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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

V. Haist[1], D. Fournier[2], M.W. Saunders[3]

[1]School of Fisheries Box 357980
University of Washington
Seattle, WA 98195

[2] Otter Reaserch Ltd.
P.O Box 2040
Sidney, B.C. V8L 3S3

[3] Department of Fisheries and Oceans
Pacific Biological Station
Nanaimo, B.C V9R 5K6

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ABSTRACT

This paper represents a major assessment for sablefish. The assessment is based on an integrated catch-age, mark-recapture model that is stratified by area and depth. The unified approach is a significant improvement over the previous assessment that analyzed catch-at-age and tagging data separately. Estimates of available biomass in 1997 range from 43,400 to 51,300t. A recommended yield range of 2,977t-5,052t was developed based on deterministic projections using varying levels of recruitment and target F levels based on the current F $(_{Current})$, $0.8F_{currrent}$ and $1.2F_{current}$. Under all scenarios with average or below average levels of recruitment the stock is predicted to decline slowly. We recommend a yield level be chosen from low-average recruitment options.

RÉSUMÉ

Cet article est le résultat d'une évaluation majeure du stock de la morue charbonnière. L'évaluation est fondée sur un modèle intégrant les données sur l'âge des prises et l'étiquetage-recapture, qui est stratifié en fonction de la zone et de la profondeur. L'approche unifiée constitue une nette amélioration par rapport à la technique précédente d'évaluation, qui consistait à analyser séparément les données sur l'âge et l'étiquetage. Selon les diverses estimations, en 1997, la biomasse disponible se situait dans une marge de 43 400 à 51 300 t. La recommandation du taux de capture est de 2 977 à 5 052 t et s'appuie sur des projections déterministes établies en fonction de taux variables de recrutement et les valeurs cibles du niveau F actuel F(actuel), 0,8 F(actuel) et 1,2 F(actuel). Après avoir envisagé toutes les possibilités incluant des taux de recrutement moyens ou sous la moyenne, nous prédisons un lent déclin du stock. Nous recommandons un niveau de capture choisi d'après les taux de recrutement moyens ou sous la moyenne.

Introduction

The primary motivation for the development of fisheries resource models is to obtain information useful for making policy decisions regarding future management of the fishery. An equally important motivation is the development of a tool for rigorously examining the data on which these decision are based. Fisheries data usually come from a variety of different sources and are collected on different temporal and spatial scales of resolution. It is often not easy to determine whether these data sources are internally consistent and consistent with one another. A fisheries model can provide a yardstick with which to evaluate the consistency of data.

The development of a fisheries model generally involves a trade-off between the complexity of the species biology and the fisheries that interact with that compexity, and the data that is available to estimate parameters of the model. Using the B.C. sablefish fishery as an example, we have been told by fishermen that the efficiency of longline gear (as compared to trap gear) decreases with depth. The age and sex structure of sablefish is depth-dependent so it is likely that there are differences in the age and sex composition of the catches from longline and trap gear. Ideally we would model the trap and longline fisheries as separte events, however there is no biological data for the longline fisheries so this is not possible. Hence, the model structure represents a simplification of the relationships because the available data does not support estimation of the parameters for a more complex model.

Sablefish have a complex biology and our understanding of their ontogeny is incomplete. Sablefish spawn in deep waters (bottom depth > 1000 m), the larvae are distributed in the surface waters either on the shelf or seaward of the shelf break, and juvenile fish are found predominantly nearshore or inshore (McFarlane et al. 1997, Ruteki and Varosi 1997). The distribution of adult sablefish is depth-dependent with older fish and males more prevalent at greater depth. Within B.C., the age and sex composition of sablefish captured at similar depths differs between northern and southern waters, with fewer male fish and greater mixing of age-classes in the northern areas. Saunders et al. (1997) attribute these differences to the relative size of the available habitat in the two areas.

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 strucure of the populations and secondly, to incorporate mark-recapture analysis so that fishing mortality estimates are better determined.

In this document we describe a catch-age model that integrates mark- recapture analysis which we have developed for the assessment of B.C. sablefish. The model treats the B.C. coast as a single stock comprised distinct regions. Movement between the B.C. regions and between the B.C. regions and a U.S. region is modelled. We present results of hypothesis tests conducted to evaluate alternate model structure, and estimates of model parameters for the model that is best supported by the data.

The age-structured 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 catch by region and year, estimates of the total catch by region and year and tag return data. Additional 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):

$\bar{R}$ 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 made 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 observed total annual available fish to the 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^T_r 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,

$\tilde{N}_{rsij}$ 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 total 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_{ri} is the instantaneous fishing mortality rate in region r for year i,

Z_{ri} is the instantaneous total mortality rate in region r for year i,

S_{ri} is the survival rate 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:

$\widehat{C_{rsij}}$ is the observed catch of age class j fish of sex s in the population in region r during year i,

$\widehat{C_{ri}}$ is the observed total catch in region r for year i,

$\widehat{p_{rsij}}$ is the observed proportion of the total 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.

We employ a form of the catch equations that assumes the population in each region is comprised of available and unavailable fish. Our rationale for using an availablity parameterization rather than fishery sectivity 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 tagged fish used in this 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, and all available fish are equally vulnerable to the fisheries. The instantaneous fishing mortality rates relate the quantities C_{rsij}, N_{rsij}, and A_{rsij}, via the catch equations. The form of the the catch equations used in this paper is given by

$$F_{ri} = q_r \exp(\epsilon_{ri}) \tag{1}$$

$$Z_{ri} = F_{ri} + M \tag{2}$$

$$S_{ri} = \exp(-Z_{ri}) \tag{3}$$

$$A_{rsij} = a_{rsj} N_{rsij} \tag{4}$$

$$C_{rsij} = \frac{F_{ri}}{Z_{ri}}(1 - S_{ri}) A_{rsij} \qquad \text{for} \quad 1 \le i \le \mathrm{N}_I \quad 1 \le j \le \mathrm{N}_J \tag{5}$$

$$R_{rsi} = \exp(\eta_{ri}) \bar{R} \qquad \text{where} \quad \sum_{ir} \eta_{ri} = 0$$

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

$$\tilde{N}_{rs,i+1,j+1} = S_{ri} A_{rsij} + \exp(-M)(N_{rsij} - A_{rsij}) \tag{6}$$

$$\begin{aligned} \tilde{N}_{rs,i+1,\mathrm{N}_J} = {} & S_{ri} A_{rsi,\mathrm{N}_J-1} + \exp(-M)(N_{rsi,\mathrm{N}_J-1} - A_{rsi,\mathrm{N}_J-1}) \\ & + S_{ri} A_{rsi\mathrm{N}_J} + \exp(-M)(N_{rsi\mathrm{N}_J} - A_{rsi\mathrm{N}_J}) \quad 1 \le i < \mathrm{N}_I \end{aligned} \tag{7}$$

$$N_{rsij} = \sum_{r'} \lambda_{jrr'} \tilde{N}_{r'sij} \tag{8}$$

$$p_{rsij} = C_{rsij} / \sum_{sj} C_{rsij} \tag{9}$$

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 sex and age compostion of the fishery 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:

$$\tilde{N}^T_{tr_t s i_t j} = p_{r_t s i_t j} s^T_r I_t \tag{11}$$

$$\tilde{N}^T_{trsi_t j} = 0 \qquad \text{for} \quad r \ne r_t \quad \text{or} \quad i < i_t \tag{12}$$

$$C^T_{trsij} = \frac{F_{ri}}{Z_{ri}}(1 - S_{ri}) N^T_{trsij} \qquad \text{for} \quad i_t \le i \le \mathrm{N}_I \quad 1 \le j \le \mathrm{N}_J \tag{14}$$

$$\tilde{N}^T_{trs,i+1,j+1} = S_{ri} N^T_{trsij} \tag{15}$$

$$\tilde{N^T}_{trs,i+1,\mathrm{N}_J} = S_{rsi,\mathrm{N}_J-1} N^T_{trsi,\mathrm{N}_J-1} + S_{rsi\mathrm{N}_J} N^T_{trsi\mathrm{N}_J} \quad 1 \le i < \mathrm{N}_I \tag{16}$$

$$N^T_{trsij} = \sum_{r'} \lambda_{jrr'} \tilde{N^T}_{r'tsij} \tag{17}$$

$$C^T_{trsi} = \sum_j C^T_{trsij} \qquad (18)$$

$$C^T_{tri} = \sum_{sj} C^T_{trsij} \qquad (19)$$

$$p^T_{trsij} = C^T_{trsij} / C^T_{trsi} \qquad (20)$$

We assume that not all of the 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. $i_M = \min_t(i_t + 1)$). Then, $\rho_{ri} C^T_{tri}$ is the predicted number of total tag returns in each year.

Modeling the movement of fish between the regions

Define the age specific movement parameters $\lambda_{rr'j}$ by

$$\lambda_{rr'j} = d_{rr'1} \exp(d_{rr'2}(-1 + 2(j-1)/(\mathrm{N}_J - 1))) \qquad (22)$$

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 which 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 simplicification in mind the equations for moving the fish between regions are based on the following sytem of ordinary differential equations.

$$\frac{dN_r}{dt} = -\Big(\sum_{r' \neq r} \lambda_{r'r}\Big) N_r + \sum_{r' \neq r} \lambda_{rr'} N_{r'} \qquad \text{for} \quad 1 \leq r \leq \mathrm{N}_R \qquad (23)$$

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

$$N_r = N'_r - \Big(\sum_{r' \neq r} \lambda_{r'r}\Big) N'_r + \sum_{r' \neq r} \lambda_{rr'} N'_{r'} \qquad \text{for} \quad 1 \leq r \leq \mathrm{N}_R \qquad (24)$$

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

$$N_r = N'_r - \Big(\sum_{r' \neq r} \lambda_{r'r}\Big) N_r + \sum_{r' \neq r} \lambda_{rr'} N_{r'} \qquad \text{for} \quad 1 \leq r \leq \mathrm{N}_R \tag{25}$$

This version is called implict because the N_r are implicity defined via the relationship. We use the implicit form because it has better properties for large values of the parameters $\lambda_{rr'}$. To solve the equations for the N_r transpose all the terms involving the N_r to the left hand side of equation (25).

$$N_r + \Big(\sum_{r' \neq r} \lambda_{r'r}\Big) N_r - \sum_{r' \neq r} \lambda_{rr'} N_{r'} = N'_r \qquad \text{for} \quad 1 \leq r \leq \mathrm{N}_R$$

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

$$B = \begin{pmatrix} 1 + \sum_{k \neq 1} \lambda_{k1} & -\lambda_{12} & \cdots & -\lambda_{1\mathrm{N}_R} \\ -\lambda_{21} & 1 + \sum_{k \neq 2} \lambda_{k2} & \cdots & -\lambda_{2\mathrm{N}_R} \\ \vdots & \vdots & \ddots & \vdots \\ -\lambda_{\mathrm{N}_R 1} & -\lambda_{\mathrm{N}_R 2} & \cdots & 1 + \sum_{k \neq \mathrm{N}_R} \lambda_{k\mathrm{N}_R} \end{pmatrix} \tag{26}$$

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 stationarity conditions

The age structured model requires $2\mathrm{N}_R\mathrm{N}_J$ 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 undesireable transient effects into the model. An alternative approach is to restrict the values of these parameters by imposing stationarity 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 stationarity conditions to express the number at age in terms of the assumed recruitment. This reduces the number of free parameters from $2\mathrm{N}_R\mathrm{N}_J$ to $2\mathrm{N}_R$ (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). 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 stationarity conditions are:

$$N_{j+1} = B_j^{-1} S_j N_j \qquad \text{for} \quad 1 < j < \mathrm{N}_J - 1 \tag{27}$$

$$N_{\mathrm{N}_J} = B_{\mathrm{N}_J-1}^{-1} S_{\mathrm{N}_J-1} N_{\mathrm{N}_J-1} + B_{\mathrm{N}_J}^{-1} S_{\mathrm{N}_J} N_{\mathrm{N}_J} \tag{28}$$

Solving equation (28) for N_{N_J} we get

$$N_{\mathrm{N}_J} = \left(I - B_{\mathrm{N}_J}^{-1} S_{\mathrm{N}_J}\right)^{-1} B_{\mathrm{N}_J-1}^{-1} S_{\mathrm{N}_J-1} N_{\mathrm{N}_J-1} \tag{29}$$

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 equal 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.

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

It is necessary to pick suitable values for the stationary survival rates. Several possible condidates 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 (pehaps 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 specifiying 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

The objective function $f = f_1 + f_2$ where f_1 is the frequentist component which is the logarithm of the probability density of the observations and f_2, the Bayesian contribution, which is the logarithm of the prior probability distribution put on the parameters.

$$f_1 = \sum_{r=1,i=i_M}^{N_I,N_R} (\rho_{ri}C^T_{tri} - \widehat{C^T_{tri}})^2/(0.1+\rho_{ri}C^T_{tri})$$
$$+\sum_{rsij} 100(p_{rsij} - \widehat{p_{rsij}})^2/(0.02+p_{rsij})$$
$$+\sum_{ri} 1000\big(\log(1.0+C_{ri}) - \log(1.0+\widehat{C_{ri}})\big)^2$$
$$+\sum_{ri} 1000\big(\log(.1+A_{ri}) - \tau\log(.1+\widehat{A_{ri}})\big)\big)^2$$

$$f_2 = \sum_{r=1,i=i_M}^{N_R,N_I-1} \big(\log(\rho_{ri}) - \log(\rho_{r,i+1})\big)^2$$
$$+\sum_{r=1,j=1}^{N_R,N_J-2} (a_{rsj} - 2a_{rs,j+1} + a_{rs,j+2})^2$$
$$+\sum_{r=1,i=1}^{N_R,N_I} \log\big(0.95\exp(-10.0\epsilon^2_{ri}) + 0.05\exp(-2.0\epsilon^2_{ri})\big)$$

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 corrsponding 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 assymptotic form of the posterior Bayes factor (Aitken 1991, pg 116) takes the form of a penalized likelihood ratio

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

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.

The following table shows the model parameters that are estimated through the minimization for a "base case" and "full model" implementation.

parameter	estimated	number of parameters: base case	number of parameters: full model
$\bar{R}$	estimated	1	1
η_{ri}	estimated only for regions 1 and 4	64	64
γ	estimated	0	1
M	not estimated, fixed at 0.08	0	0
a_{rsj}	common parameters for regions 1 thru 3 and 4 thru 7, last two age-classes have common parameter, fixed at one for females in last two age classes	54	54
ϵ_{ri}	estimated	224	224
q_r	estimated	7	7
$d_{rr'1}$	estimated where regions r and r' are contiguous	26	26
$d_{rr'2}$	estimated where regions r and r' are contiguous	0	26
ρ_{ri}	estimated for years with tag return data, common parameters for all regions except where a second set of parameters estimated for US region	0	6,12, 18 or 36
s_r^T	fixed at 0.90, except where one parameter estimated for deep regions	0	1

Model Data

The B.C. sablefish fisheries data is analyzed with the integrated model using the same data as for the 1997 stock assessment (Haist et al. 1998), with some data updated through 1997. The additional data is the 1997 fall/winter coastwide sablefish survey abundance indices and the 1997 tag recovery data. The B.C. coast is treated as six distinct regions that separate the coast geographically into a southern and a northern area and bathymetriclly into three depth zones. The depth zones are; < 500 meters (shallow), 500–800 meters (mid-depth), and > 800 meters (deep). A seventh region, the U.S., is accommodated in the model to account for tag recoveries in this area. The following table shows the specific areas included in each region, and the notation we will use in referring to them.

Region	region notation	depth (meters)	major areas	minor areas
southern B.C. shallow	SS	<500	common areas for southern B.C. regions:	
southern B.C. mid-depth	SM	500–800	3 to 5	23 to 27,
southern B.C. deep	SD	>800		11
northern B.C shallow	NS	<500	common areas for northern B.C. regions:	
northern B.C. mid-depth	NM	500–800	6 to 9	1 to 10,
northern B.C. deep	ND	>800		31, 34, 35
United States	US	all depths	10 (Alaska) 2 (Washington) 22 (Oregeon) 23 (California)	

Catch and Age Composition

Although three gear types (trap, longline, and trawl) catch and land sablefish in B.C., there currently is no information on the age structure of the catches from the different fisheries. The only source of age and sex-composition data, where depth of capture is know, is research surveys. Research surveys are conducted using trap gear and are likely to have similar age and sex specific selectivity to that of the commercial trap gear. This assumption is not likely to hold for the longline and trawl fisheries. However, in the absence of gear-specific data, the age data from research surveys are assumed to reflect the total commercial catch. Age-composition is available for the 1980–1995 time period.

B.C. sablefish landings data is available since 1918, but information on the depth of capture is only available for all fisheries from 1980 on. For the current analysis we use catch data from 1966 to 1997. For the 1966 to 1980 period information on gear type and the general area (i.e. northern or southern B.C.) of catch is known, so for these years we allocate the catch to depth zones based on the gear-specific depth distribution of the catch in the early 1980's. Between 1918 and 1966 the B.C. coastwide annual sablefish catch was relatively stable, averaging 850 tonnes per year. Since then, catches have been higher and more variable with average annual landings of 4490 tonnes (Table 1).

Survey Abundance Indices

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 region's 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.

Sablefish Tag Release and Recovery Data

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 (Saunders et al. 1995). 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 1996 that followed the systematic design. Additionally, for the earlier period, release groups were restricted to those that occurred within the general areas utilized by the commercial fishery.

Table 2 summarizes information on the minor area of release for the 85,853 tag releases used in the current analysis. There are many instances of inconsistency between the major and the minor area of release coded in the tagging data base. For example, tag releases coded as both minor area 8 and minor area 11 are at various times coded as major areas 4, 5, 6, and 9. In cases of inconsistency, the major area was assumed correct (M. Saunders, pers. comm.) for purposes of our analysis. However, the information in Table 1 is based on the coded minor area of release. The table does not include information for 421 tags for which the major area of release was consistent with the study area but the minor area was not. The extent to which these discrepancies in the data may bias the analysis is not clear. The data input to the integrated model is the total number of tag releases by region, year, and quarter.

Tag recovery information is available for 13,479 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 developed a process to 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 or where the recovery date was earlier than the tagging date were excluded from the analysis (35 recoveries). An additional 169 tags were not included because they had incomplete information and there was no basis on which to allocate them to a recovery strata (i.e. no recoveries for that year with more complete information).

A summary of tag recoveries by period of release (1979–1982 and 1991–1996) and major area of recovery is presented in Table 3. The proportion of tags recovered in the U.S. region is higher for the 1979–1982 releases than for the 1991–1996 releases. This is true for both recoveries in the southern part of the U.S. region and in the northern part. However, it is not reasonable to make inferences from these comparisons because the data have not been standardized for the relative fishing mortality rates between regions and differences between the number of years-at-large for tag groups in the two time periods. We merely make this observation because it warrants further examination.

There are also some interesting differences in the sex ratios of sablefish recovered in the different regions (Table 4). In general, the sablefish recovered in Alaska show a higher proportion of males than the B.C. recoveries of the same tag release groups. This holds for all release groups except the 1991–1996 releases in the northern deep region, however samples sizes are small for many of the comparisons. As stated in the previous paragraph it is not possible to make inferences from these observations because there are many factors that may influence the observed sex ratios, which are not randomized or standardized, however these differences warrant further examination.

Model Analyses

A number of fits of the integrated model to the B.C. sablefish data were conducted to explore the stability of results under alternative assumptions. Through this process we developed a "base" model structure that appeared to have reasonable properties. In part this structure relates to assumptions we make 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. Features of the "base" model structure are:

- 15 age-classes (age 2 to 16+)
- recruitment only to the northern and southern shallow regions
- common catchability (q_r) 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-class 15 equal to that for age-class 16+
- availability fixed at 1 for age-class 16+ 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 regions

- no relationship between survey abundance estimates and model estimates of abundance (i.e. weight of zero for this component of likelihood function)

Direct estimation of movement parameters was restricted to those that shared common borders. These are noted with a "1" in the table below.

from	to						
	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	

We used the posterior Bayes factor hypothesis testing procedure as outlined above to test numerous alternative model structures. These are:

1) a different average recruitment level prior to 1966 than for 1966–1997

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" zones less than in shallower zones

5) age-dependent movement of sablefish among region

Each of the hypotheses was added to the model structure in a step-wise fashion. The integrated model was fit to the full 1979–1996 tag release and recovery data set and to a restricted 1991–1996 tag release and recovery data set. The catch and age-composition data were the same for both sets of analyses. Estimates of the log-likelihood function value and the posterior Bayes factor are shown in Table 5 for the alternative model structures.

For the analyses based on the full tag release and recovery data set, the addition of each model hypothesis provides "overwhelming" sample evidence for the more complex model structure over the simpler model structure. The results of analyses with the limited tagging data set suggest that for two of the hypotheses tested, the data do not provide convincing support for the more complex model structure. These hypotheses are that average recruitment prior to 1966 is different than the average from 1966 to 1996 and that the initial survival of tagged fish in "deep" zones is less than in shallower zones. In the hypothesis testing process, the model structure for these two hypotheses was maintained, even though they were not strongly supported by the data. Each was then independently removed from the full model structure. The values for the posterior Bayes factor when each of the hypotheses was removed from the full model suggests that the data "overwhelmingly" support the "average recruitment" model structure and strongly support the "deep zone tag survival" model structure.

A summary of the results of the sablefish analysis that are of interest in the context of stock assessment is given below for both the analyses with the full and with the limited tag release and recovery data set. These results pertain to the model that includes the full range of hypotheses tested.

Model fit to age-composition and tagging data

The number of tag recovery observations fit with the integrated model is large (2905 and 798 observations with the full and partial tag recovery data sets, respectively), so we do not attempt to interpret the individual fits, rather we have summarized the information. We summarize the total observed and predicted tag recoveries by release and recovery region and the number of years-at-large (1 through 4+) for all 1979–1982 tag releases and for all 1991–1996 tag releases. For the analysis based on the entire tag release data set, the fits for the 1991–1996 releases are somewhat better than for the 1979–1982 releases (Figures 1 and 2). This is particularly true for the recoveries of tags released in the southern and northern mid-depth regions, where a high proportion of releases and recoveries occur. There are some patterns in the fits that suggest sablefish movement may not strictly follow the Markovian process we assume in the analysis. For example, for fish tagged northern B.C., the predicted recovery of tags in southern B.C. shallow and deep regions is consistently higher than the observed values, suggesting that movement at any point in time may not be independent of previous movement. For the analysis with the restricted (1991–1996) tag release data set, the fits between observed and predicted tag recoveries are somewhat better than those from the analysis with the entire tag release data set, however, the general pattern of the fits is the same (Figure 3).

We have further summarized the tagging data fits by summing the predicted and observed tag recovery data across all tag releases for each tag release period. We present these results by the number of years-at-large and tag release period in Figures 4 and 5. Overall, the fits for the 1991–1996 tag release data are better than those for the earlier period. The most persistent lack-of-fit is between observed and predicted recoveries of tagged fish at large for 4 and more years for the 1978–1982 release period.

The observed and predicted age and sex composition is shown in Figure 6 for the analysis utilizing the partial (1991+) tag release data set. Results are similar for the analysis with the full tag release data set. For both analyses the model overestimates the proportion of males in the northern and southern shallow regions and underestimates these proportions for the two mid-depth and deep regions. For all regions except the southern deep region the proportion of old fish (age 16+) has decreased over the 1980–1995 time period. This decline is more marked in the northern regions than in the southern ones.

Model parameter estimates

The estimated proportions of the first and the last age-class (age 2 and age 16+) moving between regions are presented for the analysis with the partial tag release data set (Table 6) and with the full tag release data set (Table7). The estimated movement rates between southern B.C. and northern B.C. regions are small, in general less than 3% annually. The estimated movement rates to the U.S. region are substantially higher, in particular, movement from northern B.C. regions which average about 15% per year. Movement in the reverse direction, that is, from the U.S. region to the B.C. regions, is minimal with all parameter estimates less than 1%. However, because we do not include data on tag releases in the U.S. region, there is essentially no information in the model to estimate movement from the U.S. to B.C. regions, and the values for these parameters are likely biased.

Annual tag reporting rates for the B.C. and the U.S. fisheries, estimated using the full and the partial tag release data sets, are shown in Figure 7. For the earlier years, the estimated trends in the reporting rates are similar for the B.C. and U.S. fisheries with higher levels in the early 1980's, decreased rates through the late 1980's and increasing rates in the early 1990's. Since 1994 the trends have diverged with a decline in reporting rates for the U.S. fisheries and increased reporting rates for the B.C. fisheries. It should be noted that the estimates of the U.S. reporting rates are confounded with the value of the U.S. fishing mortality rate, which we fix in the current analysis. When we assume a higher value for F in the U.S. region, as we describe below, the estimates of U.S. reporting rates decrease substantially.

In our model structure, we have assumed that there is an immediate 10% mortality for all tagged fish. Because of concern that fish caught in the deeper locations have a higher mortality associated with the tagging process we include a parameter in the model to estimate the mortality of fish tagged in the southern and northern deep regions. The estimated mortality of fish tagged in deep areas is 25% for the analysis using the partial tag release data set and 33% for the analysis using the full tag release data set.

Estimates of the age and sex-specific proportions of fish available to the fisheries for the northern and southern B.C. regions are shown in Figure 8. Because of the predominance of female fish in the catch, particularly in northern B.C., the model estimates suggest that a very low proportion of male fish are available to the fishery.

Stock Abundance and Recruitment time series

The estimates of available biomass (1966–1997) and of year-class size (1964–1992) for the analyses using the partial and full tag-release data series, are shown in Figure 9. This figure provides some insight into the fundamental difference between these two analyses. The trends in year-class size are similar for the two analyses except for the relative sizes of the first two and the last three in the series. The first year-class size (i.e. 1964) is that which is used generate the initial stationary population. Hence the estimated initial population size for the analysis using the 1991+ tag release data is significantly larger than the analysis using the 1979+ tag release data. We do not expect that the initial population size is well determined, given the data available for the analysis. The first age composition data occurs in 1980. This data represents the age and sex composition of available fish in the different regions. Small changes in the proportions of the total stock that occur in each region will substantially alter the age and sex composition of the total stock. Therefore the age-composition data probably provides little information regarding the 1964 population size. The relative year-class size for the 1990 to 1992 cohorts are also not well determined from the age-composition data. The last age-composition data available for the analysis is for 1995, so these year-classes are only represented in a few years data. Updating the age composition data through 1997 may make the estimates of the relative size of these year-classes more similar for the two analyses.

Inclusion of Survey Abundance Data

We did an additional set of model runs that incorporated the assumption that annual sablefish survey CPUE estimates are proportional to the available number of sablefish in each region. Survey abundance indices are available for some of the B.C. regions beginning in 1988, but are not available for all regions until 1992 (Figure 10). The survey CPUE estimates show a general downward trend over this time period.

For the analysis that used the partial tag release data series, the decline in available biomass over the 1964–1997 period is accentuated when the survey CPUE assumption is added to the model (Figure 10). The estimated biomass declines from over 200,000 t. in 1964 to 20,000 t. in 1997 and the trends in predicted CPUE are similar to those in the observed estimates. For the analysis using the full tag release data series the trends in the predicted CPUE do not follow those in the data observations.

Sensitivity to US Zone Fishing Mortality rate

An additional series of analyses were conducted to evaluate the sensitivity of model parameters, in particular the estimates of B.C. sablefish biomass, to the assumption of a constant US fishing mortality rate of 0.08. We did a series of runs with the F level for the U.S. fishery ranging from 0.04 to 0.20. Results from these analyses are shown in Table 8. The estimate of B.C. coastwide available biomass in 1997 was relatively insensitive to increasing the U.S. F to 0.20, with available biomass increasing by a factor of 1.04 and 1.07 for the analyses with the partial and the full tag release data, respectively. The estimates of available biomass in the U.S. region were more sensitive to the specified U.S. F level, and biomass estimates decreased substantially with higher F's. It is important to note that these estimates of available biomass for the U.S. region are only for the sablefish that migrate from B.C., not estimates for the total stock.

The parameter for the U.S. fishing mortality rate is not fixed in the integrated model analysis, rather there is a penalty function for deviating from the specified level. For the analyses describe so far the weight applied to the penalty function was high, and the annual estimates of F for the U.S. zone are very close to the specified level (i.e. 0.001). To investigate the potential of time-trends in the U.S. fishing mortality rates, we did a run where the penalty weight applied to the U.S. F values was decreased to 5 for the analysis with the full tag release data set. In this case the estimated F's were all close to the specified value of 0.08, except for the estimate for 1980 through 1983 where the values were 0.18, 1.00, 0.22, and 0.25.

Discussion of Model Analyses

The difference in the stock reconstruction when the full tag release data set is fit relative to that when only the partial tag release data set is fit is of some concern as we do not have an objective method to determine which data set is more appropriate for the sablefish analysis. The major difference between the two analyses are the estimated population sizes for the first years and the resulting stock trajectory to the current period. Estimated available stock biomass for the terminal year is similar for the two analyses. The tag release groups included in the 1979–1982 release data were selected on the basis that they covered a fairly broad geographic area within the range utilized by the commercial fisheries, so the expectation is that recoveries should follow similar patterns to those of the more recent tagging programs.

The estimated movement parameters suggest relatively low rates of movement between the southern and northern B.C. regions, with annual rates between individual regions generally less than 3%. Movement rates to the US region are higher, in particular movement from northern B.C. to the US zone (primarily Alaska) which averages approximately 15% per year. These results, in conjunction with analyses of US sablefish tagging data, provide a consistent picture of sablefish stock structure in the northeastern Pacific. Kimura et al. (1997) analyzed tag return data from Alaskan and west coast US sablefish tagging programs and concluded that the data provided compelling evidence that Alaska and west coast sablefish constitute separate populations (for management purposes, not separate biological populations). They suggest the dominant circulation pattern in the northeast Pacific, the counter-clockwise Alaska Gyre and the clockwise Central Pacific Gyre as a possible mechanism for both separation and partial exchanges between Alaska and the west coast stocks. Our results suggest that sablefish in northern B.C. are part of the Alaskan population and sablefish in southern B.C. belong to the west coast population. Analyses of Alaska tag return data showed a tendency for smaller fish to move in a north-westerly direction and larger fish to move in a south and easterly direction (Heifetz and Fujioka 1991; Maloney and Heifetz 1997). Similarly, tag-returns from juvenile fish tagged in northern B.C. indicate high rates of movement in northerly directions (Beamish and McFarlane 1983, McFarlane and Saunders 1997). Juvenile fish tagged off the west coast of Vancouver Island were more likely to be recaptured in that region, and those that did move were as likely to move north as south (McFarlane and Saunders 1997). Our analysis suggests a similar pattern with younger fish having higher movement rates from northern B.C. to the US region. However we have not included data on age or size of fish at recapture in the integrated model and hence, the primary source of information for estimating age-specific movement is the fishery age-composition data. The length of fish at tagging is available for all recaptures, and it would be useful to incorporate this information in the model fit.

We have not attempted to model sex-specific movement, but believe that there is a sex related component to movement. The data presented in Table 4 suggests that a higher proportion of male fish migrate from B.C. to the US regions, although this does not seem to hold for all tag release groups. The sex ratio of tag recoveries may be confounded with seasonal differences in the sex ratio of the catch. We have summarized the sex-ratio of tag returns by region and month of recapture (Table 9). This data indicates a lower proportion of males in the tag returns from fish recaptured between January and March in southern B.C. and between February and March in northern B.C. Alaska recoveries show a higher proportion of males in the tagged fish recaptured between June and September. We do not know if these differences reflect seasonal differences in the sex-ratio of the catch. Modelling sex-specific movement would likely improve our understanding of the dynamics of the sablefish populations, but would require more detailed information on seasonal changes in the sex ratio of the catch.

Stock Projections

The 1996 sablefish stock assessment document (Saunders et al. 1996) presented results from a series of analyses conducted to determine appropriate harvest reference points for the B.C. sablefish fishery. The analyses were based on spawning stock biomass per recruit (SSBR) calculations, and the appropriate target fishing mortality rates (F) were considered to be those that reduced the SSBR to 40 to 45% of the unfished level. These analyses resulted in target fishing mortality rates of 0.11 to 0.13.

Application of the target fishing mortality rates that resulted from the SSBR calculations to the stock estimates from the current assessment is not a reasonable approach for two reasons. First, the SSBR calculations were based on fishery selectivity parameters and the integrated model we use for this years assessment is based on availability parameters and assumes equal selectivity for all fish that are available. Second, the level of fishing varies between the different regions so application of a single F to all regions would be inconsistent with the current fisheries. For example, the 1997 estimates of F for the different regions were:

	SS	SM	SD	NS	NM	ND
1979+ release data	0.174	0.251	0.025	0.017	0.343	0.120
1991+ release data	0.095	0.520	0.023	0.027	0.340	0.222

A re-evaluation of SSBR should be conducted based on the integrated model structure, however that is not possible for the current assessment. We base our projections of future harvest and stock abundance on the current F levels in the different regions.

We conduct deterministic stock projections for the years 1998 through 2006, for 3 fixed levels of recruitment and 3 fixed levels of fishing mortality. The recruitment levels are; 0.6, 1.0, and 1.4 times the mean of the 1966–1994 estimates. The region-specific F levels are; 0.8, 1.0, and 1.2 times the 1997 estimates. 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 stock projections begin with the estimated numbers-at-age (by sex and region) in 1997 for age-classes 5 through 16+ from the integrated model stock reconstructions. We do not use the estimates for age-classes 2 through 4 because there is no age data after 1995 and those estimates are biased. Recruitment of age-class 2 fish for 1995 through 2006 is equal to the specified fixed level.

The trajectory of catch and available biomass estimated for the alternative recruitment levels and harvest rates are shown in Figures 11 and 12. For all projections assuming an average level of recruitment, catch and available biomass decline steadily through to 2006. Assuming a higher level of recruitment, catch and available biomass are relatively constant for the analyses based on the full (1979+) tag release data, but show a steady decline for the analyses based on the partial (1991+) tag release data.

Yield Options

A summary table of 1999–2006 annual yields under varying levels of F and assumed recruitment is presented below. We use results of the 1991+ model since the recruitment time series, in particular the size of the 1992 year-class relative to those from the 1980's is more realistic. The range in yields for 1999 is from 2977 to 5052t. Under all but the high recruitment scenarios the biomass will decline slowly. While there is anecdotal evidence that the strength of the 1997 and 1998 year-classes is good, there is no evidence that the year-classes impacting 1999 yield calculations are exceptional.

Yield (t)

	0.8·Fcurr			Fcurr			1.2·Fcurr		
year	low R	med R	high R	low R	med R	high R	low R	med R	high R
1999	2977	3353	3728	3518	3972	4425	4002	4527	5052
2000	2774	3322	3870	3246	3902	4558	3657	4413	5168
2001	2608	3303	3997	3028	3854	4679	3388	4333	5277
2002	2453	3253	4054	2831	3776	4721	3153	4226	5300
2003	2326	3207	4089	2674	3708	4742	2967	4136	5305
2004	2248	3196	4145	2576	3684	4791	2852	4098	5344
2005	2160	3161	4163	2472	3636	4800	2732	4038	5343
2006	1982	3027	4072	2273	3484	4695	2518	3872	5226

Biomass (t)

	0.8·Fcurr			Fcurr			1.2·Fcurr		
year	low R	med R	high R	low R	med R	high R	low R	med R	high R
1999	41706	45814	49921	40862	44934	49006	40072	44110	48148
2000	39288	45252	51216	38175	44057	49938	37151	42955	48759
2001	37008	44672	52337	35705	43218	50730	34523	41895	49266
2002	34683	43672	52662	33262	42021	50780	31986	40053	49083
2003	32833	42928	53022	31333	41116	50898	30000	39499	48999
2004	31697	42757	53818	30125	40792	51458	28738	39051	49364
2005	30212	42038	53864	28633	39993	51352	27249	38192	49136
2006	27162	39672	52181	25760	37733	49706	24530	36029	47528

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Table 1. Annual B.C. sablefish landings by region, 1966-1997.

	annual sablefish landings (tonnes) by region						
year	SS	SM	SD	NS	NM	ND	total
66	271	23	0	503	107	0	905
67	843	143	1	488	171	1	1647
68	649	98	1	1535	620	2	2904
69	1983	366	2	1929	792	3	5076
70	1127	199	1	2956	1219	4	5506
71	1045	156	1	1641	678	2	3524
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
mean	1169	595	152	1104	1097	371	4487

Table 2. The number of tag releases by time period and area of release.

		Number of tag releases										
		Southern B.C. Minor Areas						Northern B.C. Minor Areas				
year	months	23	24	25	26	27	11	8	31	34	35	3
1979	5- 8	2506	5665	3					5624	134		
1980	1- 3		356			3276	782	2711	277	1151		
1980	6- 7								1384	4	427	451
1981	3								680	175		
1981	6								327	402		
1981	11					2			533			
1982	10-11	9				2612	102		2714			
1991	10	907				367	103		356	268	445	
1992	10-11	857			532	502	297		716	366	314	
1993	10-11	1989			1394	683	669		1057	890	337	
1994	10-11	836			356	434	333	312	667	459	207	
1995	10	1990		1706	176	1049	711	2346	3055	1547	163	
1996	5	2426	433	1083	332	1490	2138	2510	2834	1169	1000	
1996	9-10	1388		991	228		2216	1124	1945	268	154	

Table 3. Total tag recoveries, with known area of recovery, by period of release and area of recovery.

tag recovery area		tag recoveries from fish tagged in period	
major area	area description	1979-82	1991-96
23	California	21	1
22	Oregeon	24	5
2	Washington	88	18
3	S.W.coast Vancouver Island	1505	436
4	N.W.coast Vancouver Island	1140	1260
5	S. Queen Charlotte Sound	325	468
6	N. Queen Charlotte Sound	618	501
7	S. Hecate Strait	38	13
8	N. Hecate Strait	84	3
9	W. coast Queen Charlotte Islands	2354	1986
10	Alaska	649	358
	coastwide total	6846	5049

Table 4. Sex ratio of tag recoveries (proportion male) and number of sexed recoveries (in brackets) by period of tagging and area of recovery. The area notation is defined in the text. Recovery strata with fewer than 5 observations are not included in the table.

tagging		recovery area							
area	period	S.U.S.		S.B.C.		N.B.C.		N.U.S.	
SS	79-82			0.310	(377)	0.381	(21)	0.444	(9)
SS	91-96			0.265	(370)	0.130	(23)		
SM	79-82	0.480	(25)	0.384	(1829)	0.338	(80)	0.458	(24)
SM	91-96			0.409	(1279)	0.409	(110)	0.600	(15)
SD	79-82			0.377	(239)	0.364	(11)		
SD	91-96			0.361	(208)	0.286	(14)		
NS	79-82					0.250	(136)	0.419	(31)
NS	91-96			0.231	(13)	0.259	(54)	0.200	(5)
NM	79-82	0.500	(6)	0.285	(137)	0.415	(2234)	0.453	(117)
NM	91-96			0.498	(211)	0.533	(2037)	0.342	(79)
ND	79-82			0.000	(10)	0.243	(218)	0.333	(9)
ND	91-96			0.333	(9)	0.227	(185)	0.444	(9)

Table 5. Results of hypothesis tests concerning alternative model structures. N is the number of model parameters, function value is the negative of the log-likelihood value, and A is the posterior Bayes factor.

Parameter added to model structure	N	Function Value	A	N	Function value	A
base model	414	3237.00		414	9864.52	
pre-1966 recruitment level	415	3235.70	0.385	415	9813.29	<0.0001
annual reporting rates	421	3059.20	<0.0001	433	8857.03	<0.0001
US annual reporting rates	427	2946.64	<0.0001	451	8611.76	<0.0001
"deep" tag survival	428	2946.19	0.901	452	8590.24	<0.0001
age-dependent movement	454	2808.70	<0.0001	478	8111.81	<0.0001
Parameter removed from model structure						
pre-1966 recruitment level	453	2816.58	<0.0001			
"deep" tag survival	453	2813.22	0.0154			

Table 6. Estimates of the proportion of sablefish moving between regions. Results are from the analysis utilizing the partial (1991+) tag release data set. The underlined values indicate the movement parameters that are estimated directly in the analysis (i.e. independent model parameters).

moving	proportion moving annually from						
to	SS	SM	SD	NS	NM	ND	US
age 2							
SS	0.867	<u>0.445</u>	0.019	<u>0.009</u>	0.037	0.021	<u>0.005</u>
SM	<u>0.053</u>	0.409	<u>0.017</u>	0.008	<u>0.033</u>	0.019	<u>0.001</u>
SD	0.010	<u>0.079</u>	0.961	0.002	0.009	<u>0.030</u>	<u>0.000</u>
NS	<u>0.008</u>	0.006	0.000	0.654	<u>0.078</u>	0.043	<u>0.001</u>
NM	0.004	<u>0.020</u>	0.001	<u>0.146</u>	0.633	<u>0.351</u>	<u>0.005</u>
ND	0.001	0.001	<u>0.000</u>	0.008	<u>0.034</u>	0.403	<u>0.005</u>
US	<u>0.058</u>	<u>0.040</u>	<u>0.002</u>	<u>0.173</u>	<u>0.177</u>	<u>0.133</u>	<u>0.983</u>
age 15+							
SS	0.674	<u>0.065</u>	0.003	<u>0.000</u>	0.002	0.001	<u>0.002</u>
SM	<u>0.079</u>	0.319	<u>0.015</u>	0.000	<u>0.010</u>	0.005	<u>0.000</u>
SD	0.145	<u>0.583</u>	0.980	0.001	0.020	<u>0.040</u>	<u>0.001</u>
NS	<u>0.009</u>	0.003	0.000	0.801	<u>0.132</u>	0.056	<u>0.001</u>
NM	0.004	<u>0.013</u>	0.001	<u>0.024</u>	0.672	<u>0.285</u>	<u>0.005</u>
ND	0.001	0.001	<u>0.000</u>	0.003	<u>0.032</u>	0.509	<u>0.010</u>
US	<u>0.087</u>	<u>0.016</u>	<u>0.001</u>	<u>0.171</u>	<u>0.132</u>	<u>0.104</u>	<u>0.980</u>

Table 7. Estimates of the proportion of sablefish moving between regions. Results are from the analysis utilizing the full (1979+) tag release data set. The underlined values indicate the movement parameters that are estimated directly in the analysis (i.e. independent model parameters).

moving	proportion moving annually from						
to	SS	SM	SD	NS	NM	ND	US
age 2							
SS	0.755	<u>0.126</u>	0.014	<u>0.008</u>	0.013	0.008	<u>0.020</u>
SM	<u>0.142</u>	0.660	<u>0.071</u>	0.005	<u>0.045</u>	0.027	<u>0.004</u>
SD	0.016	<u>0.073</u>	0.901	0.001	0.005	<u>0.003</u>	<u>0.001</u>
NS	<u>0.034</u>	0.007	0.001	0.556	<u>0.042</u>	0.025	<u>0.002</u>
NM	0.007	<u>0.022</u>	0.002	<u>0.045</u>	0.621	<u>0.373</u>	<u>0.001</u>
ND	0.001	0.002	<u>0.000</u>	0.005	<u>0.063</u>	0.424	<u>0.001</u>
US	<u>0.045</u>	<u>0.109</u>	<u>0.012</u>	<u>0.381</u>	<u>0.211</u>	<u>0.139</u>	<u>0.971</u>
age 15+							
SS	0.321	<u>0.144</u>	0.026	<u>0.000</u>	0.003	0.002	<u>0.001</u>
SM	<u>0.186</u>	0.242	<u>0.044</u>	0.001	<u>0.005</u>	0.003	<u>0.001</u>
SD	0.456	<u>0.593</u>	0.926	0.002	0.013	<u>0.007</u>	<u>0.008</u>
NS	<u>0.028</u>	0.013	0.002	0.892	<u>0.229</u>	0.119	<u>0.005</u>
NM	0.003	<u>0.002</u>	0.000	<u>0.054</u>	0.582	<u>0.304</u>	<u>0.007</u>
ND	0.001	0.000	<u>0.000</u>	0.011	<u>0.116</u>	0.524	<u>0.012</u>
US	<u>0.005</u>	<u>0.005</u>	<u>0.001</u>	<u>0.040</u>	<u>0.051</u>	<u>0.041</u>	<u>0.966</u>

Table 8. Estimates of the objective function value, exploitation rates, and available biomass in B.C. and U.S. regions with different assumptions regarding the fishing mortality rate (F) in the U.S. zone. Note: the estimates of biomass in the U.S. region is only for sablefish which have migrated from B.C.

				Available Biomass (tonnes)			
	Function	Exploitation rate		B.C. coast		U.S. region	
F	Value	males	females	1966	1997	1966	1997
91-96 release data							
0.04	2829.18	0.008	0.038	43,400	38,300	119,700	87,400
0.08	2808.70	0.014	0.078	81,400	43,900	188,100	83,100
0.12	2813.22	0.019	0.109	90,200	44,200	164,300	68,200
0.16	2818.24	0.022	0.142	89,800	44,800	140,200	59,400
0.20	2841.82	0.024	0.174	88,900	45,600	119,100	52,000
79-96 release data							
0.04	8159.71	0.007	0.037	20,000	40,500	69,600	124,800
0.08	8111.81	0.011	0.074	22,900	51,300	81,700	161,400
0.12	8092.77	0.014	0.108	25,100	53,700	77,500	151,000
0.16	8090.80	0.017	0.141	26,300	54,000	76,500	145,600
0.20	8098.15	0.020	0.173	27,300	54,700	71,500	135,900

Table 9. The proportion of tag recoveries that are male fish (P) and sample size (N) for recoveries with sex information for all recoveries from 1977-1996 tag releases by area of recovery (SBC – southern B.C.; NBC –northern B.C. and Alaska).

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.
SBC	P	0.24	0.22	0.27	0.38	0.35	0.39	0.44	0.34	0.36	0.43	0.41	0.46
	N	105	120	234	603	622	844	303	348	448	408	545	134
NBC	P	0.49	0.28	0.39	0.46	0.45	0.49	0.41	0.44	0.40	0.46	0.45	0.41
	N	313	600	969	479	516	840	591	622	528	304	299	81
Alaska	P	1.00	0.67	0.46	0.31	0.37	0.55	0.64	0.43	0.56	0.39	0.43	0.33
	N	3	3	11	32	87	55	25	30	45	33	14	12

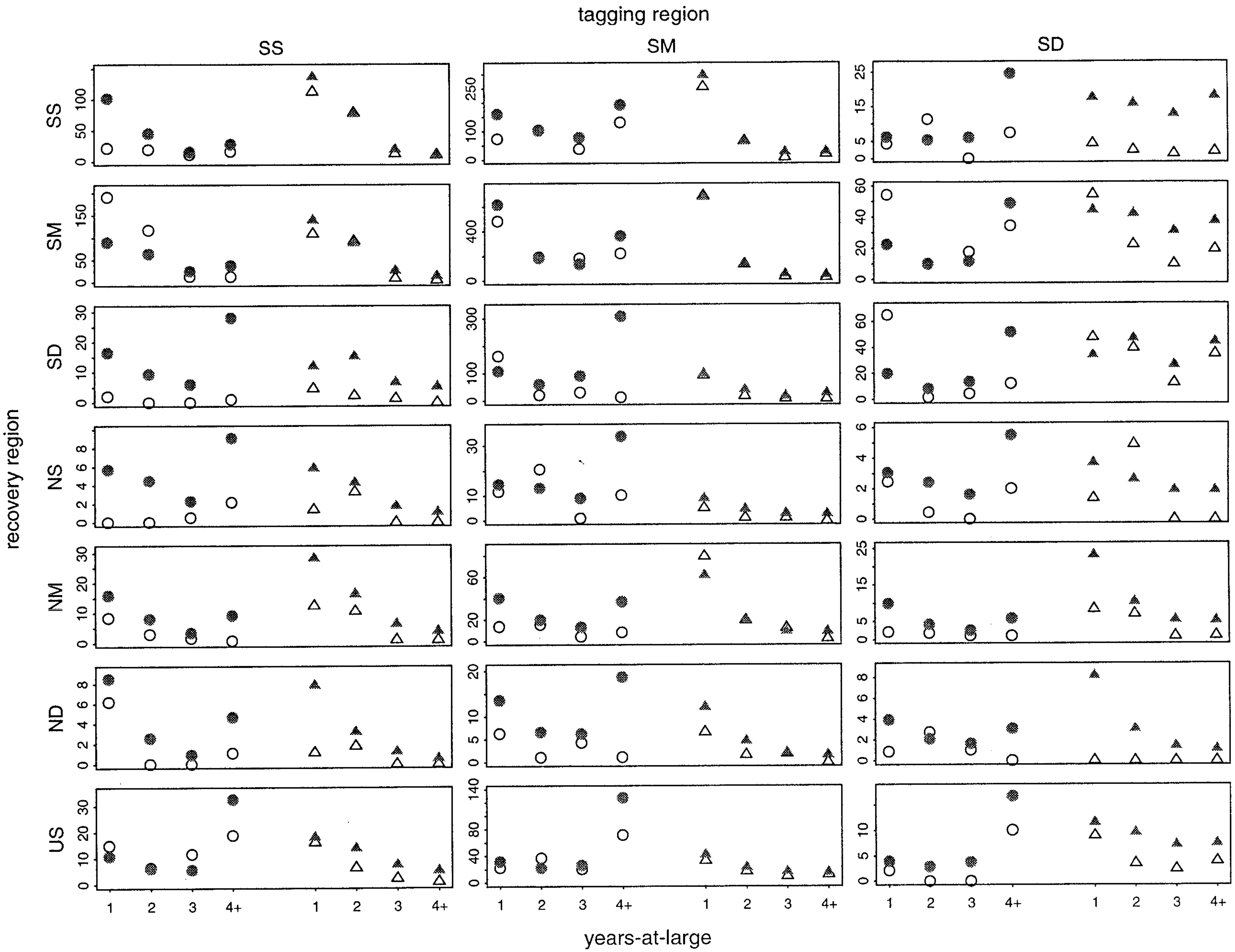

Figure 1. Observed (filled symbols) and predicted (open symbols) tag recoveries by region of release, recovery, and years-at-large for all 1979-1982 tag releases (circles) and all 1991-1996 tag releases (triangles). Results are from the analysis using the full (1979+) tag release data set.

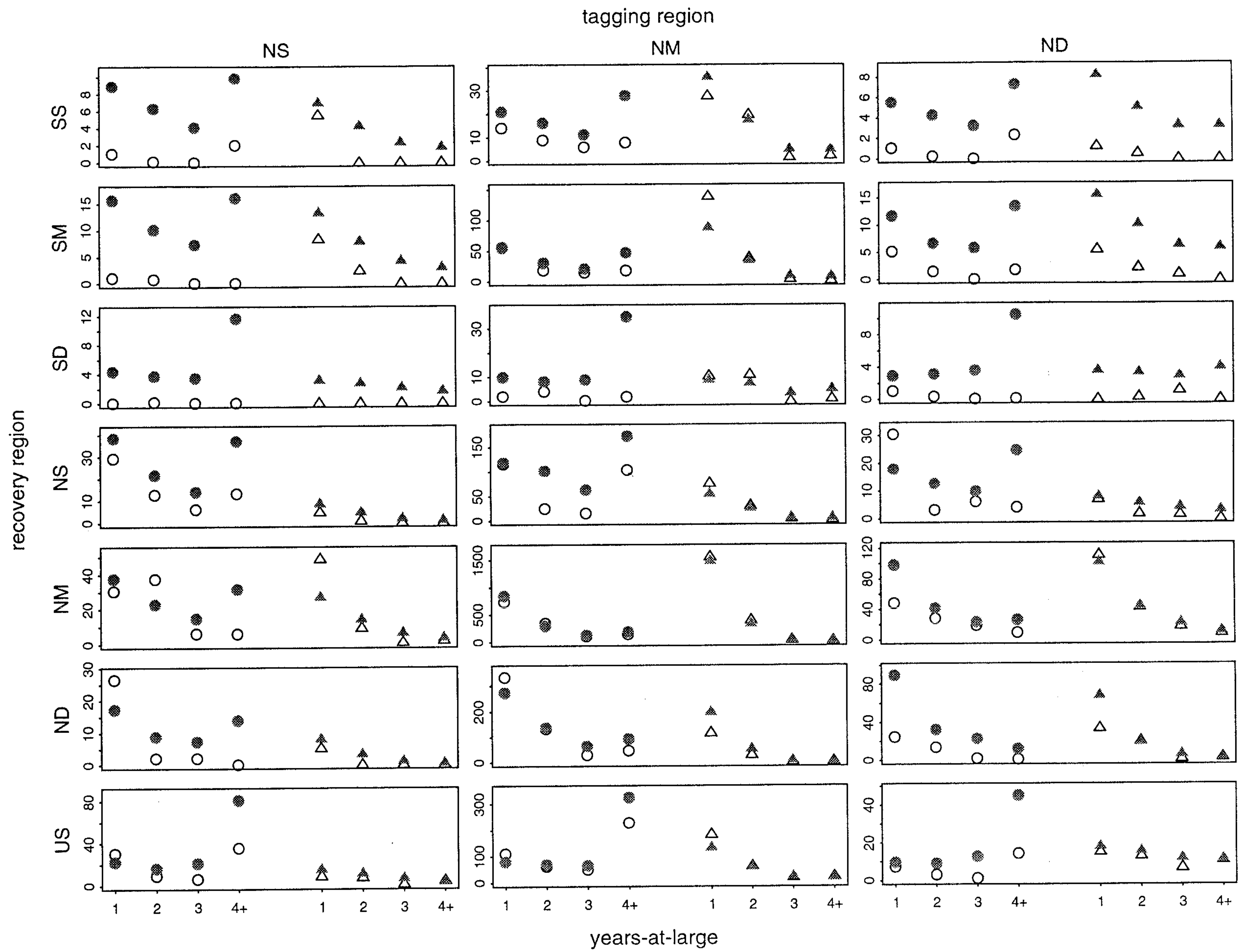

Figure 2. Observed (filled symbols) and predicted (open symbols) tag recoveries by region of release, recovery, and years-at-large for all 1979-1982 tag releases (circles) and all 1991-1996 tag releases (triangles). Results are from the analysis using the full (1979+) tag release data set.

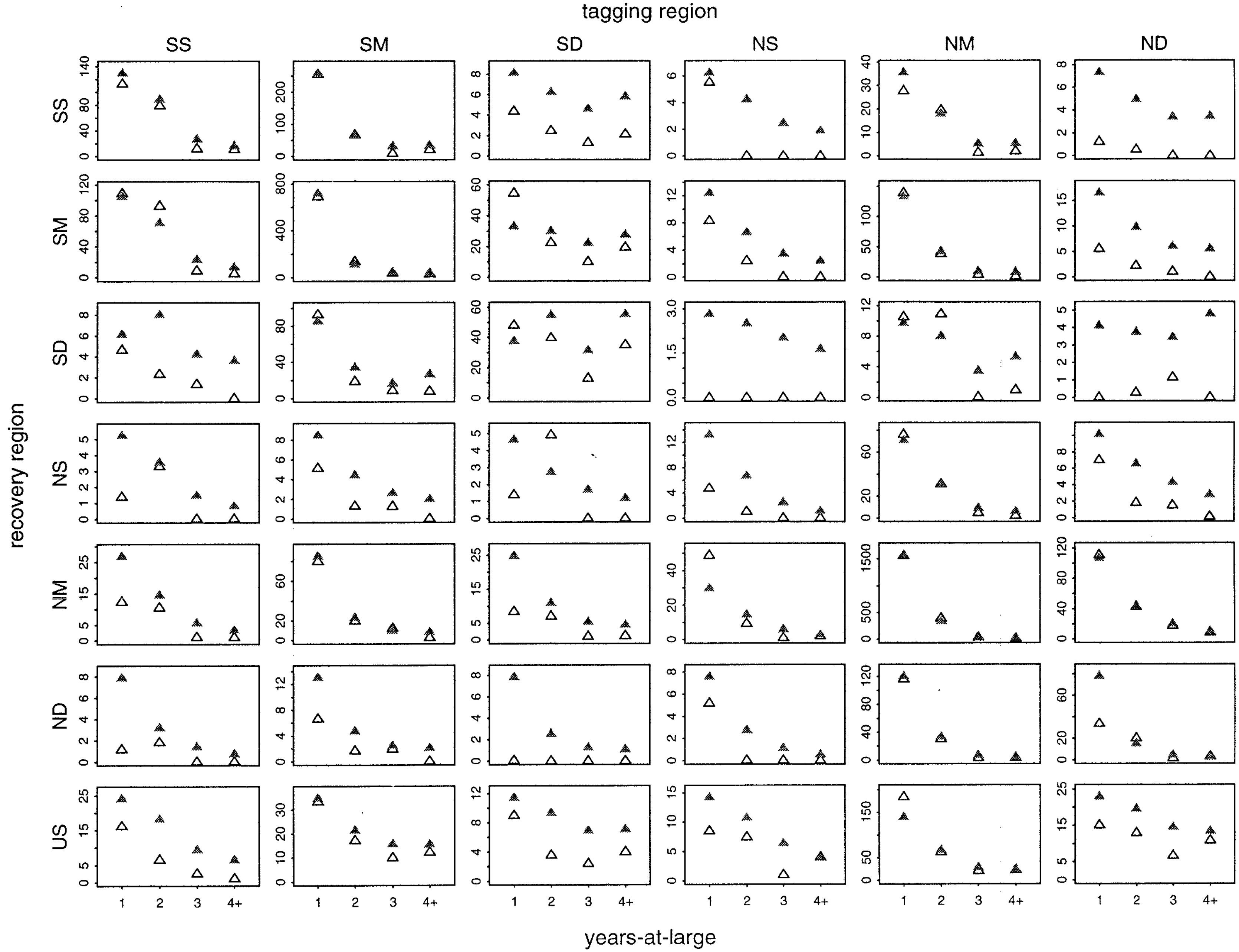

Figure 3. Observed (filled symbols) and predicted (open symbols) tag recoveries by region of release, region of recovery, and years-at-large for all 1991 to 1996 tag releases. Results are from analyses using the partial (1991+) tag release data set.

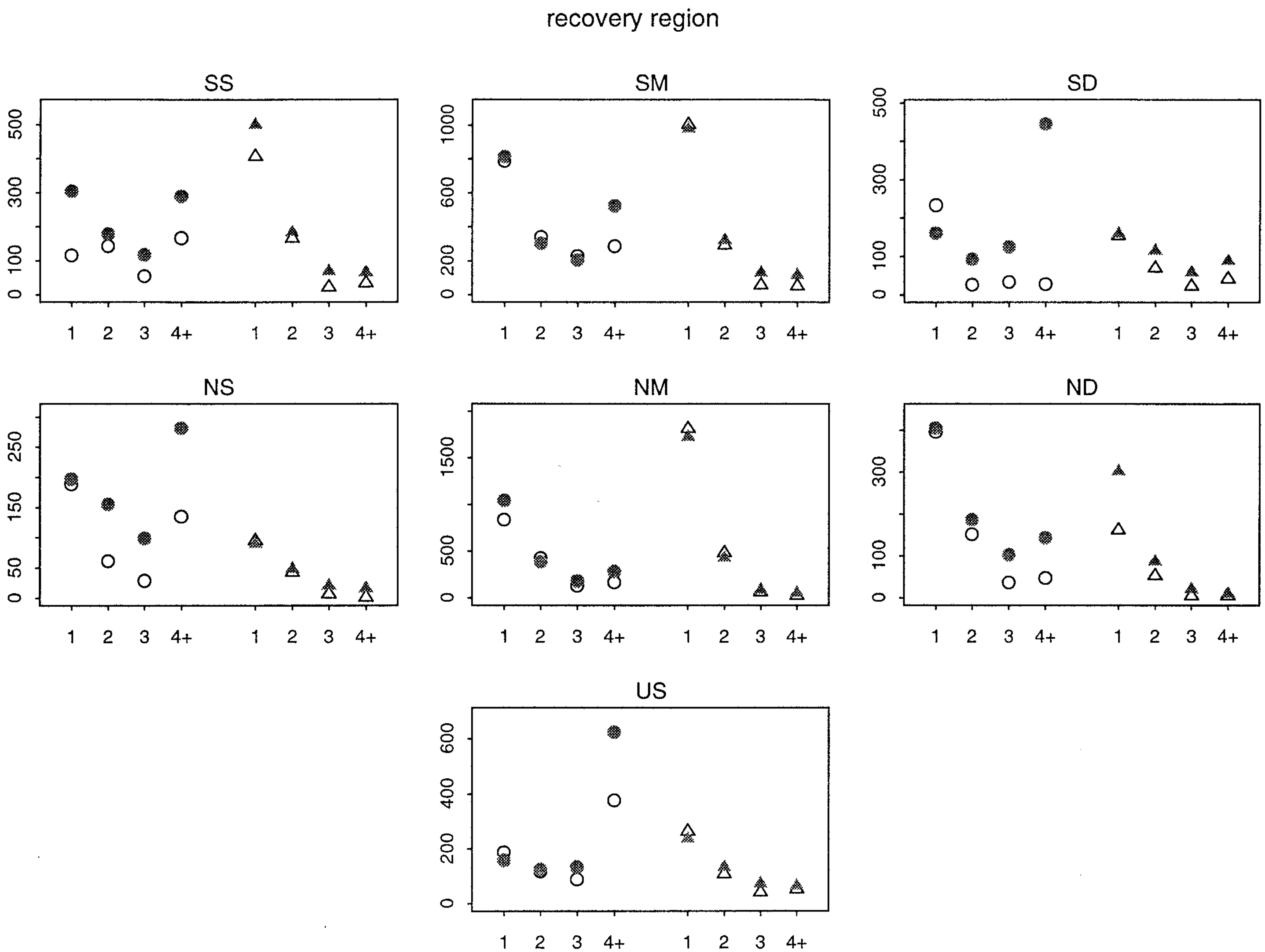

Figure 4. Observed (filled symbols) and predicted (open symbols) tag recoveries by recovery region and years-at-large for all tag release groups between 1979 and 1982 (circles) and tag release groups between 1991 and 1996 (triangels). Results are from analyses using the full (1979+) tag release data set.

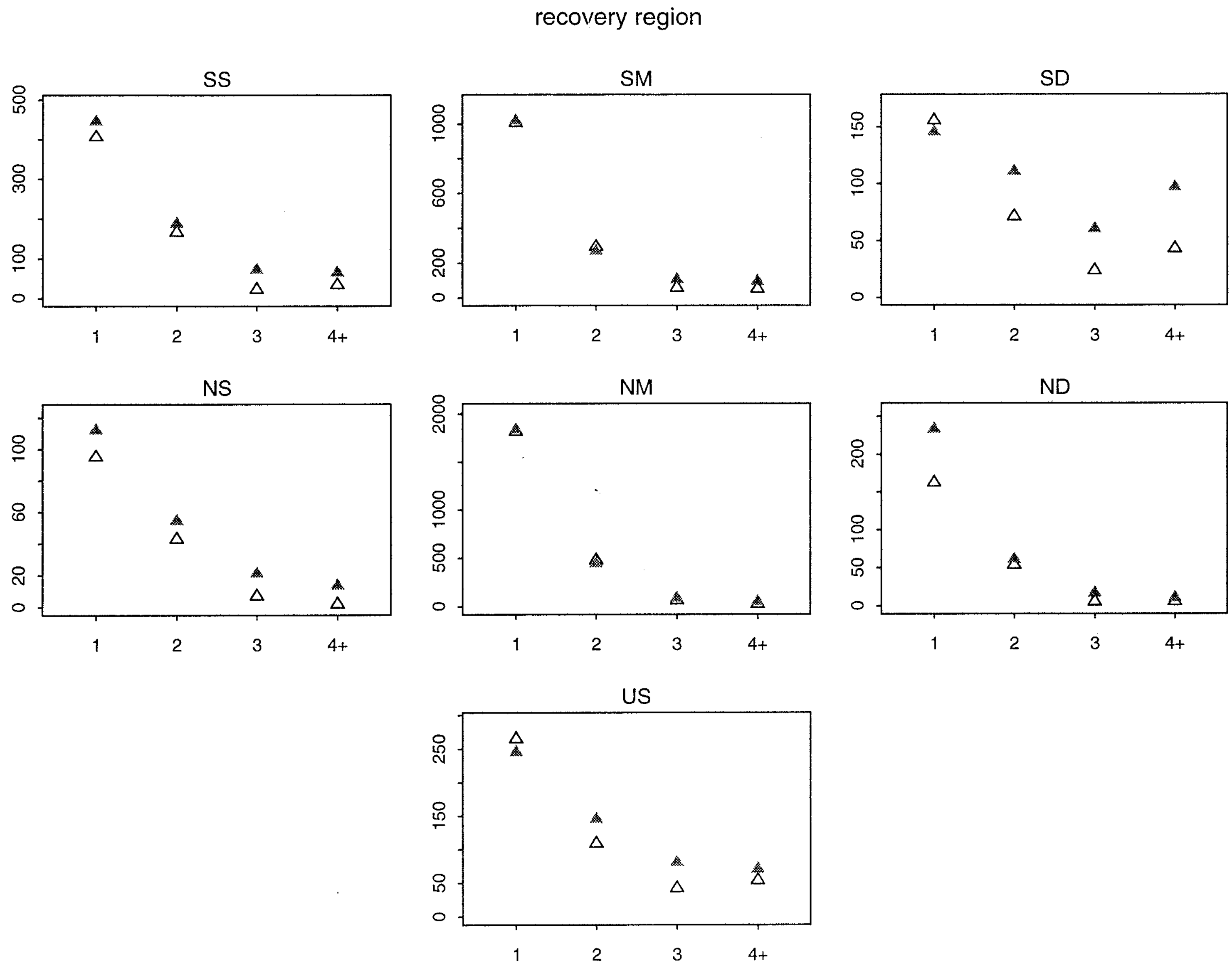

Figure 5. Observed (filled symbols) and predicted (open symbols) tag recoveries by recovery region and years-at-large for all tag release groups between 1991 and 1996. Results are from analyses using the partial (1991+) tag release data set.

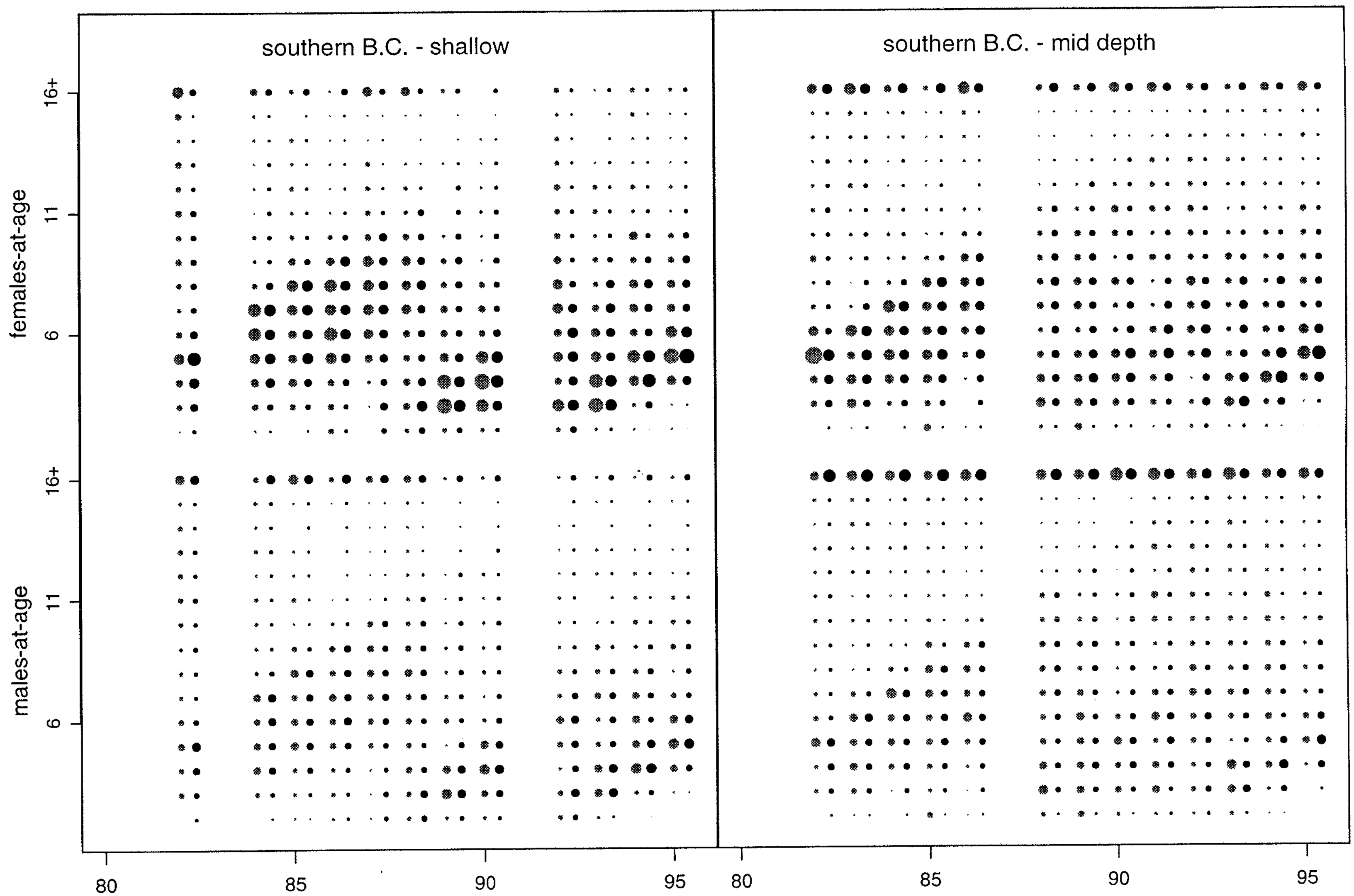

Figure 6. Observed (green) and predicted (black) proportions-at-age and sex by region. The circle areas are proportional to the values of the proportion-at-age and sex. Results are from analyses using the partial (1991+) tag release data set.

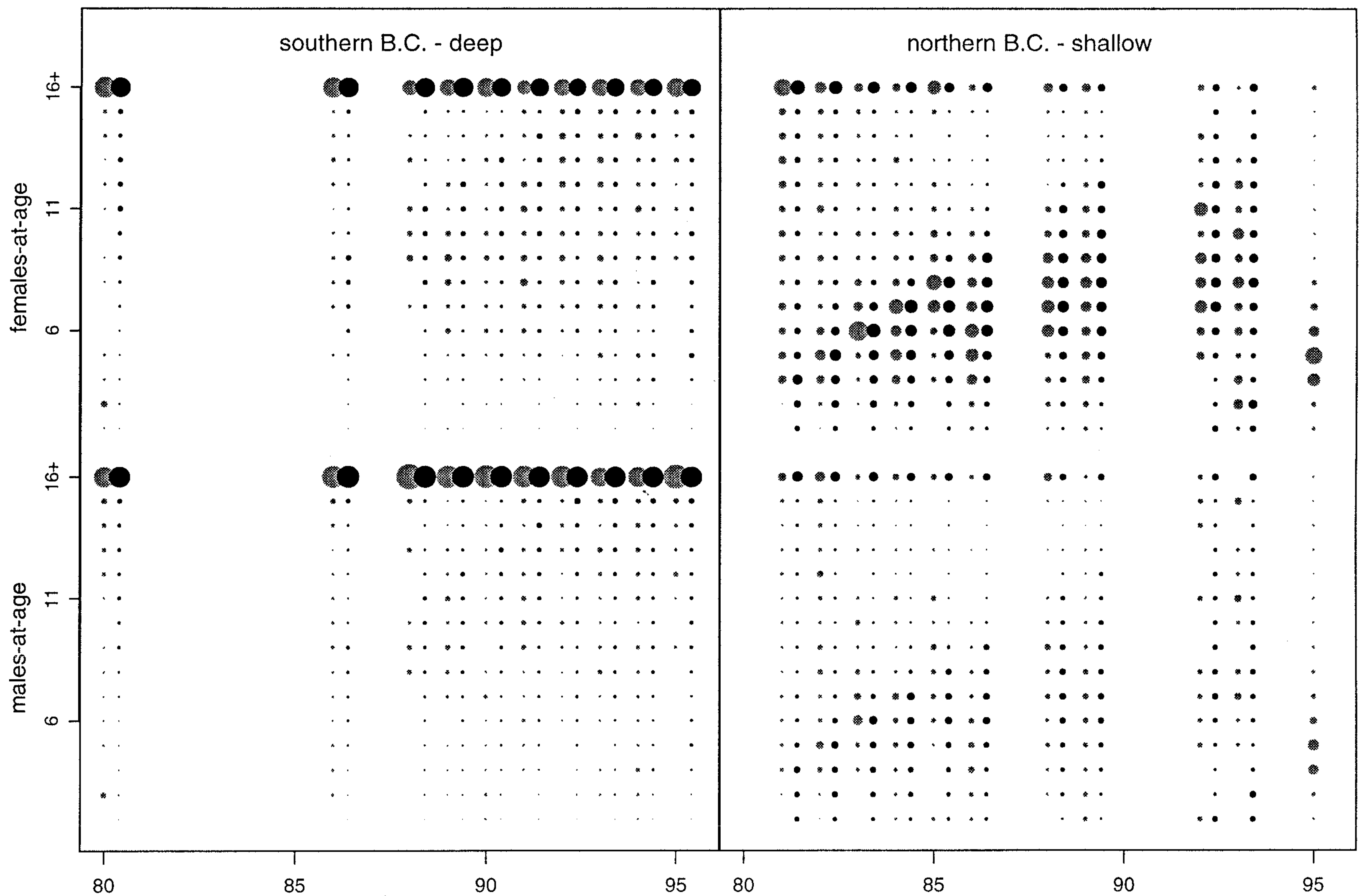

Figure 6 (cont.) Observed (green) and predicted (black) proportions-at-age and sex by region. The circle areas are proportional to the values of the proportion-at-age and sex. Results are from analyses using the partial (1991+) tag release data set.

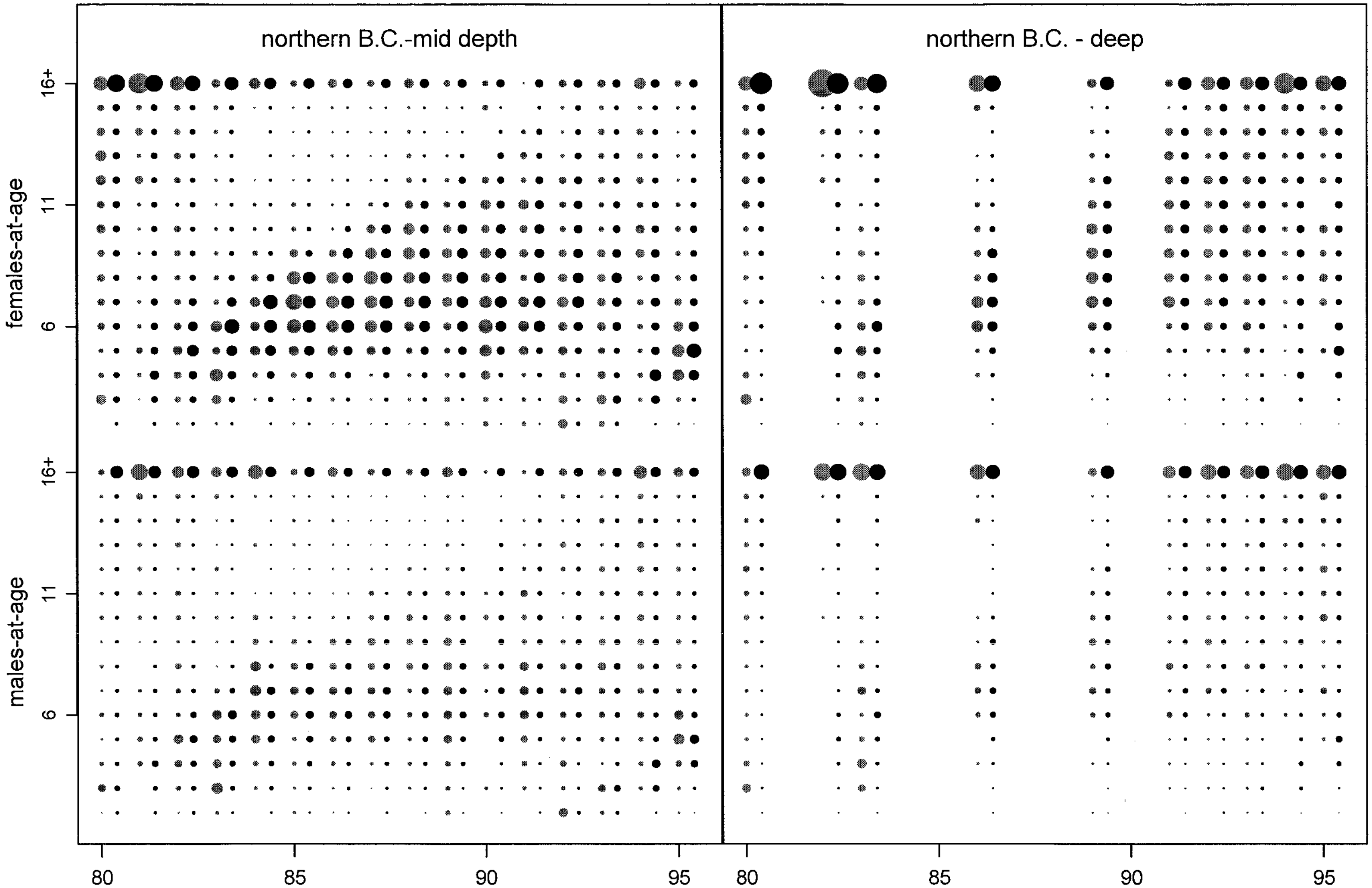

Figure 6 (cont.) Observed (grey) and predicted (black) proportions-at-age and sex by region. The circle areas are proportional to the values of the proportion-at-age and sex. Results are from analyses using the partial (1991+) tag release data set

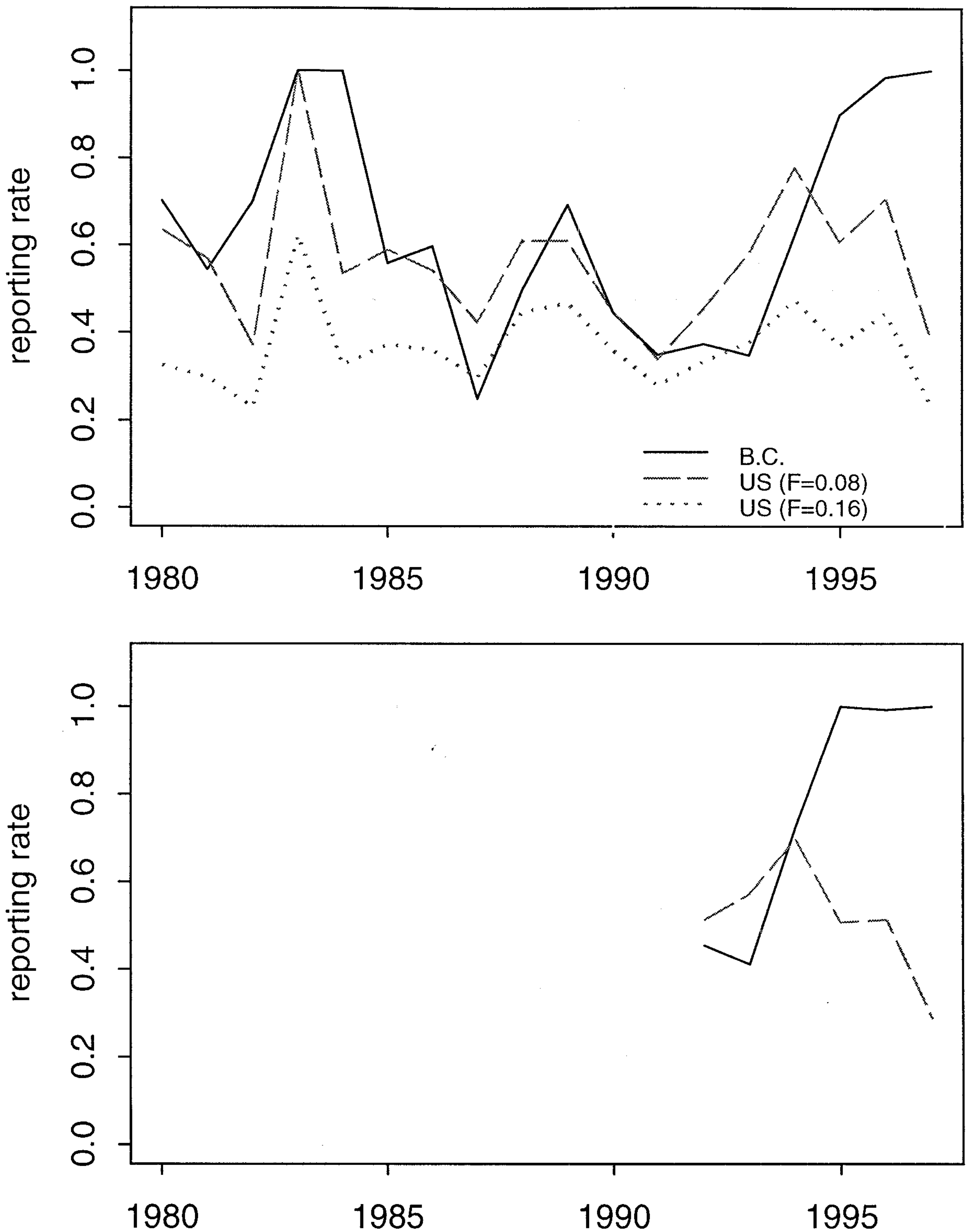

Figure 7. Estimated tag reporting rates for B.C. and the U.S. region. The upper panel shows estimates from the analysis utilizing the full (1979+) tag release data set and the bottom panel shows estimates from the analysis utilizing the partial (1991+) tag release data set.

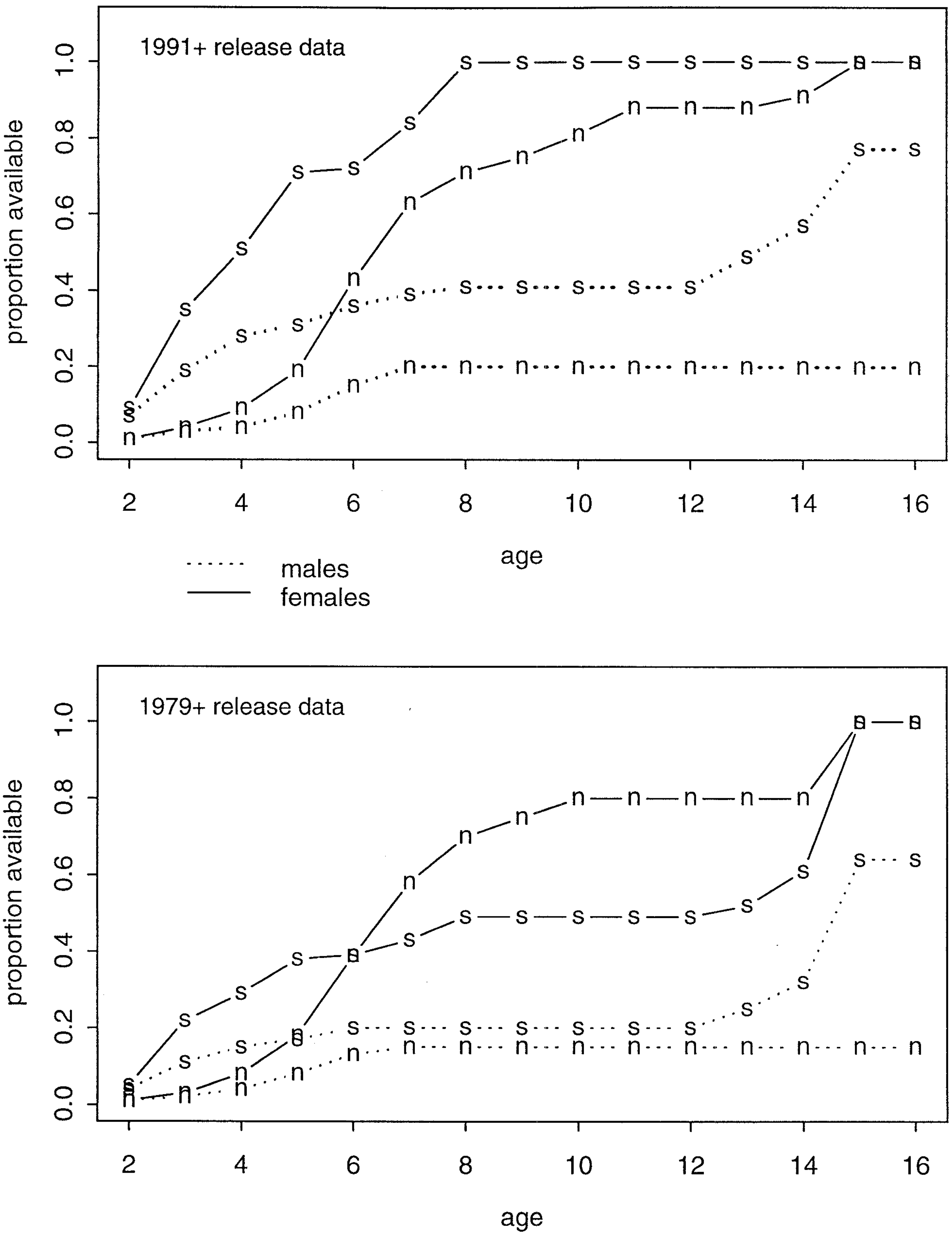

Figure 8. Estimates of the proportion-at-age available by sex for northern B.C regions (n) and southern B.C regions (s).

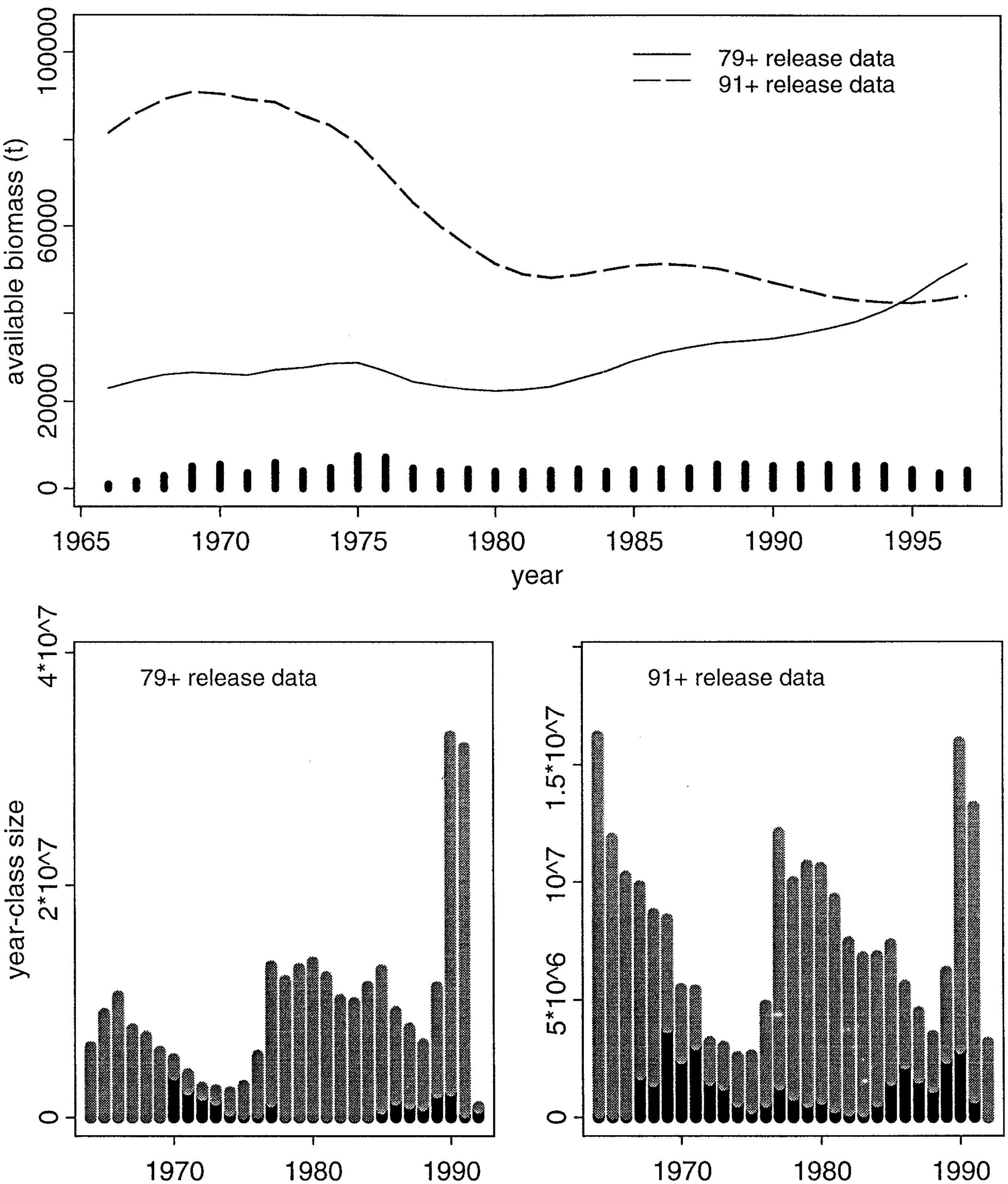

Figure 9. Estimates of available biomass, with standard errors of the estimates shown with dotted lines and B.C. coastwide catch shown as vertical bars, 1966-1997 (upper panel). The estimates of year-class size recruiting to northern B.C. (grey) southern B.C. (black) are shown in the lower panel for the 1964 to 1992 cohorts. Results are from integrated model analysis of B.C. sablefish data using alternate sets of tag release and recovery data.

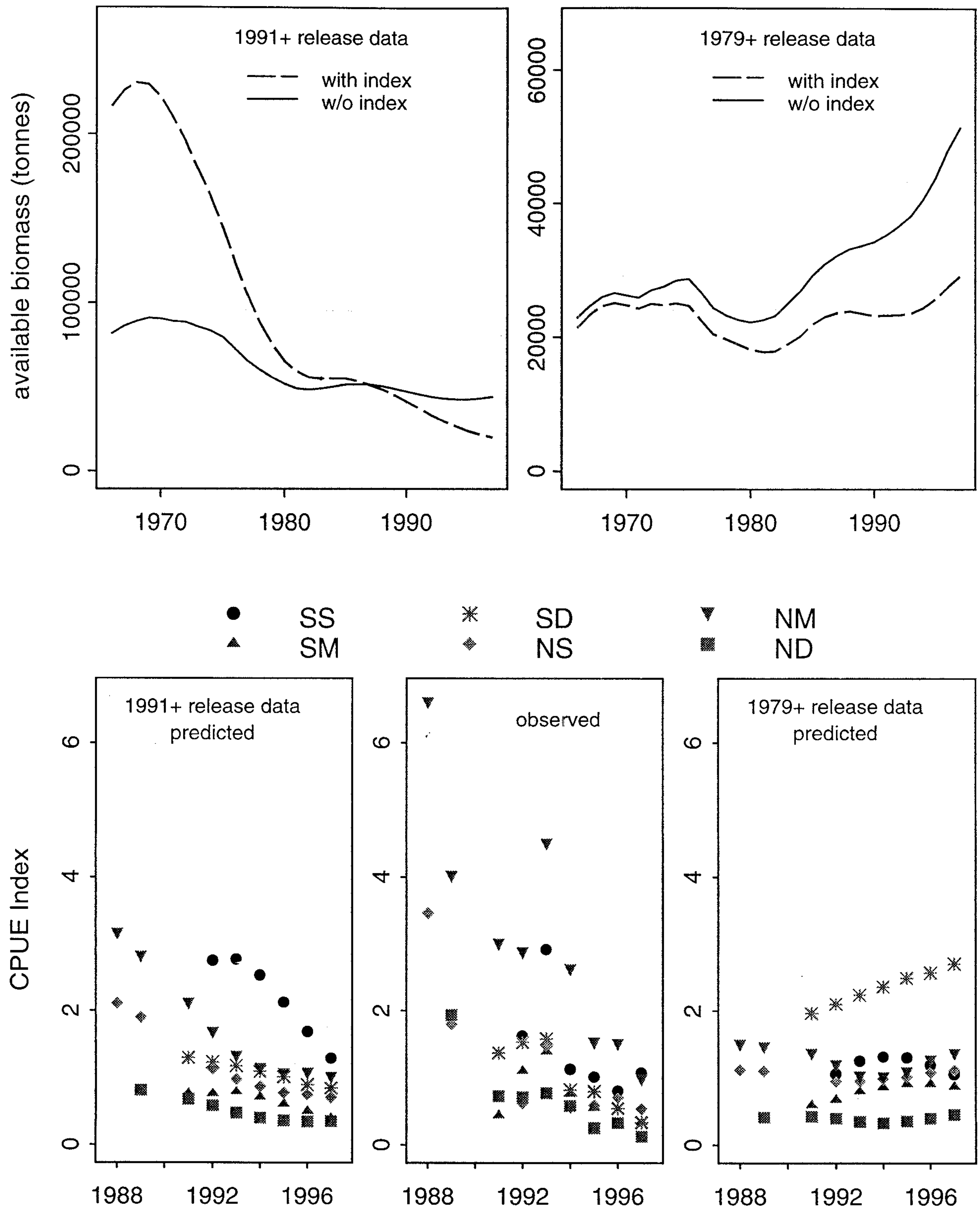

Figure 10. Estimates of available biomass in the B.C. sablefish regions from analyses that either incorporate survey CPUE abundance indices or not for analyses utilizing alternate tag release data sets (upper panel). The bottom panels show the observed and the predicted survey CPUE indices resulting from the analyses with alternate tag release data sets.

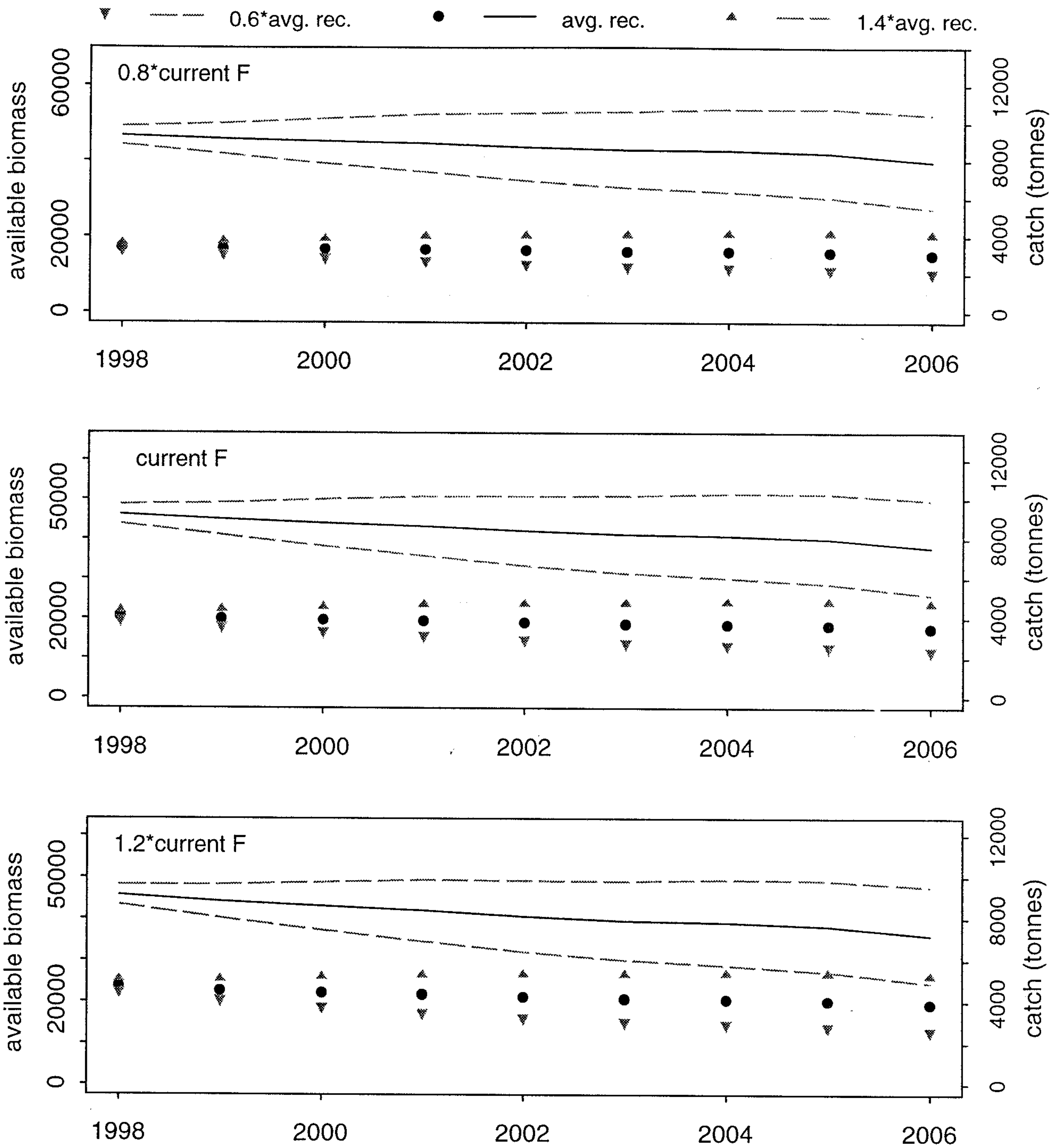

Figure 11. Projections of available biomass and catch for the B.C. regions, 1998 to 2006, assuming alternative levels of recruitment and fishing mortality (F). Results are from projections based on parameters from the integrated model analysis utilizing the partial (1991+) tag release data set.

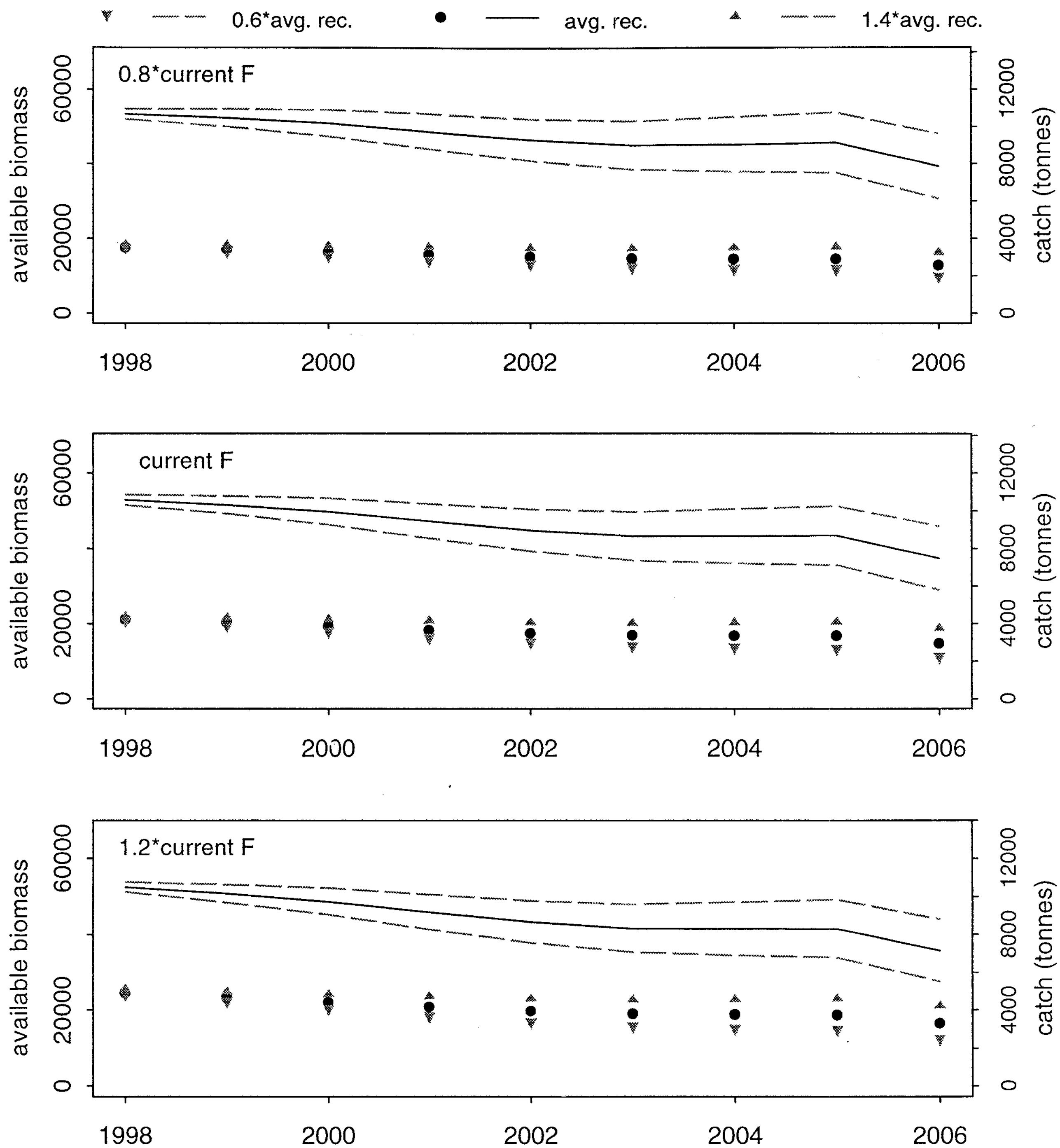

Figure 12. Projections of available biomass and catch for the B.C. regions, 1998 to 2006, assuming alternative levels of recruitment and fishing mortality (F). Results are from projections based on parameters from the integrated model analysis utilizing the partial (1979+) tag release data set.