel to the coastline. The few samples taken in similar depths on the seaward side of the ridge tend to be dominated by males. Three sets were conducted during October 1999 in this area and the percent males in the sets were 63%, 47% and 23%. The set with the lowest percent males was in the shallowest of the three sets, consistent with the trends observed elsewhere on the coast.

The estimates of female spawning stock biomass (SSB) are based on the assumption that all available females are reproductively mature. We adopt this assumption because data used to estimate the maturation ogive for B.C. sablefish stocks is from samples of recruited fish, and therefore does not represent population characteristics (Saunders et al. 1996). Because of the higher availability of females, they comprise a higher proportion of the available biomass than males (Figure 3.3).

Exploitation rates are calculated as the ratio of the number of fish in the catch to the total number of fish in the population. The exploitation rates for females have been consistently higher than those for males (Figure 3.3). Exploitation rates for the southern B.C. stock have been erratic over the 1972 through 1998 period, but have been increasing. Exploitation rates for the northern B.C. stock peaked in 1992 and have declined since then as a result of a reduction in effort in this region.

The estimated recruitment for the 1971 through 1993 year-classes is shown in Figure 3.4. Because of large errors in aging sablefish, the estimates of year-class strength will be inaccurate, however the general trends in recruitment trends should be estimated reasonably well. For example, the strong 1977 year-class in southern B.C. is followed by above average recruitment in the following three years. It is possible that a large component of the recruitment attributed to the 1978 through 1980 year-classes is actually from the 1977 year-class. The 1992 and 1993 year-classes are estimated as the smallest in the time series for the southern B.C. stock, and are below average for the northern B.C. stock. However, age-composition data is available only through 1996, so these two year-classes are represented in only 2 and 3 years of age-composition data.

The estimated historic average recruitment levels (pre-1970 year-classes) are higher than the averages estimated for the 1971 through 1993 year-classes for both stocks. However, these parameters will overestimate the true value because they are confounded with the historic fishing mortality rates, which we assume are equal to the average fishing mortality rates estimated for the 1972 through 1998 period.

There is no obvious relationship between recruitment and SSB that can be discerned from the model estimates of these parameters (Figure 3.4).

Sensitivity to Coastwide Analyses

For all model formulations examined, with the exception of the *emigration* formulation, the stock abundance estimates obtained when fitting to data for the entire B.C. coast are similar to the sum of the estimates obtained when separate analyses were conducted for the northern and southern region (Table 3.6, compare Runs 1.x plus 2.x with 3.x). For the *base case* formulation, the coastwide biomass estimates from the separate analyses of the two regions (Runs 1.3 and 2.3) are slightly higher than from the coastwide analysis (Run 3.3) for the initial year (1972), but the biomass estimates converge over the time series (Figure 3.5).

Sensitivity to Tag Release Data from 1979 onward

Analyses based on the longer time series of tag release and recovery data (i.e. 1979 onward rather than 1991 onward) are presented for only the coastwide stock reconstructions. The stock biomass estimates obtained when fitting to the longer and to the shorter tag release series show contradictory trends under the *no-emigration,all tag recoveries* model structure (Figure 3.6, Run 3.1, 4.1). The analysis based on the shorter tag release series indicates a slow decline in stock biomass from 1972 through 1998, whereas the analysis based on the longer tag release series indicates a lower initial biomass that increases slightly in the later years of the analysis.

The stock reconstructions obtained from the *no-emigration,first-year recoveries* formulation are similar for the fits to the shorter and the longer tag release series (Figure 3.6, Run 3.3, 4.3). The stock trajectories are essentially the same, with slightly higher abundance estimates for the fits to the shorter tag release series. It is reassuring that the model formulation that we believe should give the least biased results generates similar abundance estimates for both the longer and the shorter tag data series.

Sensitivity to Migration Assumption

To investigate the sensitivity of analyses to the migration assumption we compare the results of the *base case* analyses to ones that adopt the *base case* parameterization in everything but the migration assumption. The alternative data/model formulations examined are the *emigration* (Runs 1.6, 2.6) and the *no-emigration, all recoveries* (Runs 1.1, 2.1) formulations. Results are compared in terms of observed and predicted model quantities.

The trajectories of available biomass follow similar trends for the three migration assumptions, with all analyses suggesting a decrease in abundance (Figure 3.7). For the southern B.C. stock, the rate of decrease in available biomass is greatest under the *emigration* formulation. For the northern B.C. stock, the e*migration* formulation produces substantially lower estimates of available biomass for the entire time series. The 1998 estimates of available biomass from the *no-emigration, first-year recoveries* formulation are intermediate between the other two estimates for both stocks.

The best agreement between observed and predicted tag returns are obtained from the *emigration* model formulation (Figure 3.7), but for the *no-emigraion,first-year recoveries* formulation we would not expect close agreement after the first year returns because these data are not fit in the model. The *no-emigration* model formulations move substantial quantities of fish into the deep regions, where fishing mortality rates are relatively low (Table 3.6). The helps account for the high attrition rate of tags, but results in an inability to fit the longer-term (4+ years) tag recoveries. The *emigration* formulation moves large quantities of fish out of B.C. waters to account for the observed tag attrition. That movement results in estimates of the biomass of fish that have left B.C. being larger than the biomass of fish that remain in B.C.

The observed survey relative abundance indices and the predicted equivalent quantities from the three migration model formulations are shown in Figure 3.9. None of the analyses predict declines in the relative abundance indices as large as those observed. Perhaps of greater interest is the relative abundance among the depth zones. For the southern B.C. stock, the highest sablefish abundance in the surveys is generally found in the shallow region. The deep region has the next highest abundance estimates, and the lowest relative abundance is observed in the mid-depth zone. This pattern is not predicted by any of the migration formulations, with the *no-emigration, all recoveries* formulation deviating the furthest from the observations. For the northern B.C. stock, the highest relative abundance in the surveys is found in the mid-depth region with slightly higher abundance in the shallow region than in the deep region. Only the *emigration* formulation predicts a similar depth distribution.

The fits between observed and predicted age-composition data are similar for the three migration formulations, so results for only the *base case* (*no-emigration, first-year recoveries*) are presented (Figure 3.10).

Sensitivity to Terminal Year Reporting Rate Penalty Function

The penalty function for terminal year reporting rates deviating from 1 force the estimates of this parameter close to 1, for all analyses. Estimates of the 1998 reporting rates, when this penalty function is removed, are substantially lower than 1 for many of the runs (Table 3.6, Runs x.4, x.5, and x.7). Results for the *base case* model formulation, but removing this assumption, produce estimates of 1998 reporting rates of 0.33 and 0.71 for the southern B.C. (Run 1.5) and the northern B.C. (Run 2.5) stocks, respectively.

The reporting rate parameters are completely confounded with the initial tag survival rate parameter. The analyses presented so far are based on a fixed initial tag survival rate of 0.9. When this value is altered the stock reconstruction produce the same estimates for all parameters except for the reporting rates. This holds for all initial tag survival rate values where the reporting rates estimates are all less than 1.

Reporting rate estimates obtained from the *base case* stock reconstructions, but with initial tag survival rate values of 0.5 and 0.7 are shown in Figure 3.11. For the southern B.C. stock, the estimates of the 1998 reporting rate increases to 0.43 and 0.60 with the initial tag survival rate assumptions of 0.7 and 0.5, respectively. Even at the unrealistically low value for initial tag survival (i.e. 0.5), the 1998 tag reporting rate appears to be underestimated (Section 2).

Summary of Stock Reconstructions and Sensitivity Analyses

The sensitivity analyses show that separate analyses of the southern and the northern B.C. regions produce stock reconstructions that are consistent with those obtained from analyses of the coastwide data. This suggests that the separate stock analyses adopted in our *base case* model formulation does not result in the loss of information, and is therefore appropriate for the stock projections.

The consistency in the stock reconstructions between the fits to the full (1979 onward) tag release data and the truncated (1991 onward) data series, when we use the *no-emigration, first-year recoveries* model formulation, is reassuring. This result provides some support for the *no-emigration, first-year recoveries* model formulation being the least biased because there is no *a priori* reason for differences in the behavior of the earlier tag releases and those released since 1991.

We continue to be uncertain that the current formulation of the Integrated Model captures all the critical components of the sablefish population dynamics. Our *base case* assessment fits only tag recovery data for the first year following release because we believe this will provide the least biased stock reconstructions. However, this results in ignoring a large amount of the tag recovery data. This model formulation does not explain the tag return patterns after the first year-at-large. We believe that the only way the observed tag return patterns can be accounted for is to explicitly model both immigration and emigration.

The estimates of tag reporting rates that we obtain when the terminal year parameter is not constrained are not very satisfactory, in particular for the southern B.C. stock. Analyses in previous years produced more acceptable tag return rate estimates. This difference is largely attributable to the current assumption of no natural or fishing mortality for tag cohorts in the year of tagging. The low reporting rates may be biased as a result of a number of factors including: lower reporting rates or fishing mortality rates on fish that emigrate from B.C.; lower initial tag survival rates (due to tag shedding and tag-induced mortality); and fishing and natural mortality during the year fish are tagged.

3.4 Stock Projections and Yield Options

Specific management objectives have not been explicitly stated for the B.C. sablefish stocks. Certainly an objective that would be a high priority for both the industry and DFO managers is the long-term sustainability of catch levels. Our analyses and discussion of stock projections and yield options focus on the premise that sustainable harvest is the primary management target in determining short-term yield options for B.C. sablefish stocks.

Previous sablefish stock assessments have focussed on target fishing mortality rates, F-based targets. Spawning stock biomass per recruit (SSBR) analyses, conducted for the B.C. sablefish stocks, resulted in target fishing mortality rates of 0.11 to 0.13 (Saunders et al. 1996). These were based on the assumption that appropriate target fishing mortality rates were those that reduced the SSBR to 40 to 45% of the unexploited level, a common reference level for groundfish stocks. We do not propose using F-based reference points at this time because they do not consider current stock status or the sustainability of harvest levels. In the past, determination of the TAC level appears to have been associated with maintaining or adjusting status quo harvest levels, rather than following agreed to fishing mortality rate targets.

We have estimated the annual surplus production of the two sablefish stocks for 1973 through 1995 to provide a basis for determining potential long-term yields. Surplus production is calculated as the change in total stock biomass plus catch ($B_t - B_{t-1} + C_{t-1}$). Both stocks exhibit low surplus production prior to 1979, followed by a period of high production through to 1993, and a decline since then (Figure 3.12). The estimates of average surplus production are 440 t. and 1310 t. for the southern and the northern stocks, respectively. For the 1979 through 1993 period, the average surplus production was 1120 t. for the southern stock and 2130 t. for the northern stock.

We conduct deterministic stock projections for the years 2000 through 2008, for 3 fixed levels of recruitment and 3 harvest levels. The recruitment levels are; 0.75, 1.0, and 1.25 times the average level (the 1971 through 1993 year-class estimates). The harvest levels are; 0.75, 1.0, and 1.25 times the 1999 TAC. We assume that the distribution of the harvest between southern and northern B.C. will be the average observed over the 1990 through 1998 time period (0.378:0.622, south to north). This results in the following harvest levels (thousands of tonnes):

harvest option	Southern B.C.	Northern B.C.	Total
0.75 • current TAC	1275	2100	3375
current TAC	1700	2800	4500
1.25 • current TAC	2125	3500	5625

The stock projections begin with the estimated numbers-at-age (by sex and region) in 1999 for age-classes 5 through 13+ from the *base case* Integrated Model stock reconstructions. The 1999 catch by region is equal to that anticipated for the current year (Table 3.1). Recruitment of age-class 2 fish in 1996 through 2008 is equal to the specified recruitment level. Region-specific estimates of availability and movement parameters from the Integrated Model analysis are used to calculate the available numbers-at-age and annual movement between regions.

The trajectories of available biomass and female spawning stock biomass (SSB), estimated for the three recruitment levels and harvest levels, are shown in Figures 3.13 and 3.14. For the northern stock, all projections that assume an average level of recruitment indicate that available biomass and SSB will decline through to 2008. Assuming a higher level of recruitment, the biomass will be relatively constant if catch levels are reduced to 75% of the current level. For the southern region, available biomass and SSB are projected to remain fairly constant, or decline slightly, at all harvest levels, given average recruitment.

Of primary concern with respect to the long-term sustainability of catches, is that spawning stock biomass levels are maintained at levels that ensure adequate recruitment potential. Appropriate methods for estimating spawning thresholds are ones that ensure sufficient conservation without needlessly restricting the harvest. A commonly adopted "overfishing" threshold in the fisheries literature is 20% of the virgin or unexploited biomass. Recently, a theoretical study by Mace (1994) suggests a more appropriate threshold is the spawning level that corresponds to a 50% reduction in the average recruitment from that expected in the unfished state. Myers et al. (1994) evaluated a number of methods to estimate recruitment overfishing thresholds using stock and recruitment data from 72 finfish populations, and concluded that methods based on the 50% R_{max} criteria provided the most reliable threshold levels. Mace (1994) suggests for stocks with insufficient observations to characterize the stock-recruitment function, default overfishing thresholds of 20% of the virgin, or unexploited spawning stock biomass (SSB_V) are appropriate for stocks believed to have at least average resilience (compensation). A value of 30% SSB_V is suggested for stocks with unknown resilience.

The B.C. sablefish stock and recruitment estimates are not adequate to determine a S-R relationship, so we suggest using the default overfishing thresholds proposed by Mace

(1994). Certainly, SSB levels less than 20% SSB_V should be considered high risk for the sablefish stocks. SSB levels less than 30% SSB_V should be avoided.

We calculate two measures of the virgin SSB levels for the B.C. sablefish stocks. The first is the estimated 1972 SSB level. From 1913 through 1967, coastwide B.C. sablefish catches were generally between 500 and 1500 t. Given our surplus production estimates, it is likely that these catches did not significantly reduce the coastwide biomass of sablefish. In that case, our estimates of 1972 SSB may be reasonable estimates of the average SSB for the virgin populations. The second estimate of virgin SSB is based on a deterministic calculation, assuming the average recruitment estimated for the 1971 through 1993 year-classes represents the average level for the populations in an unexploited state. We do not use the model estimates of historic recruitment (pre-1970 year-classes) to estimate virgin SSB because we believe these parameters are biased due to their confounding with the historic fishing mortality rate parameters. The following table shows the two estimates of virgin SSB (SSB_V), the ratio of current SSB to virgin SSB, and the projected ratios of SSB in 2008 to virgin biomass, for the alternative recruitment and catch levels.

			harvest level								
			0.75 • current			1.0 • current			1.25 • current		
			recruitment level								
SSB_V method	SSB_V	$\frac{SSB_{1999}}{SSB_V}$	low	avg.	high	low	avg.	high	low	avg.	high
Southern B.C.											
1972 estimate	40,800	0.50	0.34	0.46	0.58	0.28	0.40	0.52	0.23	0.34	0.46
avg. recruitment	30,800	0.67	0.45	0.61	0.78	0.36	0.53	0.69	0.31	0.45	0.60
Northern B.C.											
1972 estimate	24,500	0.48	0.17	0.31	0.47	0.09	0.18	0.31	-	0.11	0.19
avg. recruitment	30,500	0.38	0.14	0.25	0.38	0.07	0.15	0.25	-	0.09	0.15

These results suggest that the current harvest level, or a slight increase in harvest, will not reduce the SSB for the southern B.C. stock to high-risk levels. For the northern B.C. stock, results are more pessimistic. Continuation of current harvest levels through 2008 would result in a reduction in SSB to 15-18% of the virgin level, given average recruitment. A reduction in harvest to 75% of the current level yields projections of 2008 SSB that are in the range of acceptable risks for all but the poor recruitment scenario.

4. Conclusions and Recommendations:

- The current stock size in southern B.C. appears to be 50-67% of virgin and in southern B.C. 38-48% of virgin. Neither of these causes us to be concerned about short-term conservation status of the stocks and current catches can be maintained in the next 2-3 years without serious conservation concern.

- However, the projections for the north suggest that current removals in the north are not sustainable, and that in the next 8 years considerable reductions in removals from the north would be required. This conclusion is dependent upon reliable estimation of past recruitments.

- Recent reductions in trawl by-catch and reduced mortality of small sablefish from the escape rings may mean recruitments will be higher than estimated.

- Our principle data source on trends in abundance is the tagging program and in particular the percentage of tags returned in the year following tagging.

- This percentage remained steady at 10-11% from 1991 to 1997, but increased to 14% in 1998.

- If this percentage remains above 11% in 1999 and 2000 it is a strong indication that the overall exploitation rate is rising, and that catches will need to be reduced in the next 2-3 years.

- If the percentage of tags returned in the year following tagging drops back to 10-11% or lower, this is a good indication that the stock size is not declining and current yields are sustainable in the medium term.

- It would be desirable to have an index of abundance such as a systematic survey to gauge trends in abundance to supplement the tagging program, such a program could be developed either by extending the current trap survey program or possibly by developing a longline survey.

- A set of decision rules should be developed to determine how quotas will change in the next few years in relation to changes in tag return percentages (effort adjusted values for both the northern and southern stocks) and any additional survey program that is instituted.

- TAC levels could be determined for a two year period based on the current assessment, given a decision rule that would require an updated assessment next year if tag return rates were higher than a specified level.

5. References

Aitken, M. 1991. Posterior Bayes factors. J. R. Statist. Soc. B, 53, No.1, p.111-142.

Fornier, D.A., J.R. Sibert, J. Majkowski, and J. Hampton. 1990. MULTIFAN a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii)*. Can. J. Fish. Aquat. Sci. 47: 301-317.

Haist, V., M. W. Saunders, R. Hilborn, and M. Maunder. 1998.Sablefish stock assessment for 1997 and recommended yield options for 1998. PSARC Working Paper G97-5.

Haist, V., D. Fournier, and M. W. Saunders. 1999. Reconstruction of B.C. sablefish stocks, 1966-1998, and catch projections for 1999, using an integrated catch-age mark-recapture model with area and depth movement. Canadian Stock Assessment Secretariat Research Document 99/79.

Hilborn, R. 1990. Determination of fish movement patterns from tag recoveries using maximum likelihood estimators. Can. J. Fish. Aquat. Sci. 47:635-643.

Heifetz, J., and J. T. Fujioka. 1991. Movement dynamics of tagged sablefish in the northeastern Pacific. Fisheries Research. 11: 355-374.

Mace, P.M. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. Can. J. Fish. Aquat. Sci. 51:110-122.

McFarlane, G.A. and R. J. Beamish. 1983. Overview of the fishery and management strategy for sablefish (*Anoplopoma fimbria*) off the west coast of Canada. p.13-35. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, AK, Alaska Sea Grant Report 83-3.

Methot, R.D., R. Lauth, F. Shaw, and M Wilkins. 1994. Assessment of the west coast sablefish stock in 1994. *In* Appendices to the status of the Pacific coast Groundfish Fishery through 1994 and recommended acceptable biological catches for 1995. Pacific Fishery Management Council. 2130 SW 5 th Ave. Suite 224 Portland Ore. 97201

Murie, D.J., W. Mitton, M.W. Saunders, and G.A. McFarlane. 1995a. A summary of sablefish tagging and biological studies conducted during 1982-87 by the Pacific Biological Station. Can. Data Rep. Fish Aquat. Sci. 959: 84p.

Murie, D.J., M.W. Saunders, B. M. Leaman, and G.A. McFarlane. 1995b. Exploratory analysis of sablefish abundance based on mark-recapture of fish tagged and released in 1991 and 1992. Report prepared by Biological Sciences Branch, DFO, for Pacific Coast Blackcod Fishermen's Association.

Myers, R.A., A.A. Rosenberg, P.M. Mace, N. Barrowman, and V.R. Restrepo. 1994. In search of thresholds for recruitment overfishing. ICES J. mar. Sci., 51:191-205.

Saunders, M. W., G. A. McFarlane, and R. J. Beamish. 1990. Factors that affect the recapture of tagged sablefish off the west coast of Canada. American Fisheries Society Symposium. 7: 708-713.

Saunders, M.W. and G.A. McFarlane. 1993. Sablefish. In: Leaman, B.M and M. Stocker (Eds.). Groundfish stock assessments for the west coast of Canada in 1002 and recommended yield options for 1993. Can. Tech. Rep. Fish. Aquat. Sci. 1919: 407 p.

Saunders, M. W., G. A. McFarlane, M. Stocker and B. M. Leaman. 1994. Sablefish. pp. 121-153 *In* M. Stocker [Ed.]. Groundfish stock assessments for the west coast of Canada in 1993 and recommended yield options for 1994. Can. Tech. Rep. Fish. Aquat. Sci. 1975: 352p.

Saunders, M. W., B. M. Leaman, V. Haist, R. Hilborn, and G.A. McFarlane. 1996. Sablefish stock assessment for 1996 and recommended yield options for 1997. PSARC Working Paper G96-5.

Smith, M.S., M.W. Saunders, and W.T. Andrews. 1996. Cruise details of sablefish (*Anoplopoma fimbria*) surveys conducted in B.C. waters 1988-1993. Can. Data. Rep. Fish. Aquat. Sci. 976: 129 p.

Table 1.1 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

[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 1.2. Total recorded quotas and catches for the Canadian domestic sablefish and groundfish trawl fisheries from 1979-1999. All weights in metric tonnes. Catches based on dockside monitoring and sales slip data.

	QUOTA			TOTAL			PERCENT OVERAGE		
YEAR	TOTAL	K FLEET	T FLEET	CATCH	K CATCH	T CATCH	TOTAL	K FLEET	T FLEET
1979	2500			2030			-18.8		
1980	3500			3793			8.4		
1981	3500	3190	310	3872			10.6		
1982	3500	3190	310	4046	3628	418	15.6	13.7	34.8
1983	3500	3190	310	4402	4123	279	25.8	29.2	-10.0
1984	3500	3190	310	4009	3824	185	14.5	19.9	-40.3
1985	4000	3650	350	4180	3951	229	4.5	8.2	-34.6
1986	4000	3650	350	4450	3900	550	11.3	6.8	57.1
1987	4100	3740	360	4599	4178	421	12.2	11.7	16.9
1988	4400	4015	385	5711	5075	636	29.8	26.4	65.2
1989	4400	4015	385	5349	4722	627	21.6	17.6	62.9
1990	4670	4260	410	4732	4275	457	1.3	0.4	11.5
1991	5000	4560	440	4917	4532	385	-1.7	-0.6	-12.5
1992	5000	4560	440	5008	4557	451	0.2	-0.1	2.5
1993	5000	4560	440	5087	4546	541	1.7	-0.3	23.0
1994	5000	4521	433	5014	4533	481	0.3	0.3	11.1
1995	4140	3709	356	4136	3709	427	-0.1	0.0	19.9
1996	3600	3169	304	3379	3168	211	-6.1	0.0	-30.6
1997	4500	4023	386	4178	3893	285	-7.2	-3.2	-26.2
1998	4500	4023	386	4492	4164	328	-0.2	3.5	-15.0
1999	4500	6394.6	386						

NOTES: 1981 - 1987 CATCH NUMBERS INCLUDE SABLEFISH BYCATCH IN THE HALIBUT FISHERY

SINCE 1994, 45.36 TONNES REMOVED ANNUALLY FROM TAC FOR NATIVE FOOD REQUIREMENTS

IN 1995, 29.48 TONNES REMOVED FROM TAC FOR SCIENTIFIC RESEARCH

IN 1996, 81.65 TONNES REMOVED FROM TAC FOR SCIENTIFIC RESEARCH

1997 - 1999, 45.36 TONNES REMOVED ANNUALLY FOR SCIENTIFIC RESEARCH

1999 K QUOTA REPRESENTS A 19 MONTH FISHERY AND THEREFORE THE QUOTA IS ADJUSTED ACCORDINGLY

1999 K FISHERY SEASON GOES FROM JANUARY 1, 1999 TO JULY 31, 2000

K QUOTAS UNDER THE IVQ PROGRAM DO NOT INCLUDE UNDERAGE AND OVERAGE CARRYOVER FROM PREVIOUS YEAR

INDIVIDUAL BOAT QUOTAS IN THE K FISHERY SINCE 1990 AND THE T FISHERY SINCE 1997

SINCE 1987 THE T FISHERY SEASON GOES FROM APRIL 1 THROUGH MARCH 31

1997 T FISHERY CATCHES ARE FOR THE PERIOD JANUARY 1, 1987 TO MARCH 31, 1998

DATA COLLECTED FROM VARIOUS SOURCES, INCLUDING MANAGEMENT PLANS, DOCKSIDE MONITORING, AND DFO SALESSLIPS

Table 1.3 History of sablefish "K" fishery including opening and closing dates, fishing days and management regime from 1981-99.

YEAR	OPENING DATE	CLOSING DATE	# DAYS OPEN	TOTAL # DAYS OPEN	MANAGEMENT REGIME
1981	1-Feb	4-Oct	245	245	DERBY FISHERY
1982	1-Feb	22-Aug	202	202	DERBY FISHERY
1983	1-May	26-Sep	148	148	DERBY FISHERY
1984	1-Mar	22-Aug	181	181	DERBY FISHERY
1985	1-Feb	8-Mar	36		DERBY FISHERY
	29-Mar	2-May	36		DERBY FISHERY
	19-Jul	11-Aug	23	95	DERBY FISHERY
1986	17-Mar	21-Apr	35		DERBY FISHERY
	12-May	9-Jun	28	63	DERBY FISHERY
1987	16-Mar	10-Apr	25		DERBY FISHERY
	1-Sep	21-Sep	20	45	DERBY FISHERY
1988	SEVEN 20 DAY FISHING PERIODS BETWEEN MARCH AND SEPT				DERBY FISHERY
1989	EIGHT 14 DAY FISHING PERIODS BETWEEN MARCH AND OCT				DERBY FISHERY
1990	21-Apr	31-Dec	255	255	INDIVIDUAL VESSEL QUOTAS
1991	1-Jan	31-Dec	365	365	INDIVIDUAL VESSEL QUOTAS
1992	1-Jan	31-Dec	365	365	INDIVIDUAL VESSEL QUOTAS
1993	1-Jan	31-Dec	365	365	INDIVIDUAL VESSEL QUOTAS
1994	1-Jan	31-Dec	365	365	INDIVIDUAL VESSEL QUOTAS
1995	1-Jan	31-Dec	365	365	INDIVIDUAL VESSEL QUOTAS
1996	1-Jan	31-Dec	365	365	INDIVIDUAL VESSEL QUOTAS
1997	1-Jan	31-Dec	365	365	INDIVIDUAL VESSEL QUOTAS
1998	1-Jan	31-Dec	365	365	INDIVIDUAL VESSEL QUOTAS
1999	1-Jan	31-Mar-00	455	455	INDIVIDUAL VESSEL QUOTAS

NOTES: IN 1988 EACH "K" VESSEL PERMITTED TO FISH IN ONE OF THE SEVEN SCHEDULED OPENINGS

IN 1989 EACH "K" VESSEL PERMITTED TO FISH IN ONE OF THE EIGHT SCHEDULED OPENINGS

1999 SEASON IS 19 MONTHS LONG AS PART OF TRANSITION TO NEW ANNUAL SEASON COMMENCING AUGUST 1

Table 1.4. Annual nominal sablefish trap fishery CPUE (kg/trap) based on interviewed catch and effort (source 5), by stock from depths between 250-450fm between April and December. Total effort (traps) estimated from total catch for all gears/interviewed CPUE.

	NORTH					**SOUTH**				
Year	Int. catch (kg)	Int. Effort (traps)	CPUE	Total catch (kg)	Total effort (00's of traps)	Int. Catch (kg)	Int. effort (traps)	CPUE	Total catch (kg)	Total effort (00's of traps)
1979	320081	17203	18.61	1173700	630.81	148026	11659	12.70	859500	677
1980	743344	49187	15.11	1602800	1060.57	1005658	64086	15.69	2192300	1397
1981	548690	38732	14.17	2408000	1699.80	482771	40970	11.78	1422600	1207
1982	433084	25980	16.67	2337900	1402.46	267709	19515	13.72	1689300	1231
1983	733488	43775	16.76	2588300	1544.71	534116	39045	13.68	1815200	1327
1984	1079997	79374	13.61	1977400	1453.28	1005659	86520	11.62	1850300	1592
1985	239066	15615	15.31	2047300	1337.22	944859	67625	13.97	2145400	1535
1986	788251	41515	18.99	2265600	1193.22	741974	62146	11.94	2182800	1828
1987	550570	34198	16.10	2044900	1270.16	786995	55680	14.13	2449800	1733
1988	1392628	47398	29.38	2414500	821.77	1146980	64176	17.87	2828100	1582
1989	1297486	47321	27.42	2518800	918.63	1163564	44346	26.24	2861600	1091
1990	1459085	56699	25.73	2675700	1039.75	899274	55668	16.15	2242200	1388
1991	1324713	51720	25.61	3741100	1460.61	110738	11475	9.65	1371100	1421
1992	1464277	69636	21.03	4149400	1973.31	115862	10499	11.04	1026600	930
1993	1320241	75901	17.39	3340300	1920.34	967765	46351	20.88	1743200	835
1994	1459822	84903	17.19	3122500	1816.04	831688	44763	18.58	1953000	1051
1995	716638	49726	14.41	2766000	1919.26	406892	33091	12.30	1284000	1044
1996	490820	41213	11.91	2093370	1758.00	635055	63298	10.03	1282630	1278
1997	942557	92480	10.19	2290730	2248.00	831960	72236	11.52	1887280	1639
1998	860594	72604	11.85	1861010	1570.00	1386730	115536	12.00	2631000	2192

Table 2.1. Number of black cod tagged in different areas by year.

Year	Hecate	North	South	Seamounts	Total
77		5,159	5,505		10,664
78		6,554	4,342		10,896
79	25,537	6,621	9,112		41,270
80	18,634	6,218	5,217		30,069
81	12,306	10,430			22,736
82		3,604	3,436		7,040
83		4,002	4,023		8,025
84	90	9,061	1,579		10,730
85		3,025	5,302		8,327
87			1,101	616	1,717
91		958	1,489		2,447
92		1,308	2,276		3,584
93		2,487	4,531		7,018
94	3,435	1,622	1,982		7,039
95	3,198	7,564	5,144		15,906
96	3,897	11,763	12,616		28,276
97	3,144	6,555	9,936		19,635
98	6,009	5,058	10,897		21,964
Total	76,250	91,989	88,488	616	257,343

Table 2.2. Number of tags returned in each year (columns) by year of tag release (rows)

	Recovery Year																						
	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	Grand Total
77	138	631	267	200	131	73	47	41	27	19	8	12	6	6	9	7	8	1	1	2	9	5	1649
78		221	319	286	128	51	43	30	9	8	5	9	11	5	3	4	2	1			2	2	1139
79			833	1387	617	411	206	169	169	224	64	89	57	35	32	42	26	7	3	21	22	31	4461
80				1080	979	646	388	313	103	113	49	60	73	48	44	33	32	6	1	25	19	14	4030
81					273	583	343	188	99	97	46	53	53	52	43	43	27	4		25	13	16	1960
82							665	357	91	61	18	32	39	24	13	27	14	1		7	11	6	1370
83								108	39	55	27	19	18	11	6	5	6	1		3	5	1	304
84								255	167	165	57	38	26	26	48	38	10	2		12	13	16	875
85									114	348	71	64	44	39	31	44	25	3	1	6	15	21	835
87											6	26	21	8	7	3				1	1	1	74
91															16	100	48	39	29	17	17	15	283
92																13	122	97	64	42	29	43	416
93																	3	423	218	70	89	89	917
94																		13	412	205	227	208	1091
95																			85	1273	913	571	2943
96																				438	2127	1288	4009
97																					1207	2177	3579
98																						310	356

Table 2.3 Number of tags recovered in depth classes for each depth of release

Release Location	Recovery Region		
	Deep >400 f.	Middle 250-400 f.	Shallow <250 f.
deep	0.33	0.55	0.11
middle	0.20	0.66	0.15
shallow	0.12	0.49	0.40

Table 2.4 Percentage of tags recovered in different areas for each area of release.

	Recovery Area							
Release Area	Hecate	North	SeaMt	South	USNth	USSth	unkn	Grand Total
Hecate	0.39	0.24	0.00	0.08	0.10	0.01	0.18	1.00
North	0.02	0.69	0.00	0.07	0.10	0.01	0.10	1.00
SeaMt	0.00	0.06	0.47	0.28	0.15	0.00	0.04	1.00
South	0.00	0.04	0.00	0.79	0.02	0.03	0.10	1.00

Table 2.5 Proportion of tags returned each year (corrected for the estimated tag return rate) by year of release.

		Year of recovery							
Tagging year	# Tagged	1991	1992	1993	1994	1995	1996	1997	1998
91	2447	0.023	0.104	0.052	0.030	0.016	0.009	0.009	0.007
92	3584		0.009	0.090	0.051	0.024	0.016	0.011	0.011
93	7018			0.001	0.113	0.041	0.013	0.017	0.015
94	3604				0.006	0.111	0.036	0.026	0.026
95	12708					0.008	0.112	0.076	0.042
96	24379						0.024	0.105	0.057
97	16491							0.094	0.146
98	15955								0.025

Table 3.1. B.C. sablefish catch by region by region, as used in the Integrated Model analyses.

year	annual sablefish landings (tonnes) by region						
	SS	SM	SD	NS	NM	ND	total
72	2454	294	2	2240	915	3	5908
73	815	372	96	1667	930	107	3987
74	1931	443	45	1573	740	47	4779
75	2774	460	14	2683	1364	118	7412
76	2406	397	15	2894	1312	72	7096
77	2162	276	20	1460	653	41	4612
78	1676	319	65	1037	670	107	3875
79	1913	424	111	724	922	287	4379
80	525	1297	371	410	847	346	3795
81	587	619	216	777	968	663	3830
82	699	686	304	516	1165	657	4028
83	761	620	433	453	1168	968	4404
84	717	885	248	444	954	579	3828
85	781	1103	262	528	1193	327	4193
86	1085	886	212	773	1029	464	4448
87	1163	1075	212	683	893	558	4584
88	1870	768	190	610	1225	819	5483
89	1370	1051	440	787	1163	681	5493
90	1220	917	183	1368	1097	329	5113
91	758	500	111	1249	2237	614	5469
92	666	253	98	985	2485	885	5373
93	601	969	197	599	1774	970	5109
94	692	1101	187	808	1558	797	5143
95	525	901	444	443	1116	747	4176
96	585	699	50	271	1447	372	3424
97	764	732	318	297	1682	293	4087
98	1046	1201	374	603	1095	140	4458
99[1]	516	592	185	1052	1911	244	4500

[1] anticipated catch for 1999

SS is southern shallow region
SM is southern mid-depth region
SD is southern deep region
NS is northern shallow region
NM is northern mid-depth region
ND is northern deep region

Table 3.2 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
1977	0 (0)	0 (0)	0 (0)	49 (1)	0 (0)	0 (0)
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 The number of tagged fish releases used in the Integrated Model analyses, by region and year.

	southern B.C.			northern B.C.		
year	shallow	mid-depth	deep	shallow	mid-depth	deep
79	302	7619	1191	34	6339	248
80	128	4763	326	227	3815	2176
81	0	0	0	1370	8514	546
82	1805	1208	0	524	2484	0
91	0	526	963	0	555	403
92	326	1030	920	45	755	508
93	530	2044	1957	170	1552	765
94	605	618	759	155	733	734
95	1923	2257	964	213	7094	257
96	1827	10477	312	147	11340	276
97	1825	7838	273	363	5803	389

Table 3.4 Assumptions employed in the Integrated Model analyses of B.C. sablefish data.

- 12 age-classes (age 2 to 13+)
- recruitment only to the shallow regions
- common catchability (q) for the two sexes
- common availability parameters among 3 southern regions
- common availability parameters among 3 northern regions and U.S. region
- availability for age 12 equal to that for age 13+
- availability fixed at 1 for age 13+ female fish
- natural mortality equal to 0.08
- fishing mortality in US region constrained to 0.08 for all years
- initial tag survival rate of 0.90 for all shallow and mid-depth regions, estimated for the deep regions
- different average recruitment level prior to 1972 than for 1972-1998
- annual reporting rates different that 1, but common across the B.C. regions
- different annual reporting rates in the U.S. region than in B.C.
- age-dependent movement
- pre-1972 fishing mortality rate equal to 1972-1998 average fishing mortality rate for each region

Table 3.5 Direct estimation of movement parameters is restricted to those regions that share common borders. These are noted with a "1" in the table below. For analyses that do not include all regions the relevant lines and columns are removed.

	to						
from	SS	SM	SD	NS	NM	ND	US
SS		1		1			1
SM	1		1		1		1
SD		1				1	1
NS	1				1		1
NM		1		1		1	1
ND			1		1		1
US	1	1	1	1	1	1	

Table 3.6. Estimate of stock abundance and 1998 reporting rates from the Integrated Model fits to B.C. sablefish data for alternative model/data formulations. Results are from fits assuming a Poisson distribution for tag return data; abundance estimates are also shown from fits assuming the robust Chi-square distribution (chi-square) for tag return data.

model/data structure						total abundance		1998 abundance by region						1998 rep. rate	tot. abund. (chi-square)	
								northern B.C.			southern B.C.					
Run	Reg.	mig.	a/s	tags	pen	1966	1998	sh	mid	dp	sh	mid	dp		1966	1998
1.1	S	N-A	a	91	Y	80	40	12.4	2.7	24.6				0.98	64	34
1.2	S	N-A	s	91	Y	67	47	13.1	3.1	30.6				0.97	33	36
1.3	S	N-1	a	91	Y	60	31	13.2	2.3	15.8				0.99	47	27
1.4	S	N-A	a	91	N	34	9	3.3	1.5	4.0				0.29	30	7
1.5	S	N-1	a	91	N	37	11	4.6	1.1	5.0				0.33	34	9
1.6	S	E-A	a	91	Y	95	14	8.4	3.4	2.5				0.99	81	14
1.7	S	E-A	a	91	N	62	12	6.7	2.9	2.2				0.76	61	13
2.1	N	N-A	a	91	Y	38	24				5.0	2.1	17.0	0.97	34	19
2.2	N	N-A	s	91	Y	33	24				5.2	2.4	16.3	0.97	28	16
2.3	N	N-1	a	91	Y	31	16				5.0	1.8	8.9	0.99	31	15
2.4	N	N-A	a	91	N	26	10				2.5	1.4	6.0	0.47	25	10
2.5	N	N-1	a	91	N	28	11				3.5	1.5	4.0	0.71	28	11
2.6	N	E-A	a	91	Y	9	7				2.6	3.2	1.1	1.00	10	6
2.7	N	E-A	a	91	N	9	6				2.1	2.8	1.0	0.75	10	4
3.1	C	N-A	a	91	Y	106	66	12.1	2.1	22.8	5.9	2.2	20.7	0.96	88	50
3.2	C	N-A	s	91	Y	93	74	12.4	2.4	27.4	6.6	2.5	22.2	0.96	71	48
3.3	C	N-1	a	91	Y	82	48	13.2	1.0	13.3	6.6	1.9	11.7	0.99	73	42
3.4	C	N-A	a	91	N	60	23	4.6	1.5	7.4	2.5	1.3	5.8	0.40	60	20
3.5	C	N-1	a	91	N	63	22	5.6	1.0	6.2	3.0	1.3	5.0	0.47	58	30
3.6	C	E-A	a	91	Y	46	34	7.5	2.4	16.3	2.2	3.5	2.2	0.99	58	32
3.7	C	E-A	a	91	N	37	20	4.6	1.8	8.2	1.5	2.6	1.5	0.55	47	20
4.1	C	N-A	a	79	Y	30	41	9.3	2.3	10.7	5.8	3.5	9.5	0.87	25	31
4.3	C	N-1	a	79	Y	68	43	13.8	1.0	9.5	7.8	2.1	9.1	0.99	55	37
4.4	C	N-A	a	79	N	25	18	4.3	1.2	4.5	2.4	1.9	3.7	0.39	24	15
4.5	C	N-1	a	79	N	64	40	12.7	1.0	8.6	7.1	2.0	8.1	0.90	52	32
4.6	C	E-A	a	79	Y	25	21	9.0	3.0	1.2	3.1	3.6	1.2	1.00	25	21
4.7	C	E-A	a	79	N	24	20	8.5	2.9	1.1	3.0	3.4	1.2	0.91	25	21

Codes for model/data structure:
Run – run number
R – region
- N for northern B.C.
- S for southern B.C.
- C for coastwide

mig. – form of emigration assumptions
- E-A for emigration, fit tag returns for all years
- N-1 for no emigration, fit only first year tag returns
- N-A for emigration, fit tag returns for all years

a/s – age- or sex-specific movement
- a for age-specific movement, fit tag recovery data without sex information
- s for sex-specific movement, fit tag recovery data with sex information

tags – first year of tag release data fit in model
pen – if Y then penalty weight for tag reporting rate in final year deviating from 1.

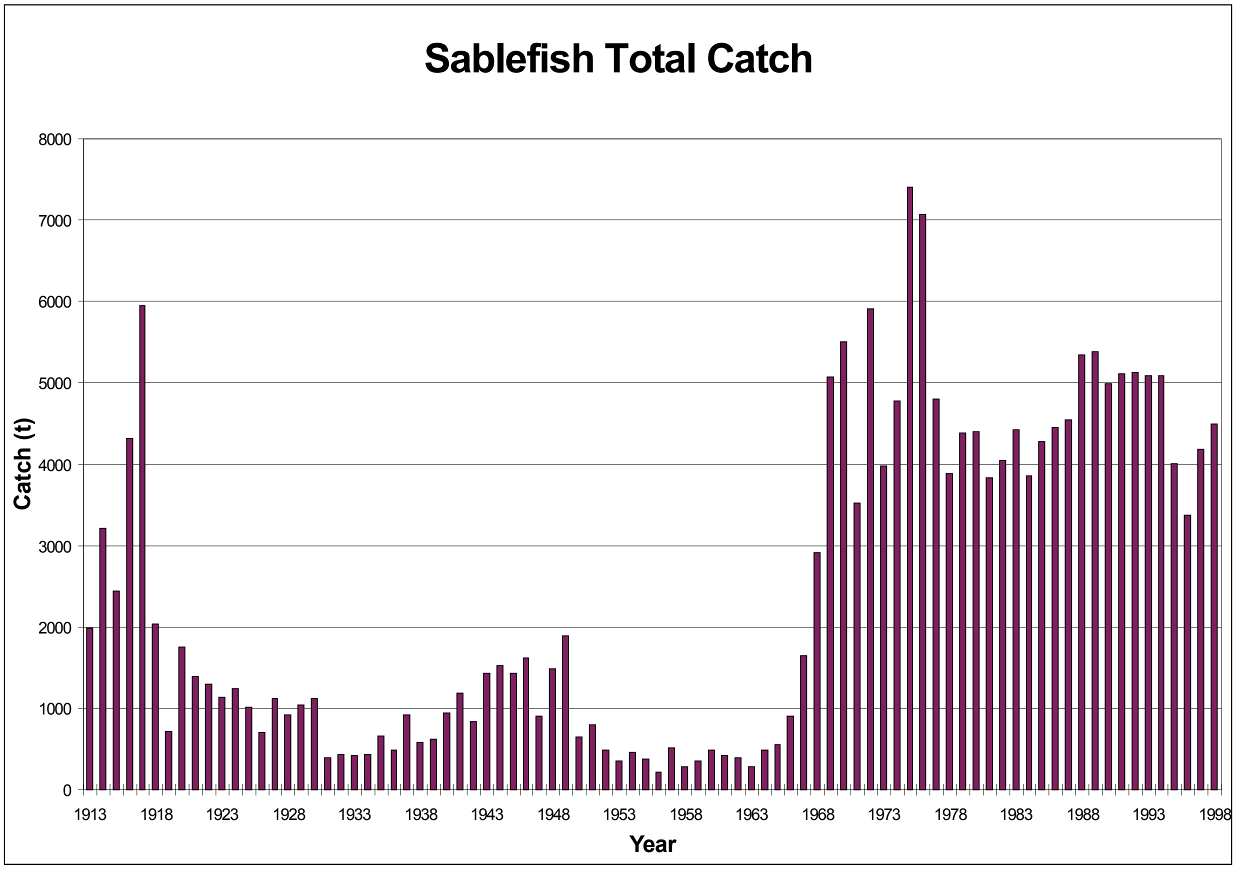


Figure 1.1. All nation catch of sablefish in the Canadian zone by gear, by year from 1919-98.

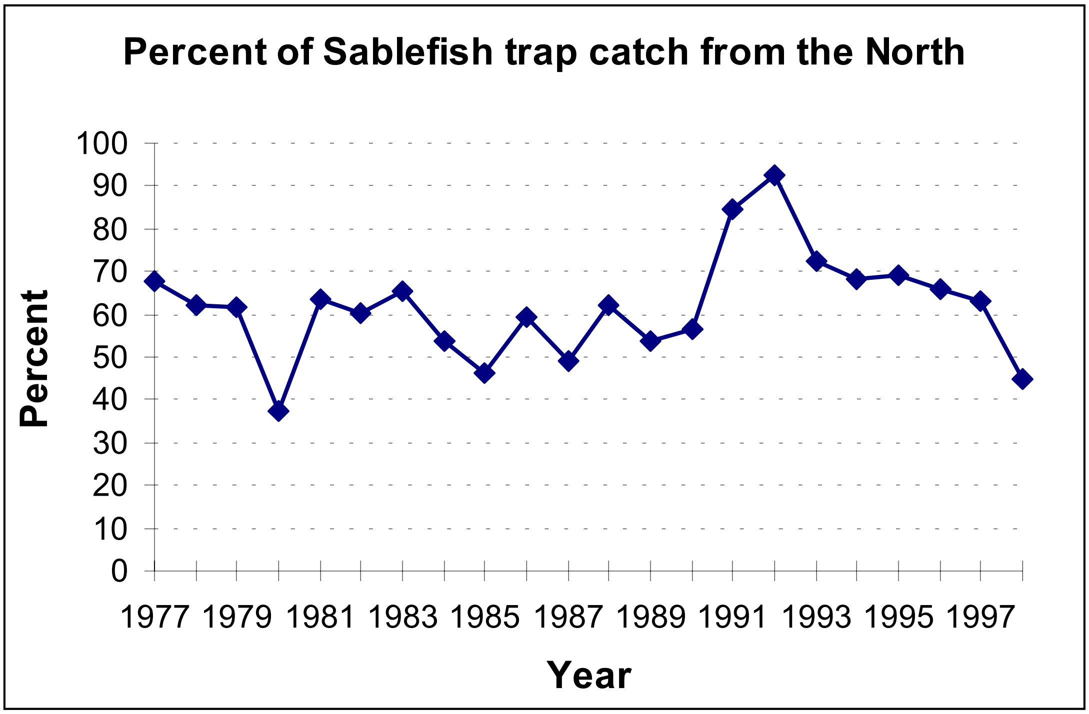


Figure 1.2 Percent of sablefish trap catch in the northern area, by year.

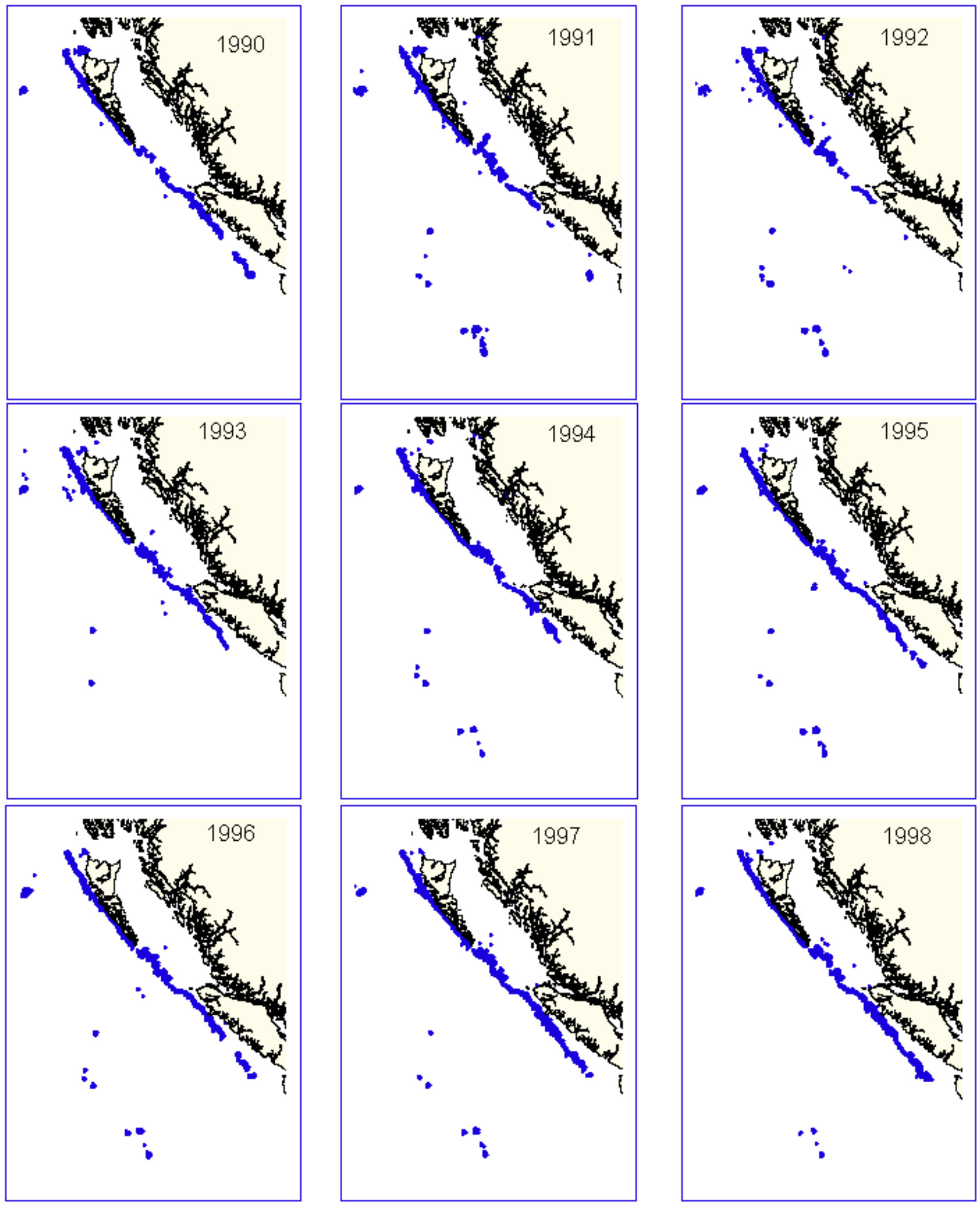
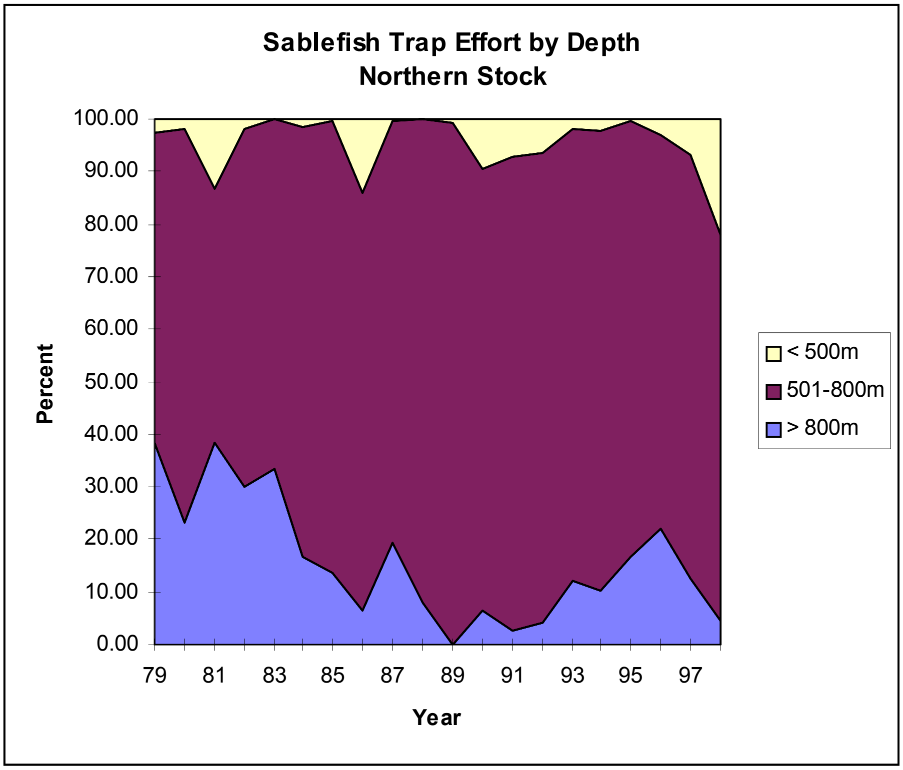


Figure 1.3 Distribution of sablefish trap fishing effort from 1990-98.



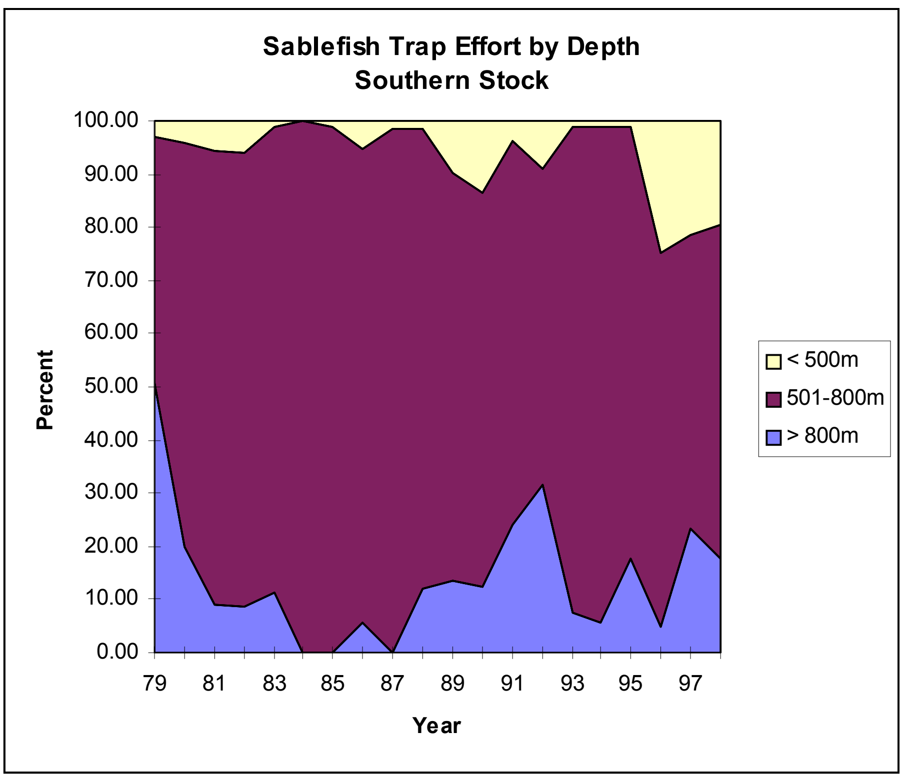


Figure 1.4. Distribution of sablefish trap effort by depth interval and stock from 1979-98.

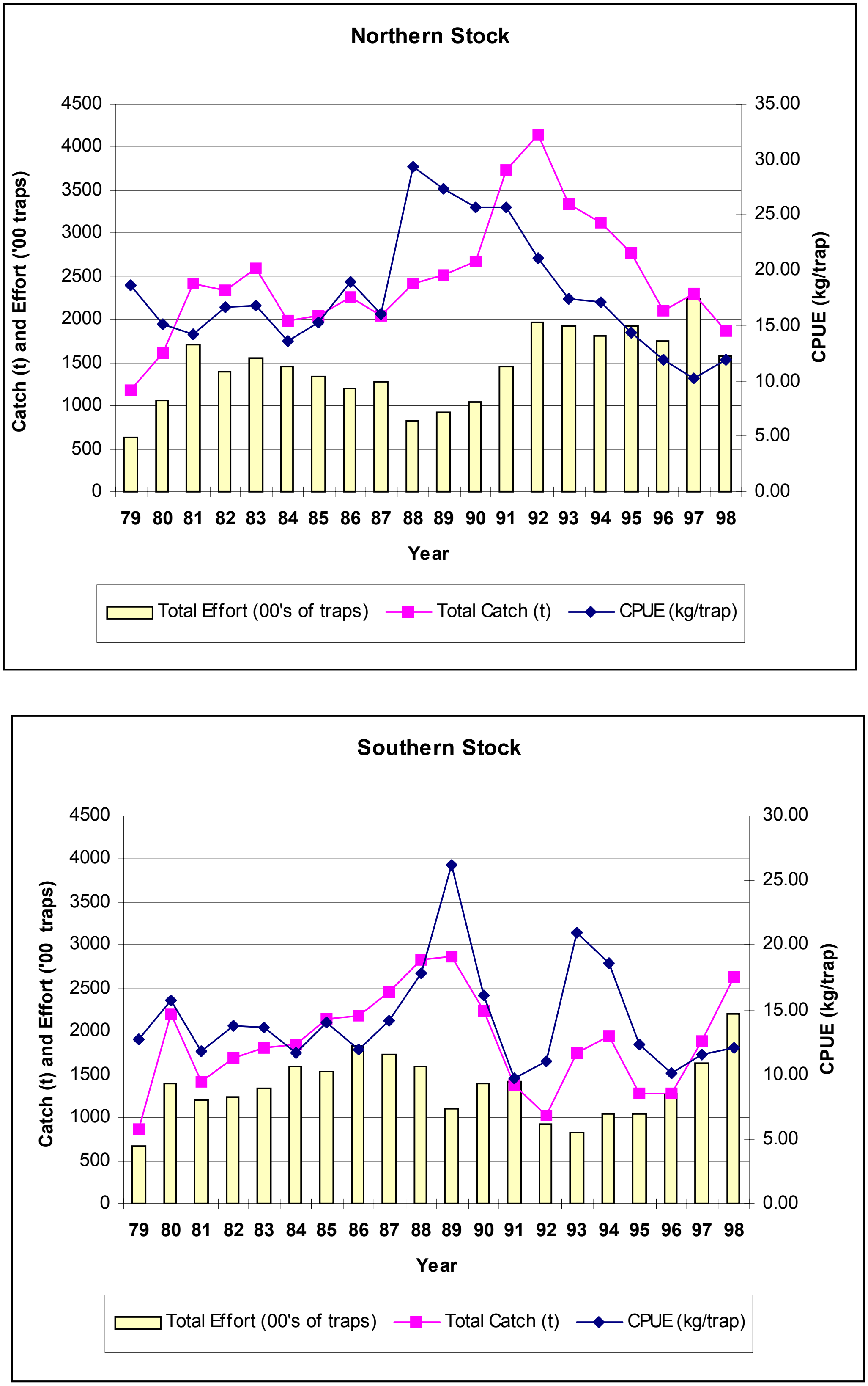


Figure 1.5 Sablefish trap fishery mean CPUE, effort and catch, by stock and year.

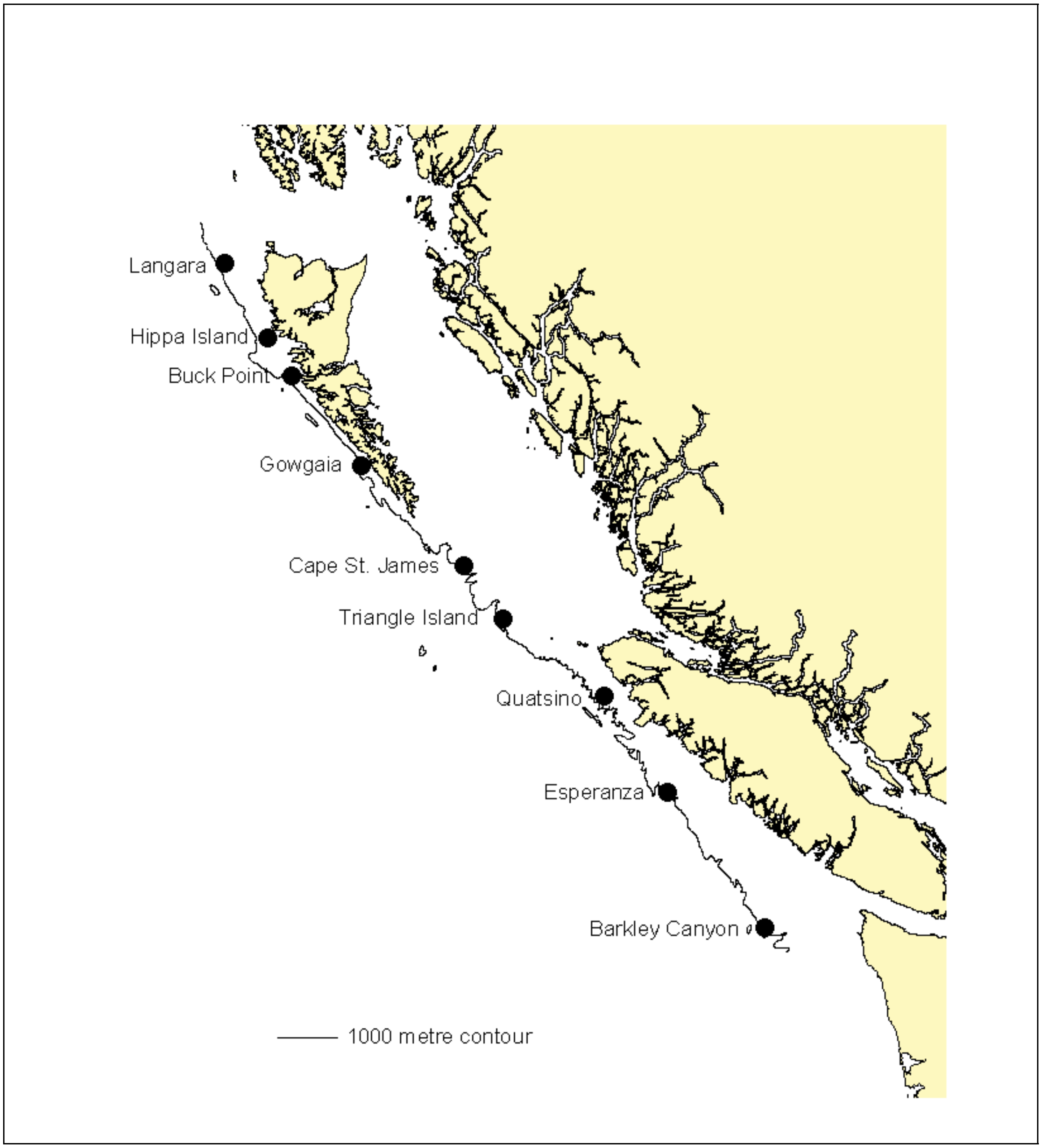


Figure 1.6 Sablefish survey sites off the west coast of Canada.

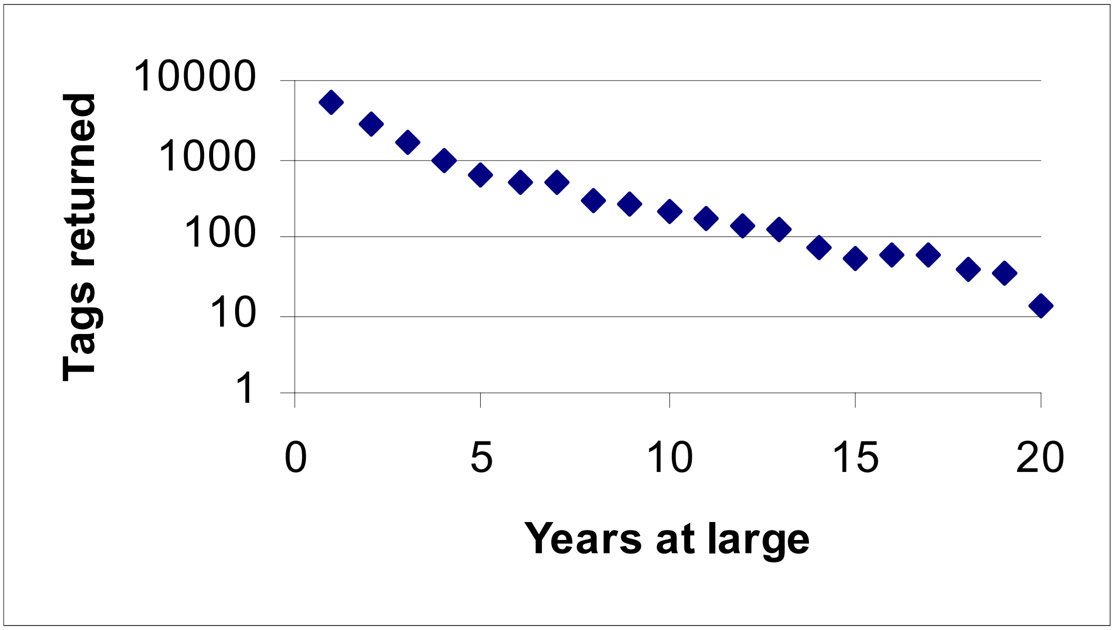


Figure 2.1 Number of tags returned vs years at large for tags released between 1977 and 1985.

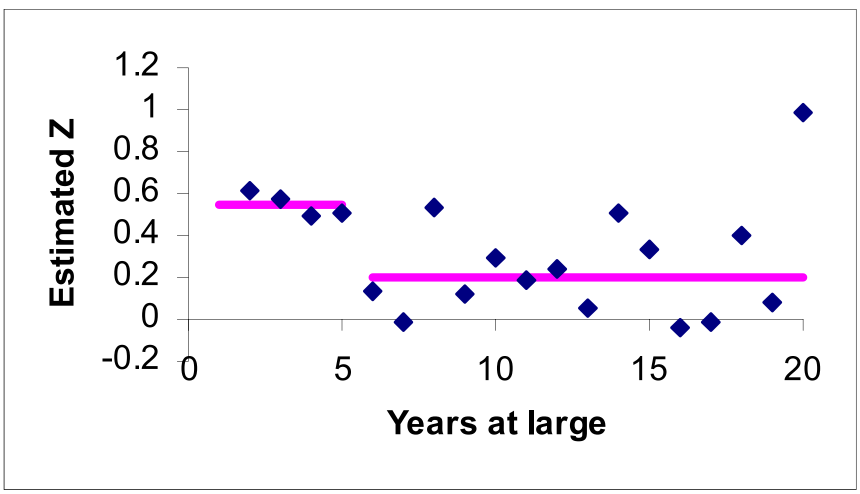


Figure 2.2 Estimated total mortality rate vs years at large for tags released between 1977 and 1985

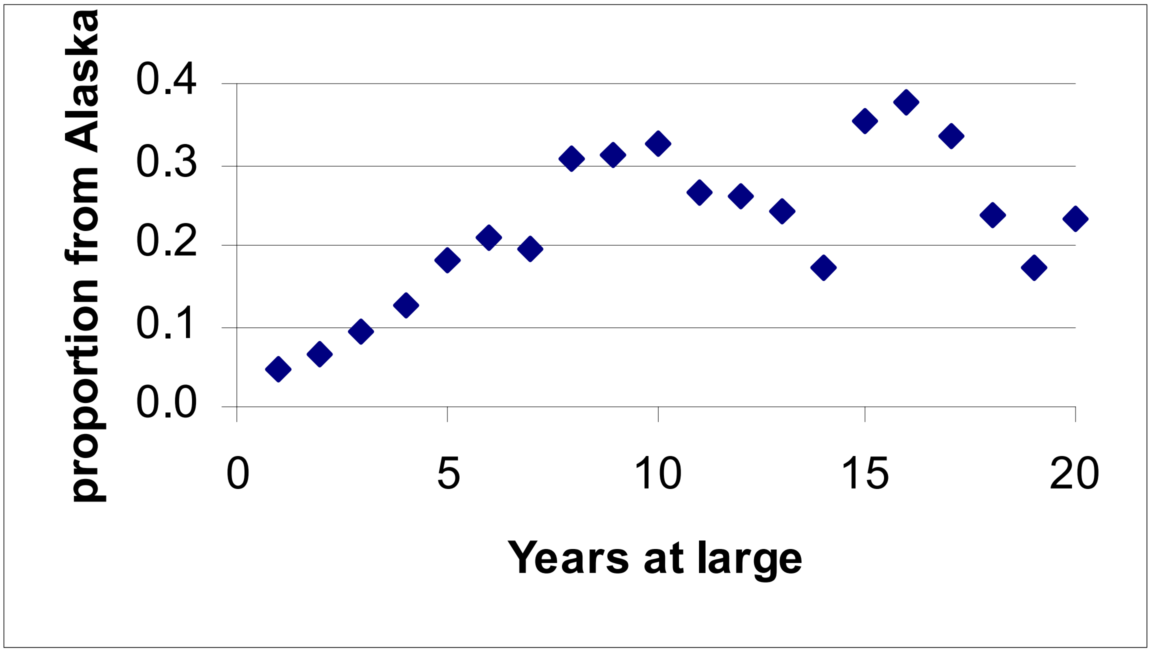


Figure 2.3 Proportion of tags returned from Alaska vs years at large for all releases

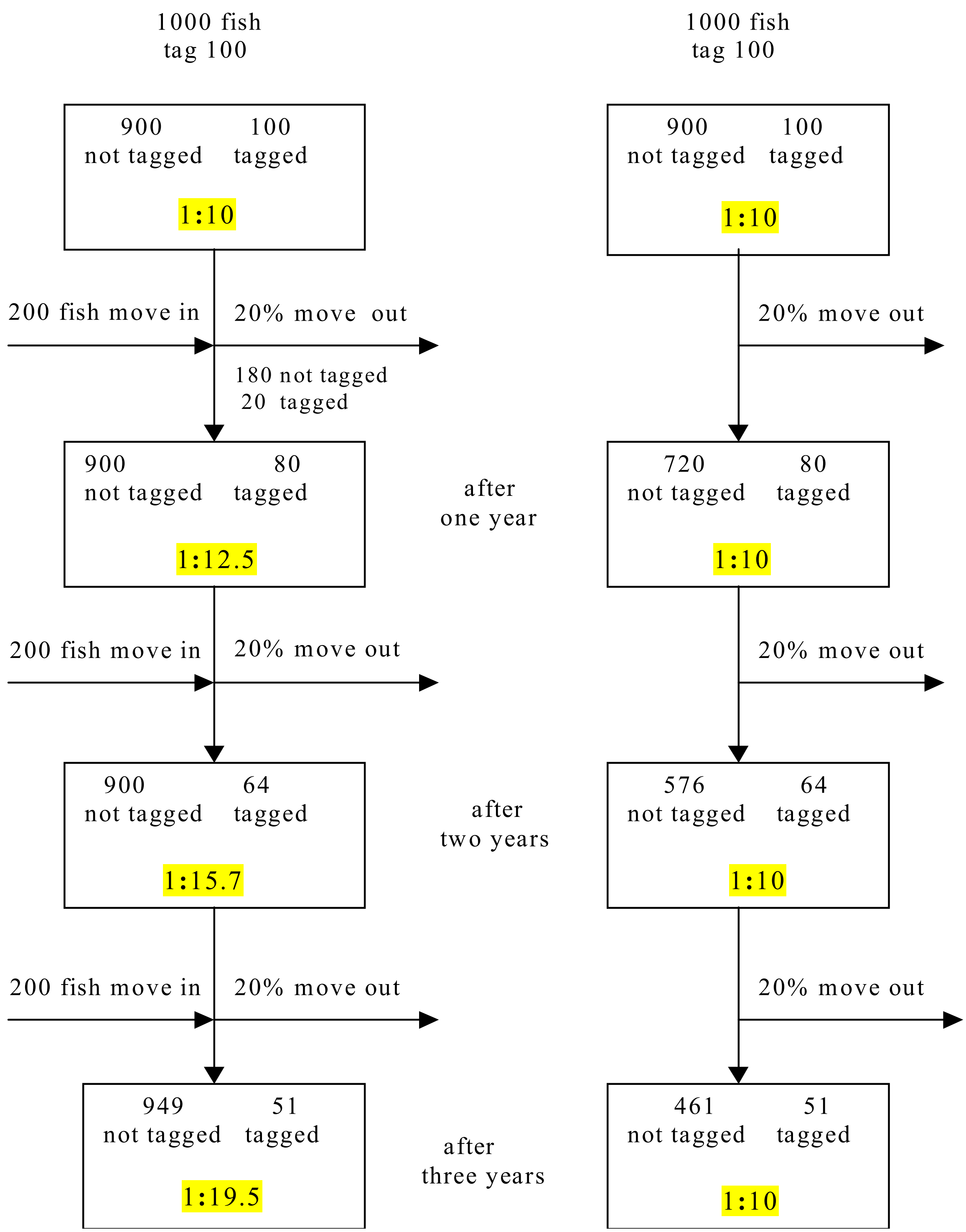


Figure 3.1 Hypothetical tagged populations to demonstrate changes in the tagged to untagged ratio due to immigration and emigration. The population on the left has both immigration and emigration while the population shown on the right has only emigration.

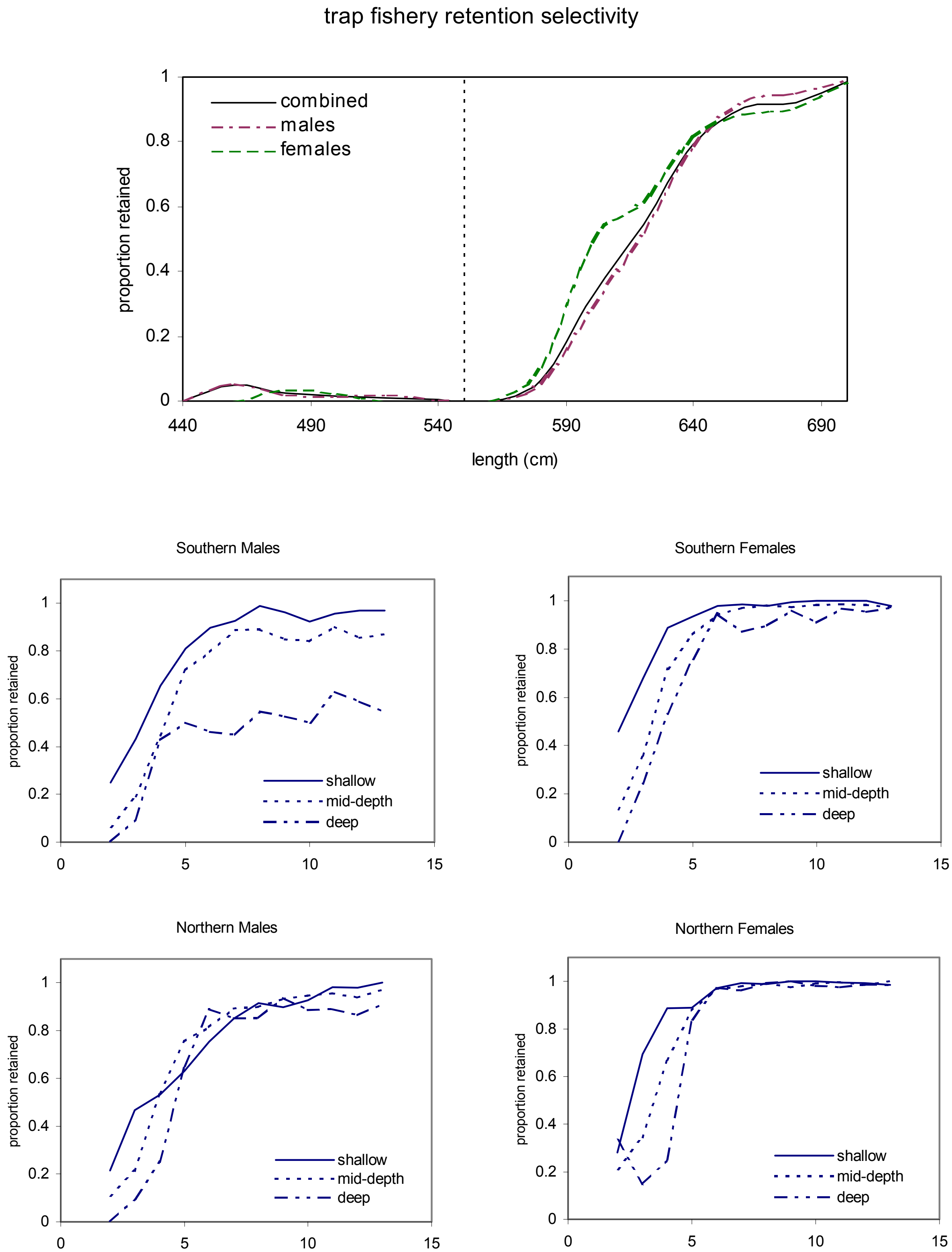


Figure 3.2 Estimated proportion of fish retained, based on 1992 and 1993 observer-collected data from trap fisheries (top panel), and the estimates of region- and age-specific fishery retention selectivity based on an assumed full retention of fish > 55 cm.

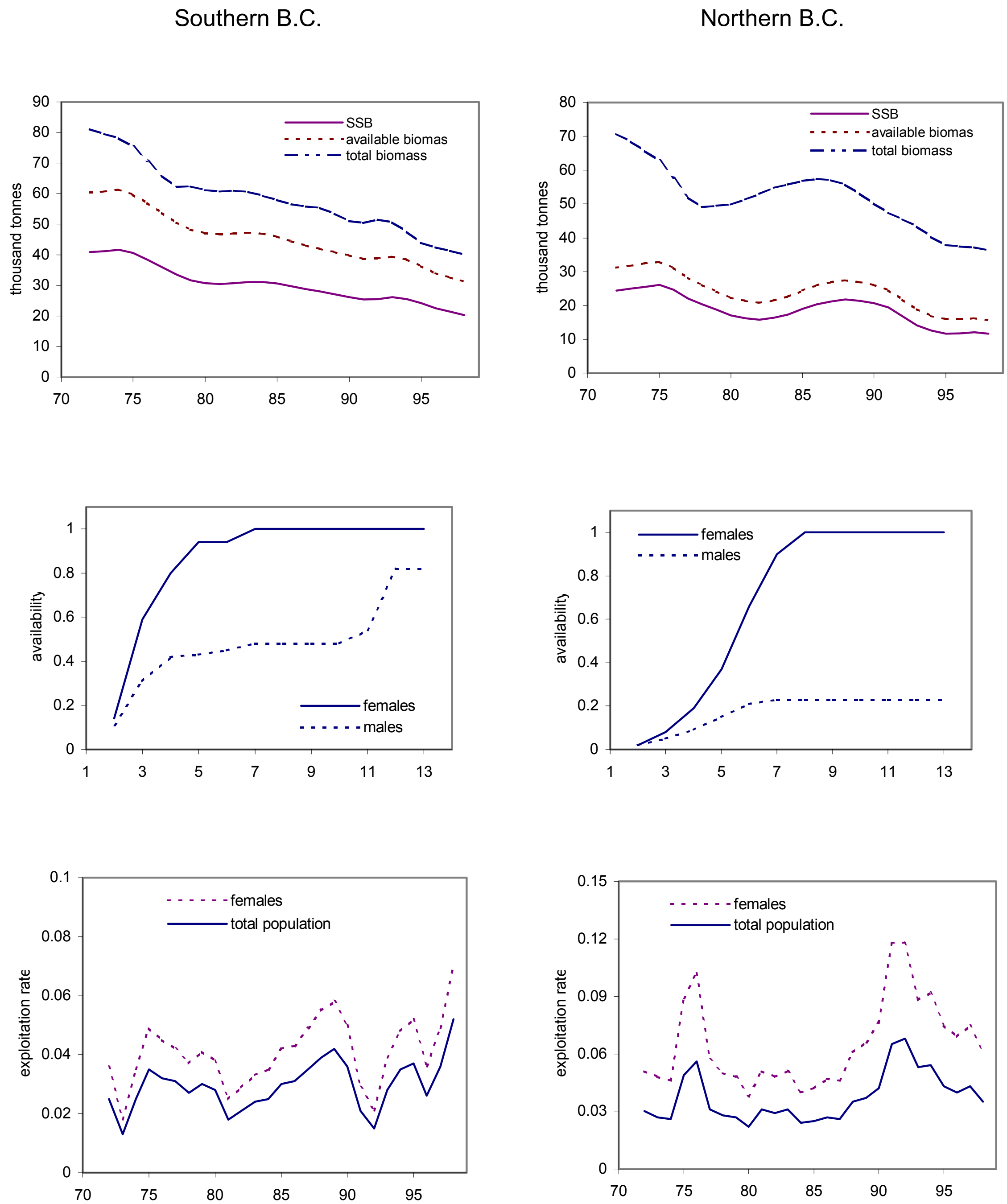


Figure 3.3. Time trajectories of biomass (top panels), exploitation rates (total numbers in catch/total numbers in population) (bottom panels), and availability-at-age estimates for the *base case* stock reconstructions.

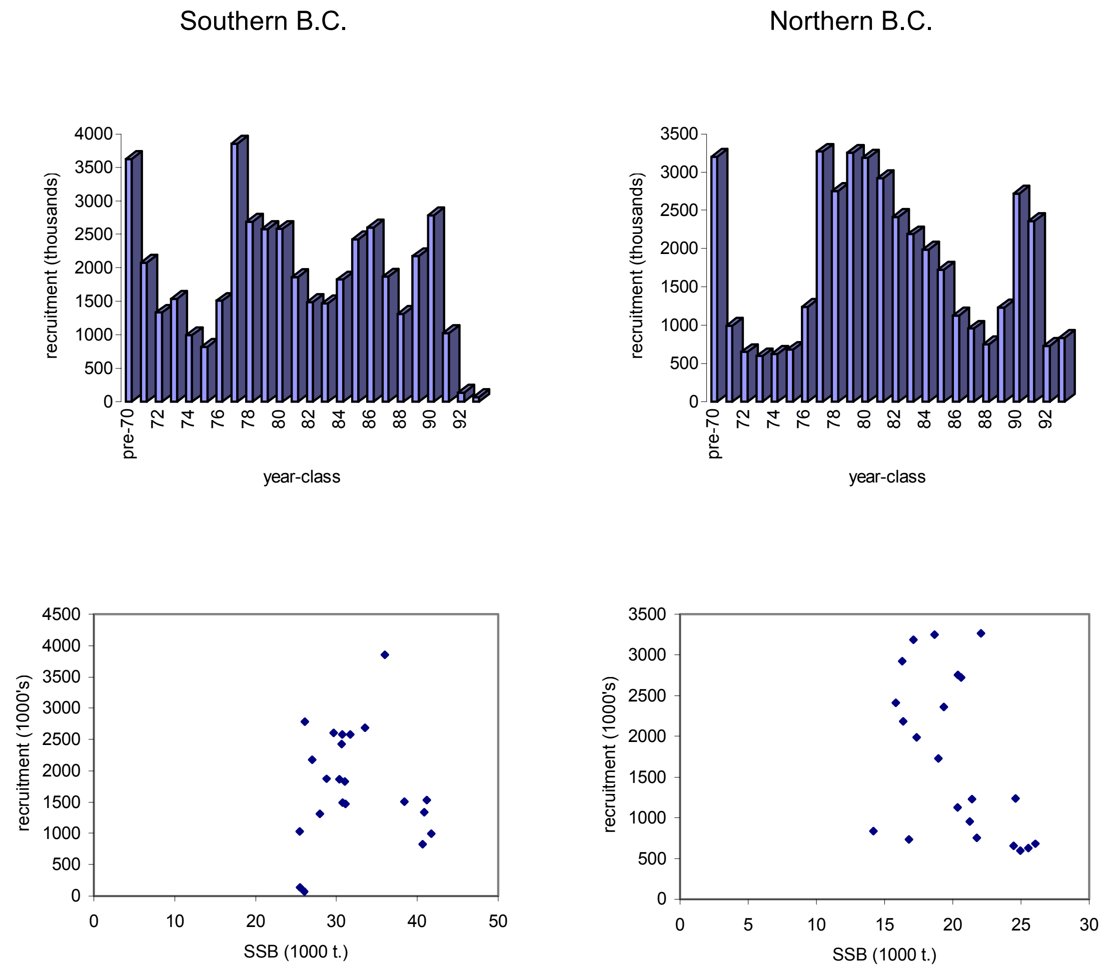


Figure 3.4 Estimated time-series of recruitment (top panels) and recruitment versus spawning stock biomass (SSB) estimates for the *base case* stock reconstructions.

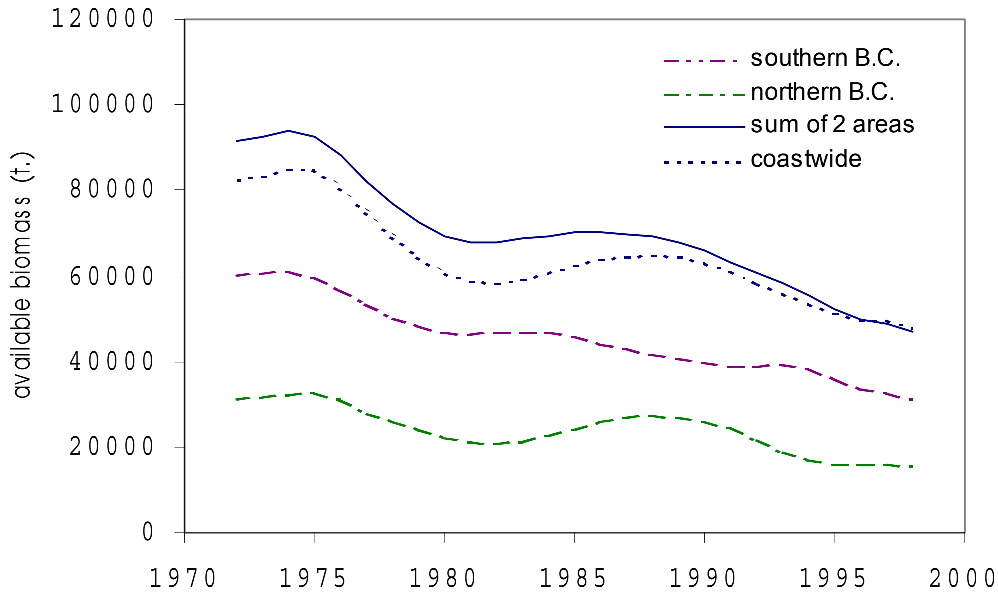


Figure 3.5 Estimates of available biomass from *base case* stock reconstructions for northern and southern B.C. and estimates from a coastwide analysis.

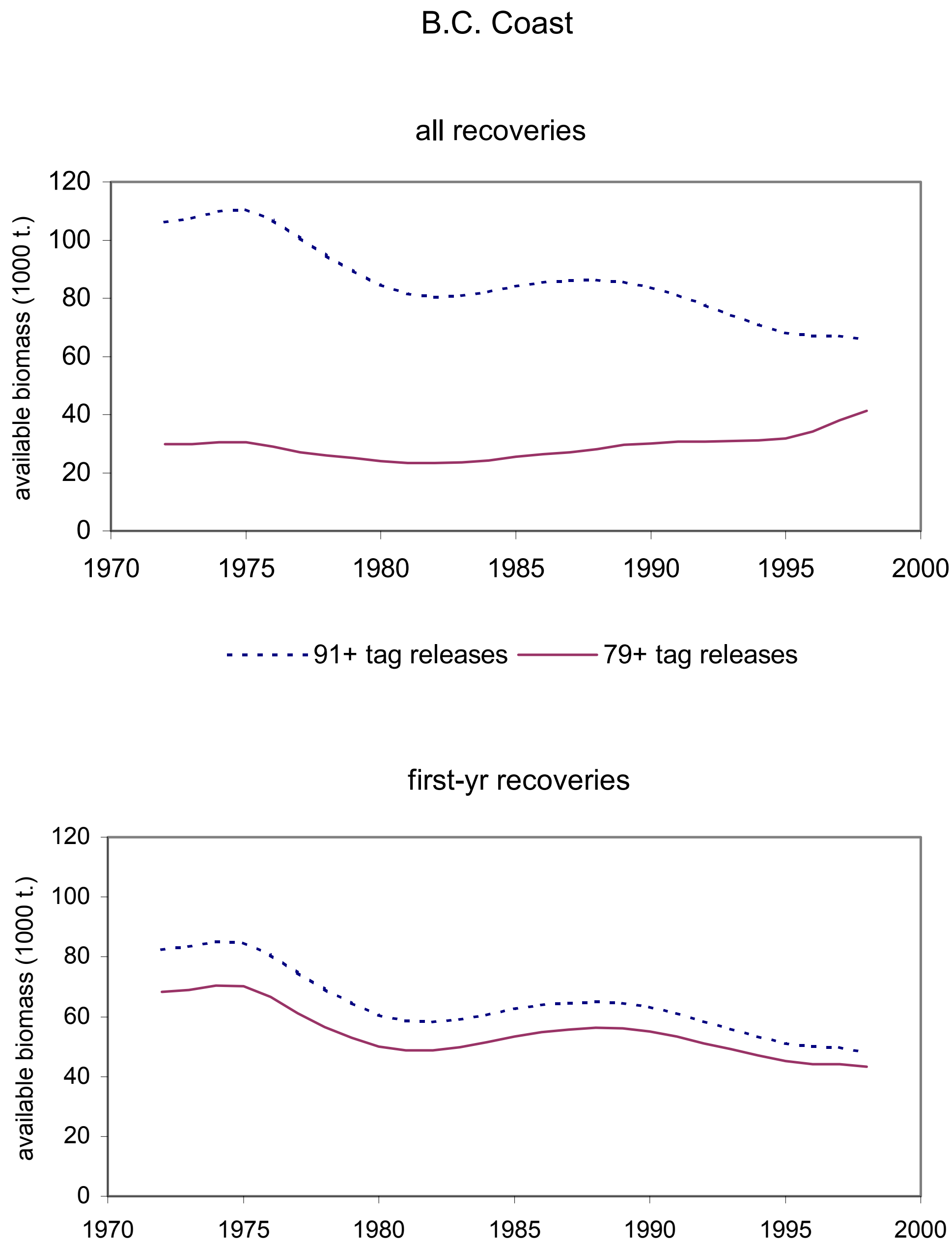


Figure 3.6 B.C. coastwide sablefish abundance estimates from the no-migration formulation of the Integrated Model fitting to either tag recoveries from all years (top panel) or tag recoveries from the year following tagging only (bottom panel). Results are for analyses fitting to tag release data from 1979 onward and fitting to tag release data from 1991 onward.

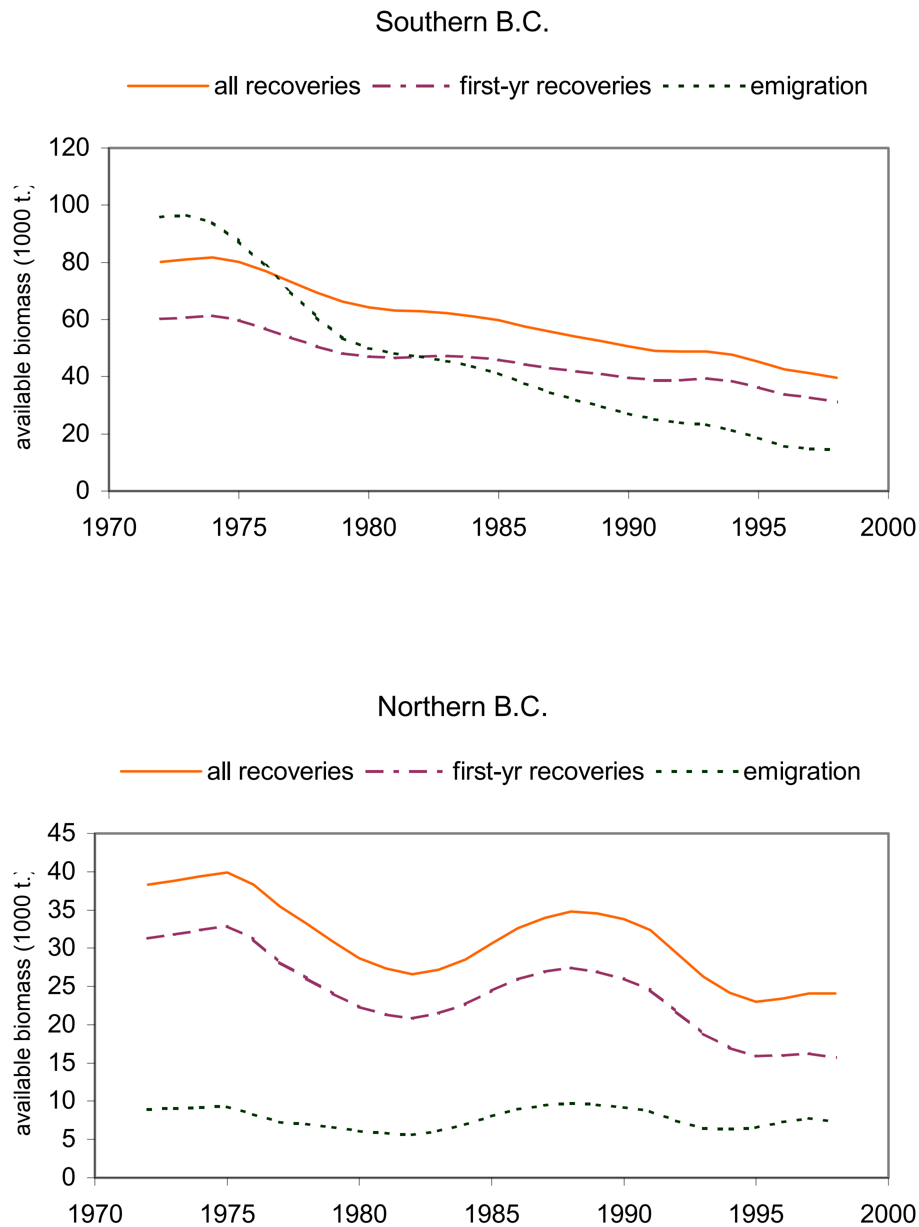


Figure 3.7. Time trajectories of available biomass estimates from Integrated Model analyses under three sets of assumptions regarding emigration of fish. The analyses follow the *base case* model structure with the exception of the migration formulation

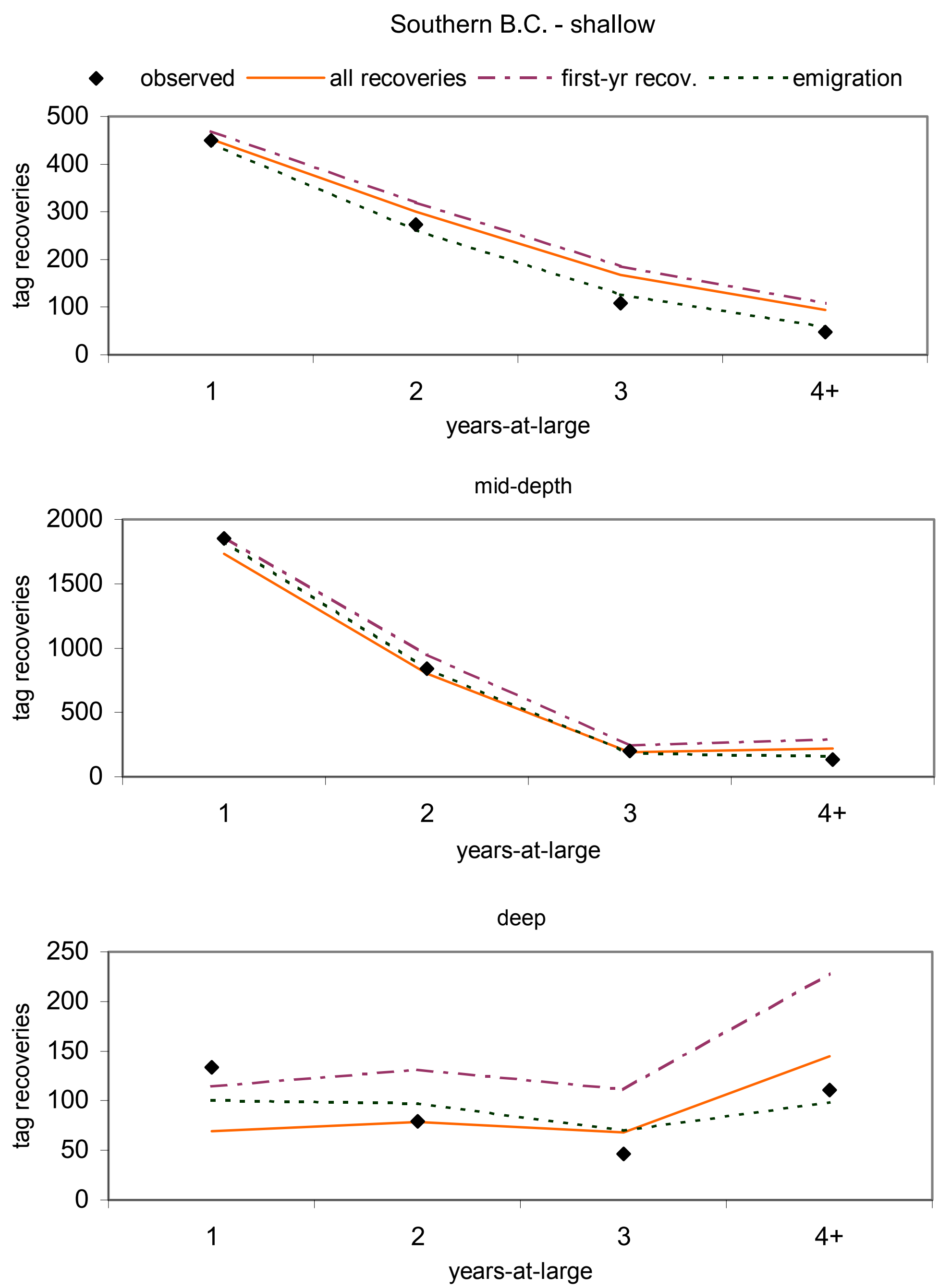


Figure 3.8a. Observed and predicted tag recoveries from Integrated Model analyses under three sets of assumptions regarding emigration of fish. The analyses follow the *base case* model structure with the exception of the migration formulation

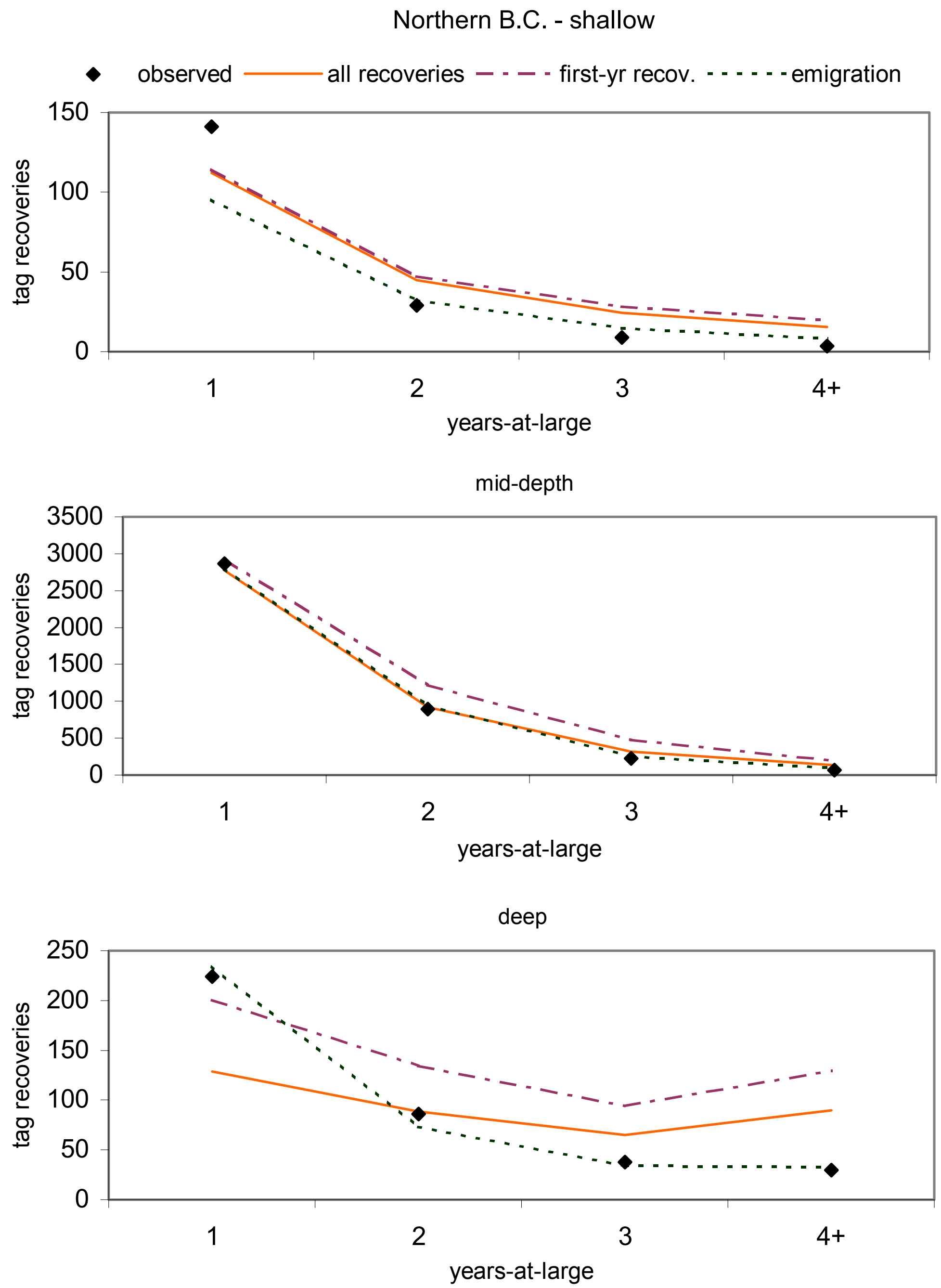


Figure 3.8b. Observed and predicted tag recoveries from Integrated Model analyses under three sets of assumptions regarding emigration of fish. The analyses follow the *base case* model structure with the exception of the migration formulation.

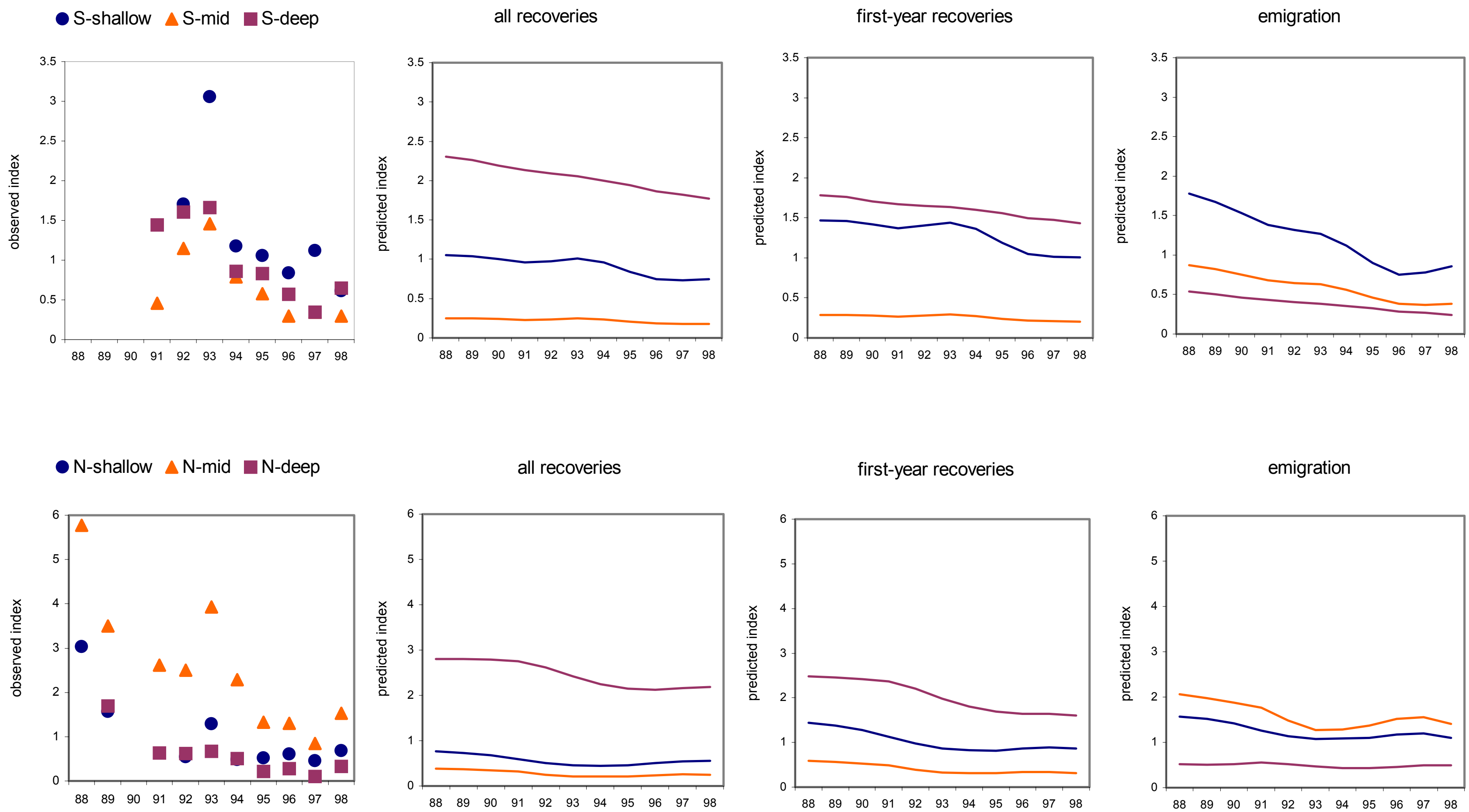


Figure 3.9. Observed and predicted relative survey indices from Integrated Model analyses under three sets of assumptions regarding emigration of fish. The analyses follow the *base case* model structure with the exception of the migration formulation.

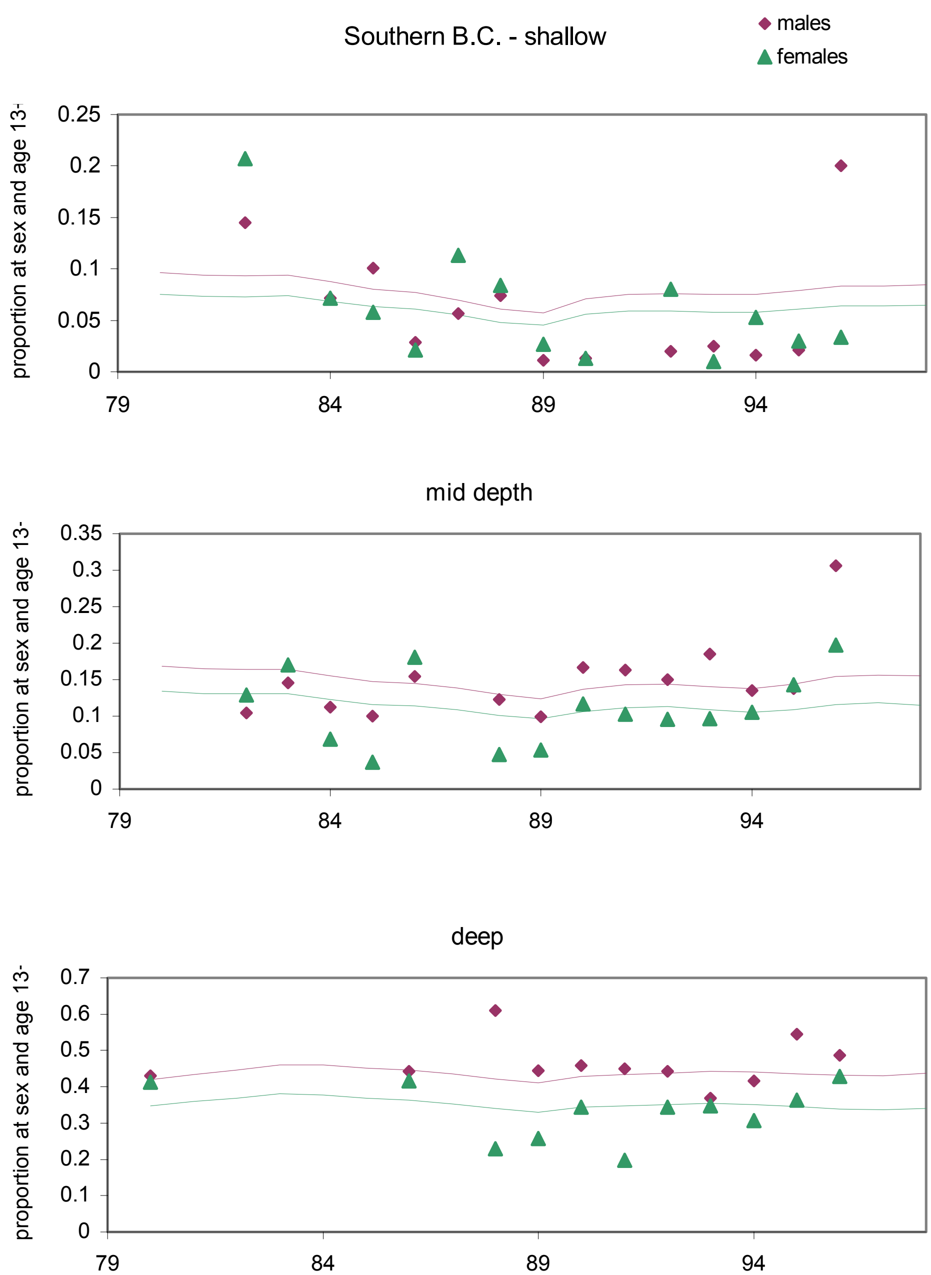


Figure 3.10a. Observed and predicted proportions by sex for age 13+ sablefish. The analyses follow the *base case* model structure with the exception of the migration formulation.

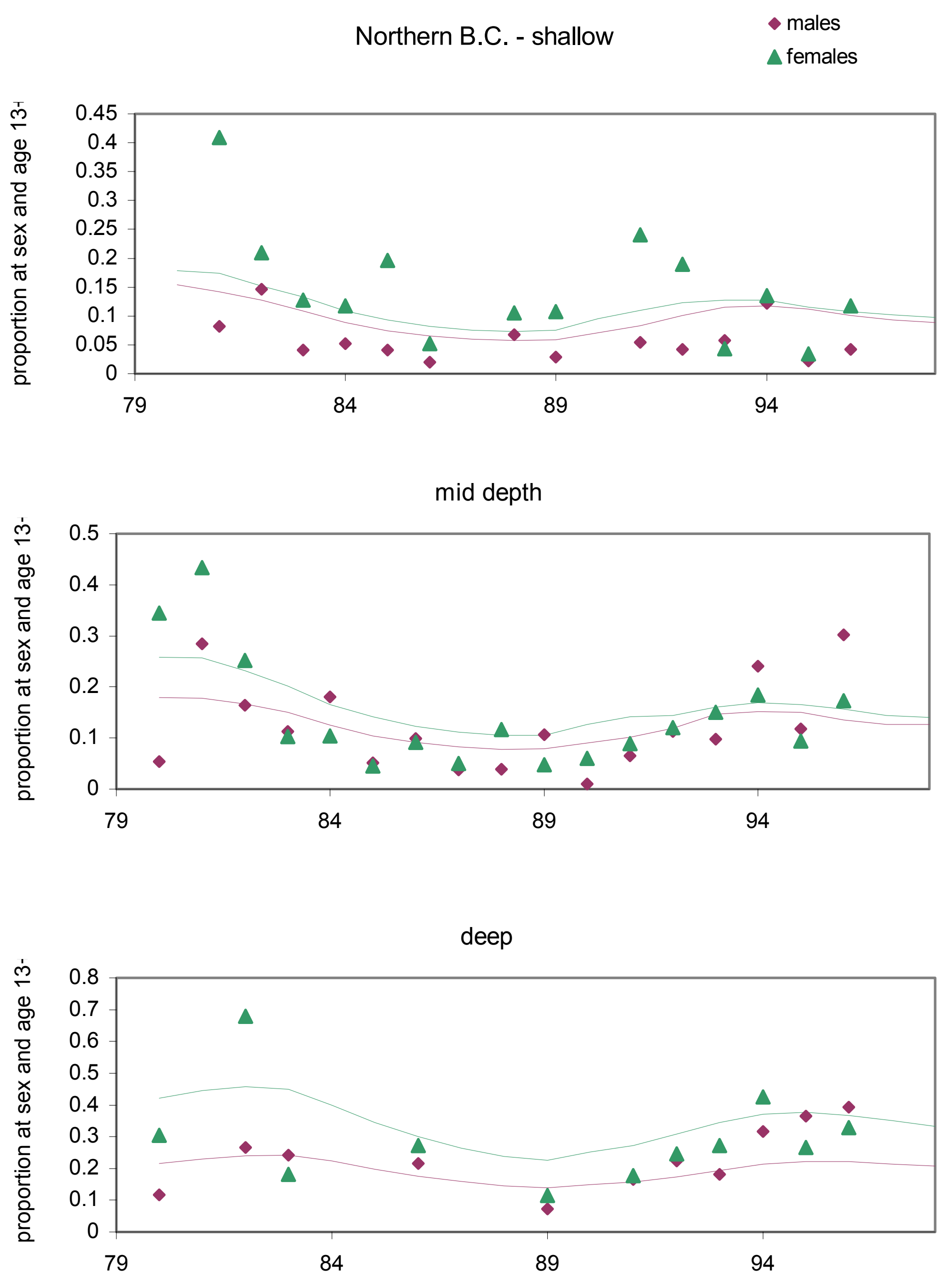
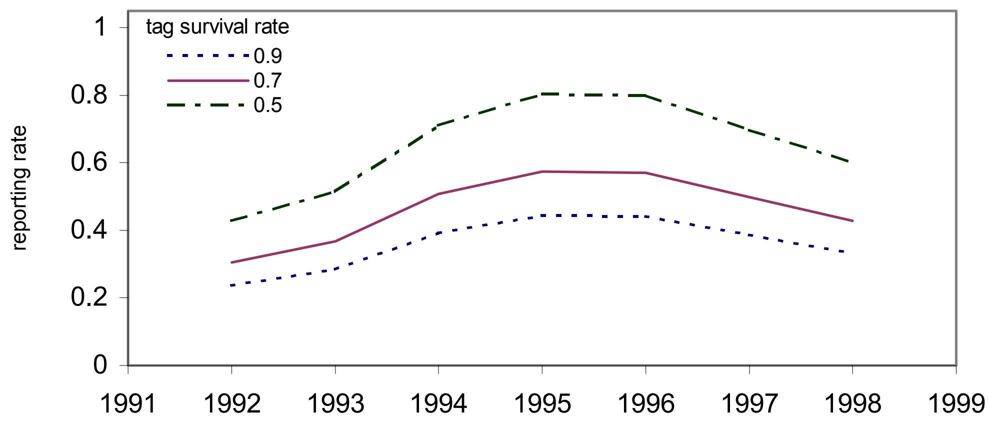


Figure 3.10b Observed and predicted proportions by sex for age 13+ sablefish. The analyses follow the *base case* model structure with the exception of the migration formulation.

Southern B.C.



Northern B.C.

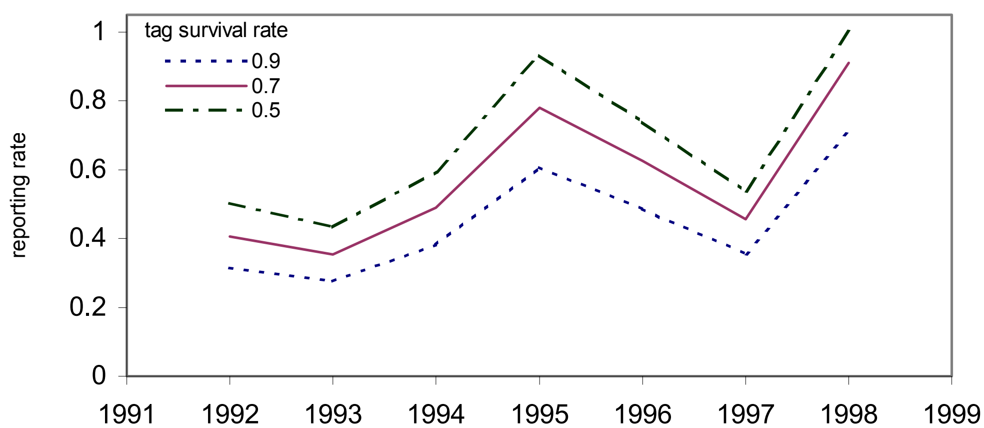


Figure 3.11 Estimated tag reporting rates for three levels of initial tag survival. Results are from the *base case* stock reconstructions, with initial tag survival rates fixed at alternative levels.

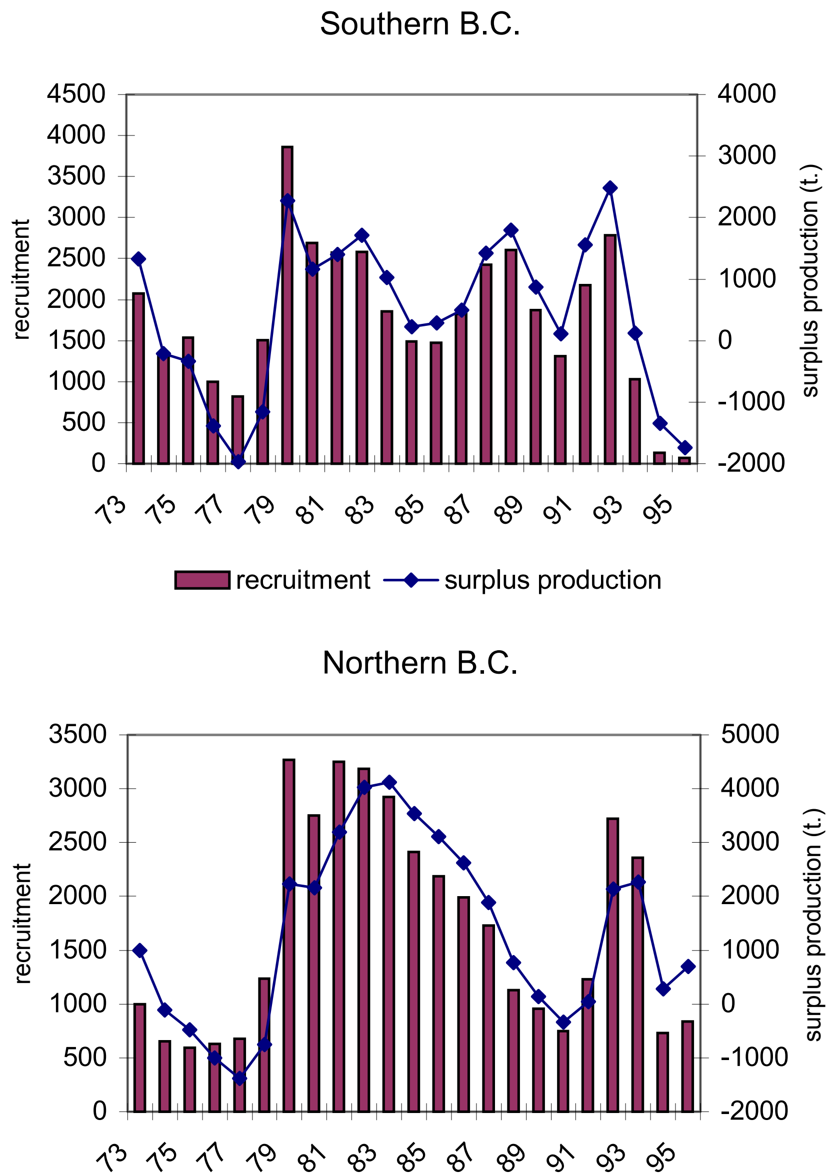


Figure 3.12. Estimates of recruitment (at age 2) and surplus production, 1973-1996, for southern and northern B.C.

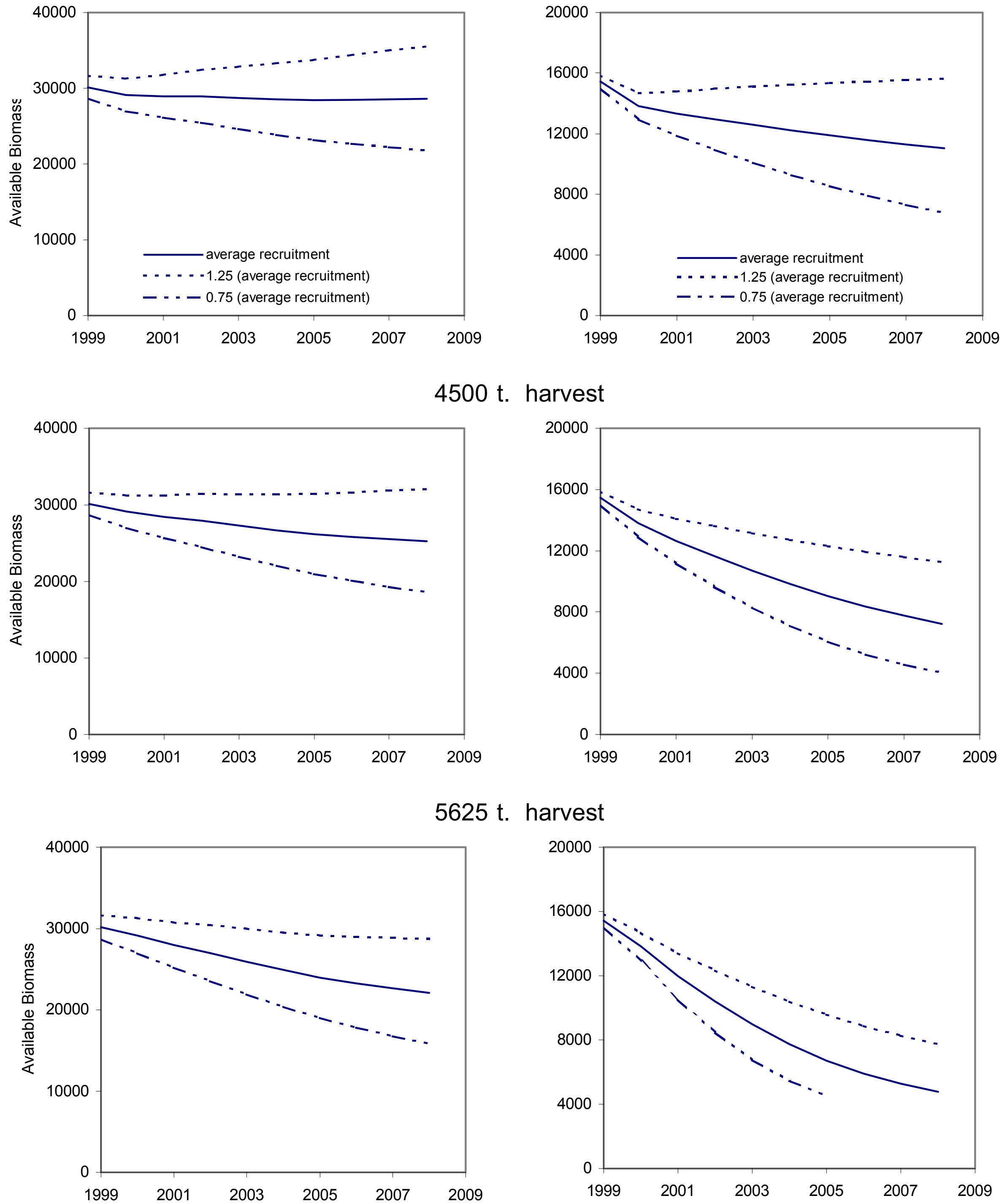


Figure 3.13 Estimated available stock biomass (t.) for the northern and southern B.C. sablefish stocks at 3 fixed harvest harvest levels and 3 recruitment levels.

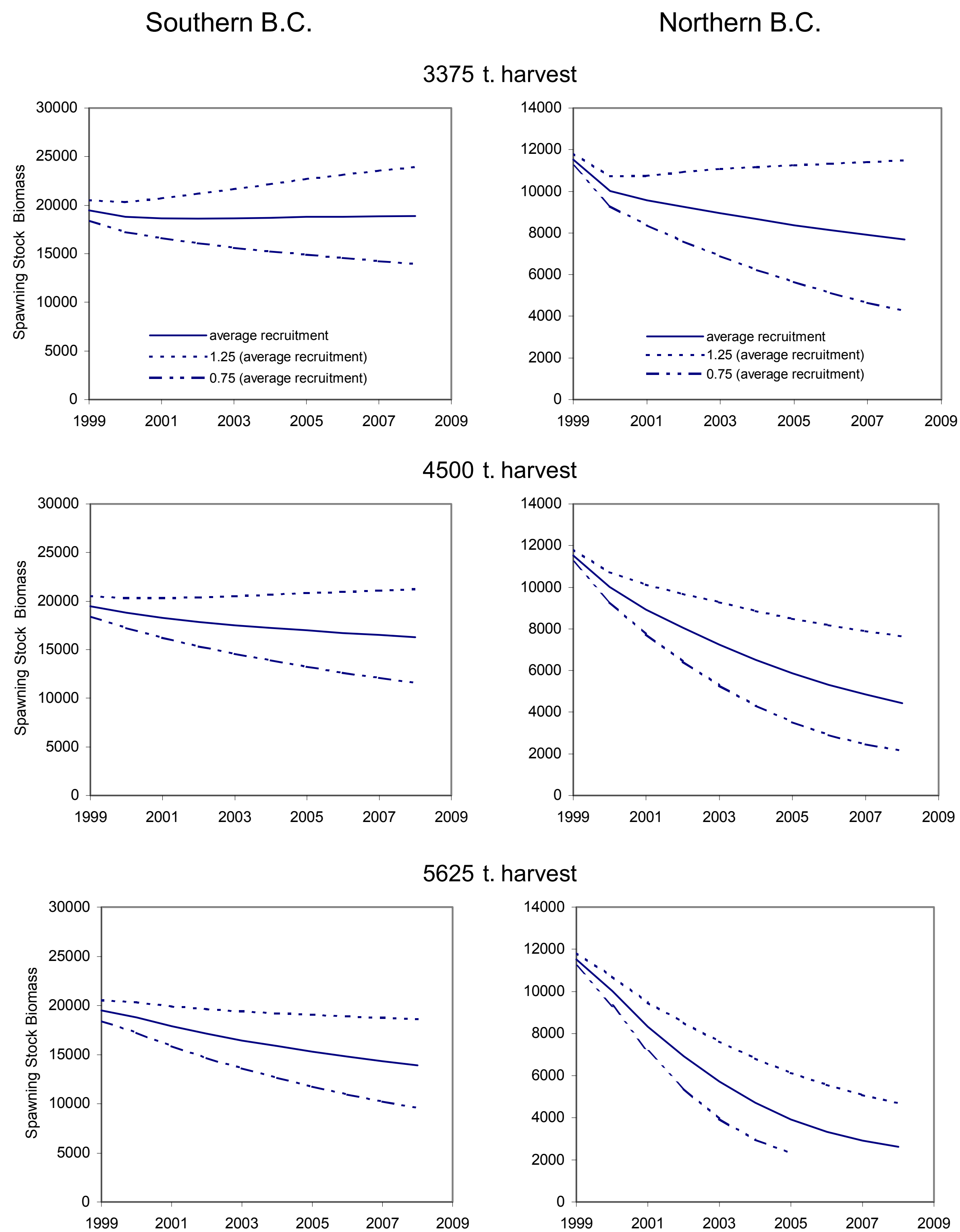


Figure 3.14 Estimated spawning stock biomass (t.) for the northern and southern B.C. sablefish stocks at 3 fixed harvest harvest levels and 3 recruitment levels.

APPENDIX A

Description of the Integrated Catch-Age Mark-Recapture Model

We have employed a spatially and sexually disaggregated age-structured model. The 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. Optional inputs to the model include assumptions about the relative abundance by region. The data are aggregated so that there is only one fishery per year in each region.

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,
η_{ri} the log-normal deviations from average recruitment for region r in year i,
γ 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,
ε_{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,
τ proportionality constant which relates the total annual available fish to the survey relative abundance index,
$d_{rr'1}$ 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',
ρ_{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^{T}_{tri} 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,

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,

$\lambda_{jrr'}$ 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,

$\widehat{A}_{ri}$ is the observed index of the number of available fish in region r for year i,

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.

r_{rsj} is the estimated proportion of age class j fish of sex s in region r that are retained in the fishery.

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 availability parameterization rather than fishery selectivity is that it allows us to assume the same 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. The data for tagged fish that are used in the analysis are restricted to sablefish caught using commercial trap gear fishing in commercial fishing areas. Hence, it is reasonable to assume that all tagged fish are fully available to the fisheries. We parameterize availability is a function of age and sex. All available fish should be equally vulnerable to the fisheries, however, not all fish that are caught are retained and landed. The instantaneous fishing mortality rates are parameterized as functions of the sex- and age-specific fishery retention selectivities. The retention selectivities are estimated independently, and are fixed quantities in the estimation procedure. 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

$$
\begin{aligned}
F_{rsij} &= q_r r_{rsj} \exp(\varepsilon_{ri}) \\
Z_{rsij} &= F_{rsij} + M \\
S_{rsij} &= \exp(-Z_{rsij}) \\
A_{rsij} &= a_{rsj} N_{rsij} \\
C_{rsij} &= \frac{F_{rsij}}{Z_{rsij}}\left(1 - S_{rsij}\right) A_{rsij} \qquad \text{for } 1 \le i \le N_I \quad 1 \le j \le N_J \\
C_{ri} &= \sum_{sj} C_{rsij} \\
R_{rsi} &= \exp(\eta_{ri}) \overline{R} \qquad \text{where } \textstyle\sum_{ir} \eta_{ir} = 0 \\
\widetilde{N}_{rsi1} &= R_{rsi} \\
\widetilde{N}_{rs,i+1,j+1} &= S_{rsij} A_{rsij} + \exp(-M)\left(N_{rsij} - A_{rsij}\right) \\
\widetilde{N}_{rs,i+1,N_j} &= S_{rsi,N_j-1} A_{rsi,N_j-1} + \exp(-M)\left(N_{rsi,N_j-1} - A_{rsi,N_j-1}\right) + \\
&\quad S_{rsiN_j} A_{rsiN_j} + \exp(-M)\left(N_{rsiN_j} - A_{rsiN_j}\right) \\
N_{rsij} &= \sum_{r'} \lambda_{jrr'} \widetilde{N}_{r'sij} \\
p_{rsij} &= A_{rsij} \Big/ \sum_{sj} A_{rsij}
\end{aligned}
$$

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 survey 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:

$$\tilde{N}^T_{tr_t s i_t j} = p_{r_t s i_t j} s^T_r I_t$$

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

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

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

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

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

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

We assume that not all tagged fish that are caught are reported each year, and estimate annual tag reporting rates by region. Let ρ_{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. $i_M = \min_t\left(i_t + 1\right)$). Then, $\rho_{ri} C^T_{tri}$ 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 $\lambda_{rr'j}$ by

$$\lambda_{rr'j} = d_{rr'1} \exp\Big(d_{rr'2}\big(-1 + 2\left(j-1\right)/\left(N_J - 1\right)\big)\Big)$$

where $\lambda_{rr'j}$ 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.

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

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

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

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

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

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

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

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,

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

then

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

Recalling that the $\lambda_{rr'}$ 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 which 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 assumed 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 two shallow depth regions. Further, we assume that the relative recruitment to these two regions 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 γ is a scaler between the average recruitment rate estimated for the period of the data analysis and the rate for the prior period.

$$N_{rs1} = \gamma \exp(\eta_r)\overline{R} \qquad \text{where } \eta_r = \sum_i \eta_{ri}$$

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.

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 which 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 overparameterized model. Using a Bayesian approach it is possible to put regularizing penalties on the parameters such as penalizing their vectors of second differences. 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, ρ_{ri}. Computationally these assumptions appear as penalty terms which 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

$$
\begin{aligned}
f_1 = & \sum_{tri} \left(\rho_{ri} C_{tri}^T - \widehat{C}_{tri}^T \ln\left(\rho_{ri} C_{tri}^T\right)\right) \\
& + \sum_{rsij} 100\left(p_{rsij} - \widehat{p}_{rsij}\right)^2 \Big/ \left(0.02 + p_{rsij}\right) \\
& + \sum_{ri} 1000\left(\log(1.0 + C_{ri}) - \log\left(1.0 + \widehat{C}_{ri}\right)\right)^2 \\
& + \sum_{ri} 1000\left(\log(0.1 + A_{ri}) - \tau \log\left(0.1 + \widehat{A}_{ri}\right)\right)^2
\end{aligned}
$$

$$
\begin{aligned}
f_2 = \; & 10 \sum_{r=1, i=i_M}^{N_R, N_I - 1} \left(\log(\rho_{ri}) - \log(\rho_{r,i+1}) \right)^2 \\
& + \sum_{r=1, j=1}^{N_R, N_I - 2} \left(a_{rsj} - 2a_{rs,j+1} + a_{rs,j+2} \right)^2 \\
& + 1000 \left(\log \rho_{1N_J} \right)^2 \\
& - 0.001 \sum_{r=1, i=1}^{N_R, N_I} \log\left(0.95 \exp\left(-10.0\varepsilon_{ri}^2\right) + 0.05\left(\exp\left(-2.0\varepsilon_{ri}^2\right)\right)\right)
\end{aligned}
$$

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. Note that the weighting for the last term in equation f_1, the fit to the relative abundance data, is set to zero for runs where these data are not included in the analyses.

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 $g_1(\theta_1)$ and $g_2(\theta_2)$ denote the two posterior distributions corresponding to two different model hypotheses for the two set of parameters θ_1 and θ_2 and let $\hat{\theta}_1$ and $\hat{\theta}_2$ 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

$$
2^{d/2} g_1(\hat{\theta}_1) \big/ g_2(\hat{\theta}_2)
$$

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. 1999), 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. $\gamma \neq 1$)
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 1999 sablefish stock assessment these hypothesis are components of the *base case* model formulation.

The following table shows the model parameters that are estimated through the minimization and the number of parameters estimated for the 1999 sablefish stock assessment "base case" implementation.

parameter	model structure	number estimated
$\overline{R}$	estimated	1
η_{ri}	estimated only for the southern and northern B.C. shallow regions	27
γ	estimated	1
M	not estimated, fixed at 0.08	0
a_{rsj}	common parameters for all three southern B.C. regions and for all three northern B.C. regions; last two age classes share a common parameter, and the parameter is fixed at 1 for females in last two age classes	21
ε_{ri}	estimated	81
q_r	estimated	3
τ	survey abundance index data not fit in current assessment	0
$d_{rr'1}$	estimated where regions r and r' are contiguous	4
$d_{rr'2}$	estimated where regions r and r' are contiguous	4
ρ_{ri}	estimated for all years where there is tag return data; common parameters for all regions, except where a second set of parameters estimated for the US region	6
s_r^T	fixed at 0.90 for the shallow and mid-depth regions (except as noted); estimated for the deep region	1
	total number of parameters estimated for ***base case*** model formulation	149

APPENDIX B

Analysis of tag reporting rates by sablefish pot vessels in BC.

by Ray Hilborn and Miguel Pascual

Objectives

The analysis of tag return rates requires an estimate of the proportion of tags that are detected and returned. Previous analysis has generally used a fixed tag return rate over time, often assuming 90% tag returns, but since tag return rates depend on a number of factors including the duration of the fishery, advertisement, ease of returning tags and fishermen's motivation to return tags, it was felt that an examination of tag return rates would be useful.

The objectives of this analysis are

a) Evaluate if reporting rates of tagged sablefish vary across fishing boats
b) Derive a measure of the degree of under reporting.

The basic idea is to look at between vessel differences in the tags reported per ton of fish landed, and assume that the vessels with the highest return rates are the most motivated to find and return tags, while vessels returning fewer tags are not reporting some fraction of their landings.

Will use a measure of the reporting rate as the dependent variable:

$$\frac{Tags\ reported(boat, area, year)}{Catch(boat, area, year)}$$

which takes into consideration the heterogeneity over space and time. Boat, area and year are used as categorical predictor variables.

Data available

- Tags reported by boat, by year and by area (only recoveries from north BC and south BC are used)
- Catch in tons by boat, area and year
Only recoveries and catches for 1991-96 were used.

Boat selection

The catch data available to us includes 24 different boats. All of these boats reported tag recoveries. An additional set of 41 boats reported tags as well, as indicated by the recovery file, but we do not possess catch information for them. Nevertheless, the recoveries of the set of 24 boats encompass 92% of the tags reported by all 65 boats, indicating that this group takes most of the catch.

Some of the 24 target boats had either small catches or fished for only a few years. In order to produce a more robust analysis (more orthogonal data), we selected 9 boats based on general information about their catch rate, as well as their spatial and temporal coverage. These 9 boats (table below) account for 74.4% of the total catch (out of the 24 boats reporting catch) and for 72.5% of the tags reported (out of 65 boats reporting tags) in the period 1991-96. All boats fished in most years and in both areas.

The following data summarize the total data for each vessel

ID	Total catch (tons)	Rank in catch (out of 24)	No. years with catch (out of 6)	North to south ratio in catch	Total tags recovered	Rank in tags (out of 65)	% tags with unreported locations	Rank in report (out of 65)
352	2750	1	6	94	281	5	18.15	5
463	429	12	5	32	44	14	34.10	14
705	644	10	6	79	115	7	27.83	7
706	2730	2	6	83	683	1	14.79	1
728	2226	3	4	79	54	12	14.81	12
732	1838	4	4	71	310	3	31.29	3
734	1597	6	6	83	381	2	24.41	2
838	1641	5	6	79	304	4	13.82	4
A39	1476	7	5	29	101	9	15.84	9

Among those boats with significant catch, only one boat (boat 742 with 752tons) was excluded from the subset because it had an inordinately large number of tag recoveries for which the location was not reported (60%). Among the boats included, the proportion of recovery records without reported location varies by 14-34%. The proportion of records with unreported locations for all the 65 boats increased over time.

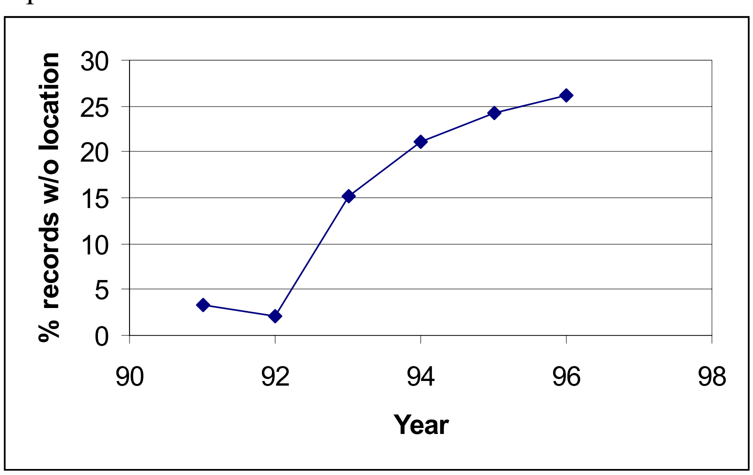


Figure 1. Proportion of tag returns without location information.

Fitting GLM model

It is possible that differences between vessels were due to differences in areas fished, or year fished. Thus we will use a Generalized Linear Model (GLM) to try to distinguish between area, year and boat effects. The most complex model fitted was:

$$\ln\left[\frac{tags\ reported(boat, area, year)}{catch(boat, area, year)}\right] = boat + area + year + boat.area + boat.year + area.year$$

The observations (in the original scale) were assumed to have a Poisson residual error. The importance of different factors in affecting the reporting rate was evaluated by the statistical significance of particular terms in the model by a stepwise analysis of deviance (ANODEV, Venables and Ripley 1994, Modern Applied Statistics with Splus, Springer Verlag) and by using an Akaike criterion (AIC). Because of the clustering nature of tag recoveries, overdispersion is expected. This was accommodated by relaxing the Poisson assumption of $\sigma^2 = \mu$ and assuming that $\sigma^2 = \gamma\,\mu$.

Results

The "best" model evaluated was one that included all the main effects (*boat*, *area* and *year*) and two double interactions (*year* x *boat*, *boat* x *area*):

Model	Residual Deviance	Df	par	Scale Param.	Scaled AIC	Testing For	Scaled Δ dev	Critical value	P-value	
Y+B+A+Y:B+Y:A+B:A	76.16	20	62	3.81	548.35					
Y+B+A+Y:B+ +B:A	**83.41**	**25**	**57**	**3.34**	**517.52**	**Y:A**	**1.90**	**11.07**	**0.86228**	**ns**
Y+B+A+Y:B+Y:A	178.73	28	54	6.38	589.99	B:A	**26.94**	15.51	0.000725	**
Y+B+A+ +Y:A+B:A	393.89	54	28	7.29	607.14	Y:B	**83.44**	48.60	0.000005	***
Y+B+A+Y:B	253.39	33	49	7.68	626.57	Y:A	**11.70**	11.07	0.039195	*
Y+B+A+ +Y:A	576.83	62	20	9.30	729.15	Y:B	**62.37**	48.60	0.002128	**
Y+B+A+ +B:A	419.54	59	23	7.11	594.71	Y:A	**3.52**	11.07	0.620898	ns
Y+B+ +Y:B	264.41	34	48	7.78	629.98	A	**1.44**	3.84	0.230921	ns
Y+ +A+ +Y:A	816.96	70	12	11.67	908.35	B	**25.81**	15.51	0.001132	**
B+A+ +B:A	2262.88	64	18	35.36	2399.97	Y	**259.23**	11.07	0.000000	***
Y+B+A	641.46	67	15	9.57	755.70	B:A	**31.21**	15.51	0.000129	***
Y+B	643.79	68	14	9.47	750.41	A	**0.24**	3.84	0.621785	ns
Y+ +A	887.37	75	7	11.83	940.68	B	**25.69**	15.51	0.001189	**
B+A	2391.91	72	10	33.22	2468.07	Y	**182.83**	11.07	0.000000	***

This indicates that there are differences in the tags reported between years; this was expected because there were more tags placed in later years. The *area* effect was not important by itself (no differences between north and south in tags/catch), indicating that the proportions of tagged fish did not differ significantly in the two areas. This was surprising as the number of tags released has been different between areas, but the result suggests that mixing between areas is rapid enough to counter this effect. Most importantly for this analysis, the *boat* effect was significant, indicating that different boats reported tags differentially. The two interactions indicate that there was a heterogeneity in the tags reported by different boats in different years (*boat* x *year*) and in different areas (*boat* x *area*).

The boat year interaction is clearly due to the fact, seen later, that some boats changed their behavior and started reporting tags at a much higher rate in later years; presumably as the IVQ system came into effect and the fishermen felt that cooperation and tag returning were a higher priority.

The boat x area interaction is harder to explain, it suggests that some are more likely to report tags from some areas than others.

Besides the statistical significance of these effects, we would like to know how big some of them are, particularly in the case of the boat effect. How much underreporting there is? To look at this, we explored the fitted reporting rate from the "best" model above for different boats and over space and time:

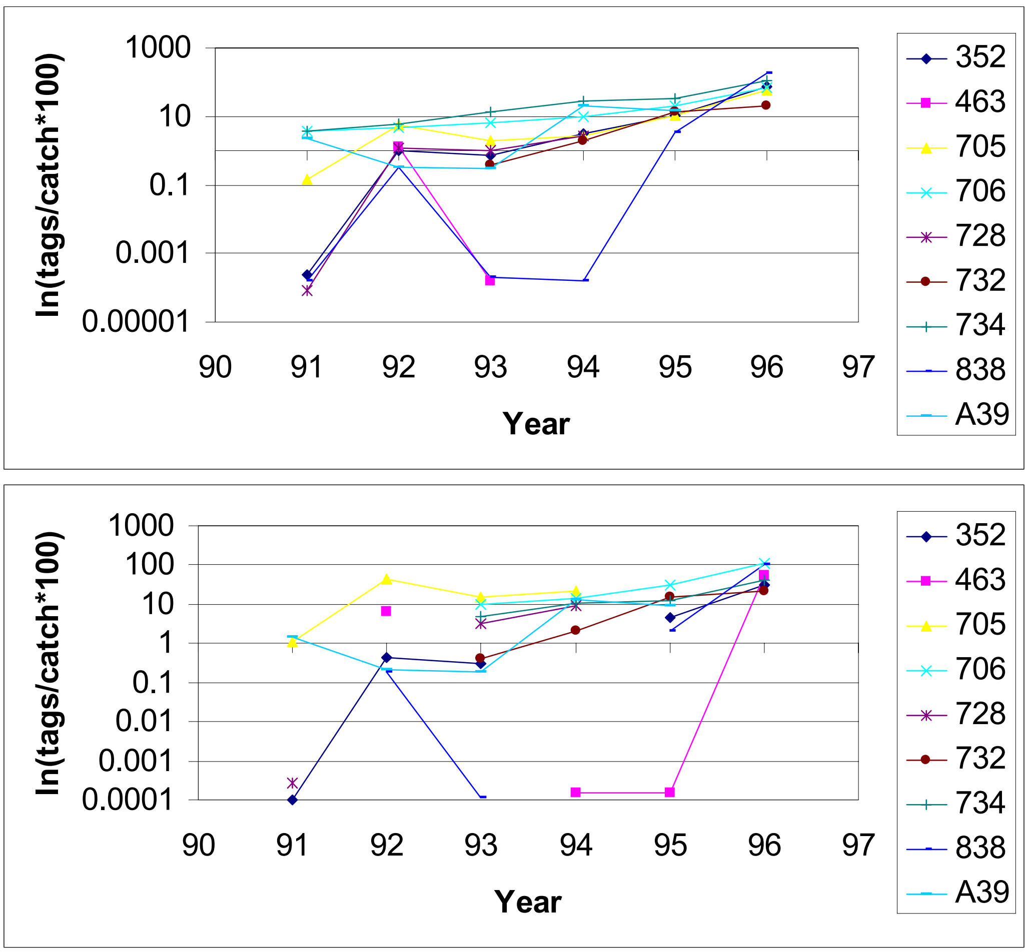


Figure 2. The tags per ton for different vessels. The top panel is for the north and the bottom panel is for the south.

Some boats clearly failed to report tags in some years (e.g., boats 463 and 838 in 93-95). Note that this could not be an artifact resulting from unreported locations, which shows a smooth trend over years. The rest of the boats show a much smoother trend over time, showing much less interannual variability. There was also what appears to be a failure in 1991 to report tags in some boats other that 463 and 838 (e.g., 352, 728).

The highest reporting rates in the north area were those of boat 734, which also shows the smoothest trend. This boat was used as a "test boat" and all reporting rates were standardized as relative reporting to those of this boat (averaged over north and south):

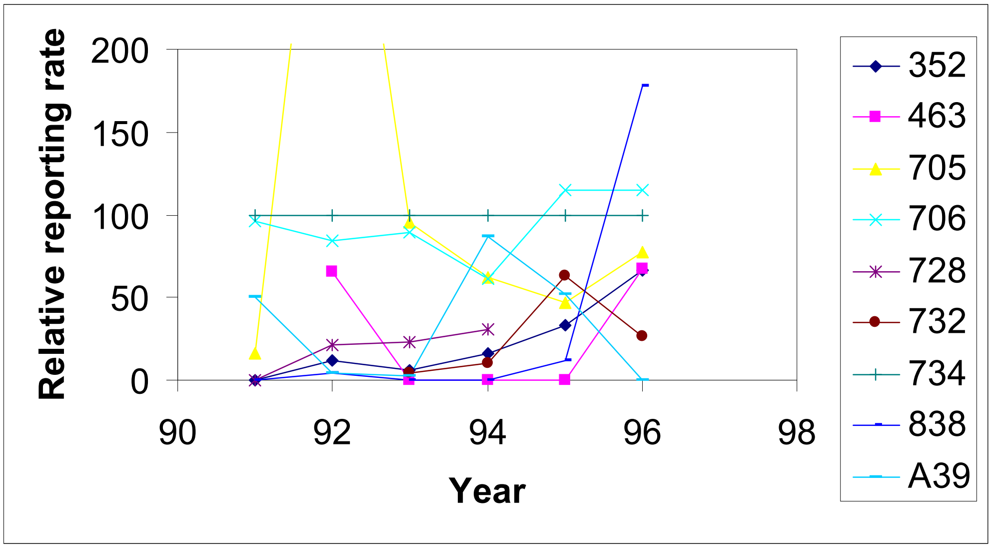


Figure 3. Tag reporting rates relative to boat 734.

The differences in reporting rates between boats and over time as estimated from this analysis are substantial.

To eliminate the effect of boats that obviously failed to report tags and examine the behavior of the rest of the boats, we dropped boats 463 and 838 and the year 1991 and repeated the model fitting and ANODEV:

Model	Residual Deviance	Df	par	Scale Param.	Scaled AIC	Testing for	Scaled Δ dev	Critical Value	P-value	
Y+B+A+Y:B+Y:A+B:A	53.96	14	42	3.85	377.72					
Y+B+A+Y:B+ +B:A	58.82	18	38	3.27	351.75	Y:A	1.26	9.49	0.86797	ns
Y+B+A+Y:B+Y:A	157.9	20	36	7.90	435.41	B:A	26.97	12.59	0.00015	**
Y+B+A+ +Y:A+B:A	161.45	34	22	4.75	331.04	Y:B	27.89	31.41	0.11207	ns
Y+B+A+Y:B	220.12	24	32	9.17	466.79	Y:A	7.88	9.49	0.09604	ns
Y+B+A+ +Y:A	310.34	40	16	7.76	433.68	Y:B	19.31	31.41	0.50187	ns
Y+B+A+ +B:A	190.37	38	18	5.01	329.12	Y:A	6.09	9.49	0.19250	ns
Y+B+ +Y:B	222.71	25	31	8.91	461.68	A	0.28	3.84	0.59514	ns
Y+ +A+ +Y:A	509.37	46	10	11.07	586.46	B	25.65	12.59	0.00026	**
B+A+ +B:A	1041.48	42	14	24.80	1149.40	Y	169.89	9.49	0.00000	***
Y+B+A	376.45	44	12	8.56	468.95	B:A	37.14	12.59	0.00000	***
Y+B	376.46	45	11	8.37	461.25	A	0.00	3.84	0.97273	ns
Y+ +A	572.59	50	6	11.45	618.84	B	22.93	12.59	0.00082	**
B+A	1137.58	48	8	23.70	1199.25	Y	88.96	9.49	0.00000	***

As expected by the smoother trends over time for the remaining boats, the interaction *boat* x *year* is now not significant. *Boat* x *area* is still highly significant. This will either mean that reporting rate varies across areas, or that some characteristic of the fishing mode in the two areas differentially affects the probability of individual boats of catching tagged fish. As with the former data set, the interaction *year* x *area* was not significant.

As before, *boat* effect is highly significant by itself, indicating that some boats reported fewer tags than others. As before, the *year* effect is very significant and *area* is not.

The estimation of reporting rates by boat, year and area that resulted from this model is:

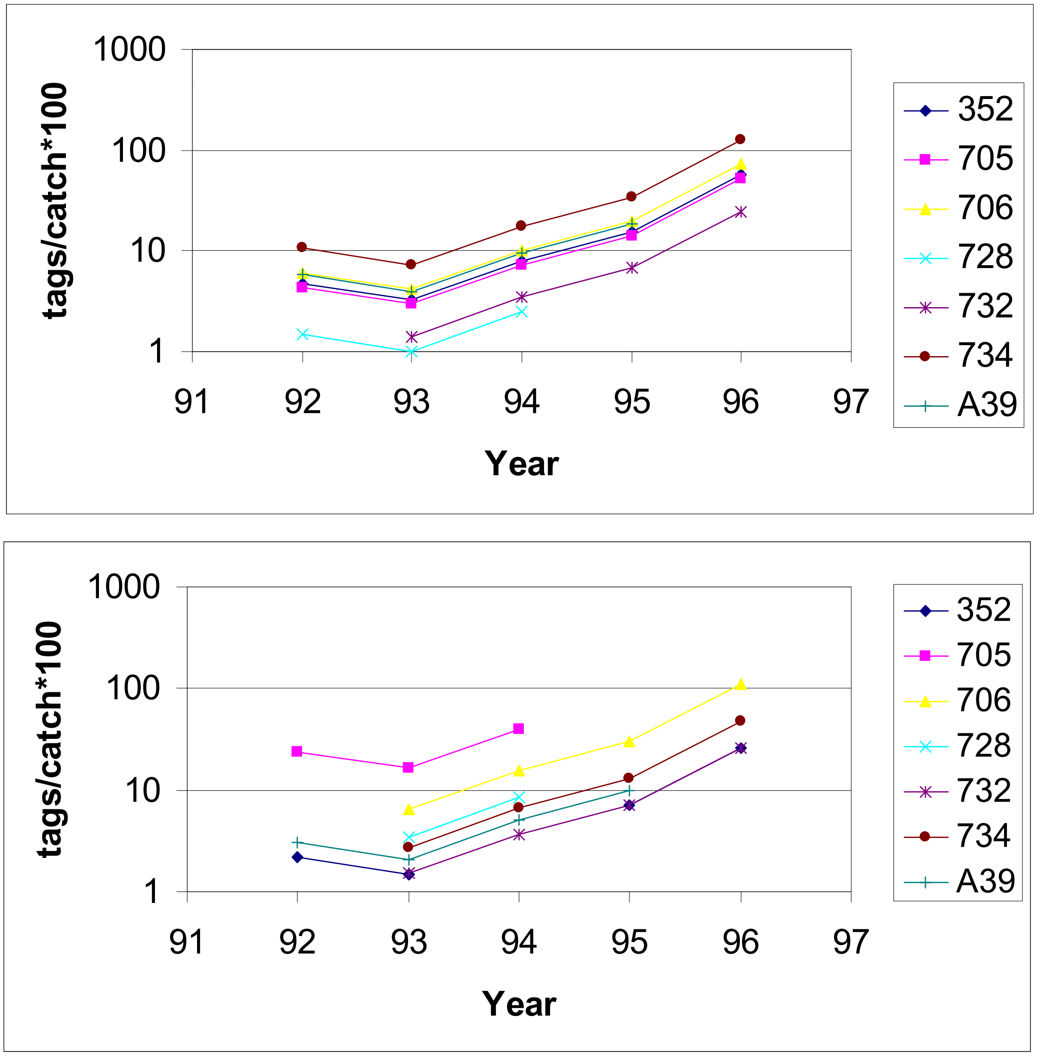


Figure 4. Tag reporting rates by vessel. Top panel is for the north and bottom panel is for the south.

The reporting rate (averaged across areas) relative to boat 734 is:

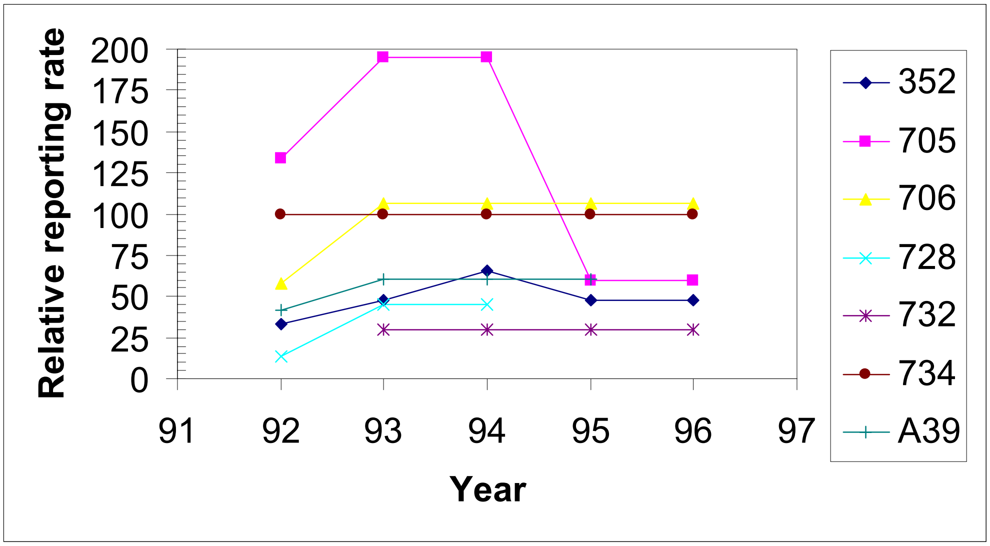


Figure 5. Tag reporting rates relative to vessel 734.

Again, the reporting rate of different boats varies greatly (as low as 25% of that of boat 734).

Estimating the overall level of underreporting

In order to do this, for all 24 boats that reported both catch and tag recoveries, we aggregated $\frac{Tags\ reported(boat, area, year)}{Catch(boat, area, year)}$ over the two areas, including also those records without a location specification.

We calculated an overall reporting rate for all boats, relative to the three boats with the best apparent record of tag reporting (705, 706 and 734). This judgement was made both from the level of reporting of these boats relative to other boats and by the consistency and smoothness of tags/catch over the years considered. For each year, a weighed average reporting rate was calculated by using the catch of different boats as the weights. This provided an overall annual reporting rate (Figure below).

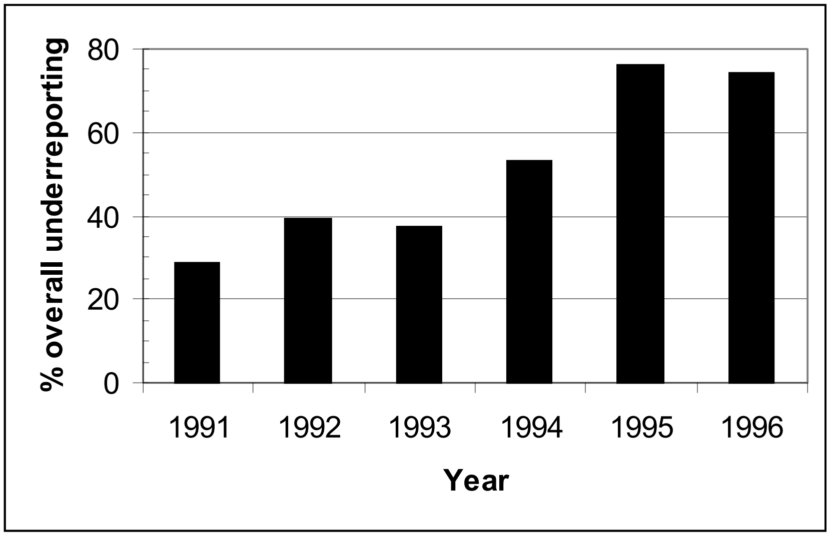


Figure 6. Estimated reporting rates for all vessels assuming that vessels 705, 706 and 734 reported all tags.

Conclusions

We conclude that there have been significant changes in tag reporting rates since 1991 and that there were considerable between boat differences. If we assume that the three vessels with the highest reporting rates report all tags, and that vessels who report fewer tags per ton landed are not reporting all tags, then the current reporting rate is about 70%. However, it may be that some boats fish in depths and areas with higher tag densities and that at present all boats are reporting all tags.