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Production model fitting and projection for Atlantic redfish (*Sebastes fasciatus* and *Sebastes mentella*) to assess recovery potential and allowable harm

Ajustement du modèle de production et projection pour le sébaste atlantique (*Sebastes fasciatus* et *Sebastes mentella*) afin d'évaluer le potentiel de rétablissement et les dommages admissibles

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ABSTRACT

A recovery potential analysis was carried out for stocks of Atlantic redfish falling within three designatable units recently assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) as either threatened or endangered. A state-space Schaefer surplus production model was fitted to trawl survey biomass estimates considered as relative indices of abundance for these different stocks. Bayesian methods were applied for parameter estimation, evaluation of stock status and stock projections for three populations of Acadian redfish, *Sebastes fasciatus*, and two populations of deepwater redfish, *Sebastes mentella*, on the Atlantic coast of Canada for the purpose of assessing recovery potential. This stock assessment methodology has been previously applied to other *Sebastes* species on the Pacific coast of Canada. The state-space version of this model allowed for the inclusion of process error which can account for deviations in dynamics from surplus production assumptions. Though apparently an esoteric methodological detail, allowing a process error estimate for each year means that the model can incorporate irregular population processes such as spasmodic recruitment events which seem to characterise Atlantic redfish populations and which can invalidate non-state-space implementations of production models.

Results suggest that the Laurentian Channel population of *S. mentella* is presently in a very low biomass state with a 0% chance of being above 40% of the most productive stock biomass level (0.4 B_{msy}) while the northern population is doing only slightly better with 1% chance of being above this level. There would appear to be little prospect for any allowable harm on the Laurentian channel population if the goal is to increase the biomass of the stock even to only 40% of B_{msy}. The situation is only slightly better for the northern population.

Results suggest that populations of *S. fasciatus*, are not nearly in such a poor state as *S. mentella* and the southern population in Unit 3 would appear to be healthy. The Laurentian Channel-Grand bank population of *S. fasciatus* would appear to be able to support a directed fishery when considered as a unit stock. The 2J3K population of *S. fasciatus* is not very abundant and even small fisheries on this stock would slow down its recovery to 40% B_{msy}. *S. fasciatus*, taken as a whole as the Atlantic designatable unit, would appear to have a very low risk of extinction and in most places could support directed fishing.

RÉSUMÉ

On a effectué une analyse du potentiel de rétablissement des stocks de sébaste de l'Atlantique de trois unités désignables qui ont été évaluées récemment par le Comité sur la situation des espèces en péril au Canada (COSEPAC) et qualifiées de menacées ou de en voie de disparition. On a ajusté un modèle de surplus de production d'espace d'états de Schaefer aux estimations de la biomasse dérivées des relevés au chalut, lesquelles sont considérées comme des indices relatifs de l'abondance de ces divers stocks. On a appliqué des méthodes bayésiennes pour l'estimation des paramètres, l'évaluation de l'état des stocks et les projections concernant les stocks de trois populations de sébastes d'Acadie (*Sebastes fasciatus*) et de deux populations de sébastes atlantiques (*Sebastes mentella*) présentes sur la côte canadienne de l'Atlantique afin d'en évaluer le potentiel de rétablissement. On a déjà utilisé ces méthodes d'évaluation des stocks pour d'autres espèces de sébastes de la côte canadienne du Pacifique. La version du modèle d'espace d'états permet d'inclure les erreurs de traitement, ce qui permet de tenir compte des déviations dans la dynamique découlant des hypothèses sur le surplus de production. Bien qu'il s'agisse d'un détail méthodologique apparemment très spécialisé, le fait d'associer une estimation des erreurs de traitement pour chaque année signifie que le modèle peut intégrer des processus démographiques irréguliers, comme des événements de recrutement épisodiques qui semblent caractériser les populations de sébastes de l'Atlantique, ce qui peut empêcher la mise en œuvre de modèles de la production qui ne sont pas des modèles d'espace d'états.

Les résultats laissent sous-entendre que la population de *S. mentella* du chenal Laurentien affiche présentement une biomasse très faible, avec une probabilité de 0 % que la biomasse soit supérieure à 40 % du niveau de la biomasse du stock la plus productive (0,4 B_{RMS}), tandis que la population du nord n'affiche des résultats que légèrement supérieurs, à savoir une probabilité de 1 % que la biomasse se situe au-dessus de ce niveau. Il semble qu'il y aura peu de possibilités de dommage admissible pour la population du chenal Laurentien si le but est d'augmenter la biomasse du stock, même à seulement 40 % de la B_{RMS}. La situation n'est que légèrement meilleure pour la population du nord.

Les résultats laissent sous-entendre que les populations de *S. fasciatus* ne sont pas dans un si mauvais état que celles de *S. mentella* et que la population du sud de l'unité 3 semble être saine. Il est possible que la population de *S. fasciatus* du chenal Laurentien-Grand Banc soutienne une pêche dirigée si on la considère en tant que stock indépendant. La population de *S. fasciatus* de 2J3K n'est pas très abondante, et même une petite pêche pratiquée dans ce stock ralentirait son rétablissement à 40 % de B_{RMS}. Il semble que *S. fasciatus*, pris dans son ensemble dans l'unité désignable de l'Atlantique, présente un très faible risque de disparition et, dans la plupart des emplacements, pourrait soutenir une pêche dirigée.

INTRODUCTION

In 2010 the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the conservation status of deepwater redfish, *Sebastes mentella*, and Acadian redfish, *Sebastes fasciatus*, in eastern Canadian waters (COSEWIC 2010). The designated unit (DU) of *S. mentella* which includes the Laurentian Channel was classified Endangered, the northern DU of *S. mentella* was classified Threatened. Two DUs for *S. fasciatus* were identified (Bonne Bay, Atlantic) which were designated as Special Concern and Threatened, respectively. The Minister of Fisheries and Oceans, as the competent minister for all aquatic species under the *Species at Risk Act* (SARA), must decide whether or not to list the four redfish populations asessed by COSEWIC as at risk on Schedule 1 of SARA taking into account all of the implications of such a listing. In order to inform the Minister of Fisheries and Oceans of the potential for these populations to decline or grow and at what rate, DFO science undertakes a recovery potential assessment (RPA). One of the main components of RPAs usually consists of quantitative long-term population projection exercise which accounts for uncertainty in future productivity conditions and various scenarios for fishing mortality, which are often termed “Allowable Harm” in the RPA context.

This document presents long-term projections over 60 years, approximately three generations, for east coast redfish populations using a state-space Schaefer surplus production modelling approach fitted with Bayesian methods and which has previously been applied to Pacific *Sebastes* species for assessment and projection (Stanley et al. 2009). Population trajectories are determined under different fishing scenarios which can be seen as “allowable harm”. Sensitivity of these results was examined in relation to priors and deviations from reported historical catch.

ISSUES RELATED TO BIOLOGY AND ASSESSMENT OF EAST COAST *SEBASTES*

East coast *Sebastes* species are enigmatic in that they are very slow growing, long-lived, low fecundity, live-birth with considerable subpopulation structure, poorly understood movement dynamics and yet these species have achieved very high biomass in east coast fish communities and supported large fisheries in the past. The fact that the two species are very difficult to distinguish without careful examination means that commercial catch data represent the aggregate of the species and even scientific survey data often do not distinguish the species. All these facts mean that scientific and commercial data on redfish populations utility hinges on assumptions regarding catch splitting and some of the data may not be useful for assessing population status of individual species.

The present modelling approach attempts to deal with the lack of knowledge of *Sebastes* growth through incorporating life history information into the prior information for the key population parameter, instantaneous growth rate, and through sensitivity runs on catch.

THE PRECAUTIONARY APPROACH AND MANAGEMENT MILESTONE IN THE *SEBASTES* RPA CONTEXT

The precautionary approach framework (PA) in DFO is a series of points in stock state and prescribed exploitation rates as a function of stock state to promote healthy and sustainable fisheries (DFO 2006). COSEWIC and the Species At Risk Act (SARA) are designed to protect species and populations from extinction which is a different objective that the PA. The PA, however, does establish points which could be regarded as milestones for management because undoubtedly management would re-evaluate any SARA recovery plan once and if a point such as the PA limit reference point is attained. In this context, the point equivalent to 40% of the biomass at maximum sustainable yield (0.4Bmsy) or 80% of the virgin biomass is reported as an important milestone. In Canada, 0.4Bmsy is recognised as a default for the limit reference point when a stock-recruit based limit point cannot be estimated from an age-structured model (DFO 2009). In DFO 2009, the thought behind these default reference points is based upon Schaefer production model dynamics and conventional norms for choosing a reference points and targets in Schaefer production space. It is therefore logical to assume that these default points are the preferred points when a Schaefer production model is actually the modelling method used which is the case in the present study. Many of the production model fitting results and projections are presented in relation to points such as 0.4Bmsy, 0.8Bmsy and Bmsy which define the critical cautious boundary, the cautious healthy boundary and the target (DFO 2009).

DATA AND METHODS

SURVEY INDICES

Population size indices used for model fitting came primarily from DFO groundfish surveys in the spring, summer or fall. Swept area biomass for mature individuals is used as the index.

Unit 1: data are from DFO's summer survey in the northern Gulf of St. Lawrence from 1990 converted to Teleost-Campellen equivalent swept area biomass.

Unit 2: The Groundfish Enterprise Allocation Council (GEAC) survey which was conduced in 2000, 2001 and every other year since. The GEAC survey was expressed in Teleost-Campellen equivalent swept area biomass.

Unit 3: the Scotian Shelf summer survey since 1970 in Western IIa gear swept area biomass was used as the sole stock size index for this stock.

2J3K: data are from the DFO fall survey from 1978-2009 converted to Teleost-Campellen equivalent swept area biomass.

3LN: data are from the DFO fall survey from 1991-2009 converted to Teleost-Campellen equivalent swept area biomass. A spring index from 1991-2009 was also available in 3LN and converted to Teleost-Campellen equivalent swept area biomass.

30: data are from the DFO fall survey from 1991-2009 converted to Teleost-Campellen equivalent swept area biomass. A spring index from 1991-2010 was also available in 3O and converted to Teleost-Campellen equivalent swept area biomass.

In many cases and especially for 2J3KLNO, redfish data were not split between species but were retrospectively split using meristics and associations of individual tows with depth as *S. mentella* is usually present in deeper waters than *S. fasciatus*.

CATCH DATA

Catch data for most regions extends back to 1959 or 1960. In all cases, catch was reported for unspeciated redfish. In order to fit models to these data by species it is necessary to speciate the catch time series. This was done by determining the proportion of each species in the survey catch from each area each year and then applying a loess smoother to these proportions. The loess smoothed proportion for each year was then applied to total catch to split it into species groups. As the survey time series does not extend as far back as the catch data, the mean proportion was applied in years before survey data were available (Figures 1-6).

LIFE HISTORY PARAMETERS FOR *S. FASCIATUS* AND *S. MENTELLA*.

The growth parameters for *S. fasciatus* and *S. mentella* were obtained from Saborido-Rey et al. (2004). The stock assessment methodology required the use of only the growth parameters for females and the values applied are shown in Tables 7a and 7b. The length-weight conversion factors for females of the two species in Canadian waters were obtained from Don Power (pers. commn) (Table 7c). There are no available empirical estimates of the rates of natural mortality (M) for Canadian redfish. It is generally assumed that M is relatively low as it is for most *Sebastes* species and that it is lower for *S. mentella* than *S. fasciatus*. In the NAFO application of Virtual Population Analysis methods (i.e., Extended Survivors Analysis (Shepherd, 1999)) to assess redfish in NAFO Division 3M, the value for M have been presumed to be 0.1 yr^{-1}. We've presumed this as the median value for *S. mentella* and presumed that the median for *S. fasciatus* is slightly higher at 0.125 yr^{-1} (Table 7d) We've applied a standard deviation in the natural logarithm of M of 0.25 but also applied lower and higher cutoff points to this prior probability distribution (Table 7d).

We've assumed that the stock-recruit function for both species can be represented by a Beverton-Holt (B-H) stock recruit function given that there's no evidence of cannibalism. Forrest et al. (2010) carried out a meta-analysis of stock-recruit data for *Sebastes* populations in the Pacific Ocean and provided a posterior predictive distribution for steepness parameter of the B-H stock-recruit function. This distribution had a mean of 0.67 and an standard deviation of 0.17. Steepness is defined as the fraction of average unfished recruitment obtained when spawning stock biomass is reduced to 20% of unfished conditions. The posterior predictive distribution reflects the distribution of possible values for steepness for populations that have not been included in the meta-analysis. This distribution serves as a good candidate for a prior distribution for steepness for populations of *Sebastes* not included in Forrest et al. (2010) and thus for *S. fasciatus* and *S. mentella*. Because steepness is bounded between 0.2 and 1 for the B-H model, the distribution applied used a transformation of the beta density function (see Table 7d for details).

Estimates of the median age at maturity for *S. mentella* and *S. fasciatus* are available for a number of management units (COSEWIC 2010). For *S. mentella* these range from about 10.36 years in the Gulf of St. Lawrence to 15.08 years on the Grand Banks (Table 8). For *S. fasciatus* estimates of median age at maturity range from about 8.03 years in Unit 3 to 10.31 years for NAFO Area 3O (Table 8). We've averaged the values for median age at maturity across different management units where estimates are available to provide estimates of the median age at maturity for the five assessed redfish stocks (Table 8).

DESIGNATABLE UNITS AND MODELLED POPULATION UNITS

COSEWIC evaluates species on the basis of “designatable units” (DU) which does not necessarily correspond to the same scale of populations that have coherent internal short term dynamics which generally forms the basis of population modelling exercises. COSEWIC defines designatable units as:
“discrete and evolutionarily significant units of the taxonomic species, where “significant” means that the unit is important to the evolutionary legacy of the species as a whole and if lost would likely not be replaced through natural dispersion.[1]”
In the case of *Sebastes fasciatus*, COSEWIC defined two DUs: one being the small population in the Bonne Bay fjord on the west coast of the island of Newfoundland, the second DU was the entire remaining east coast of Canada. Preliminary spreadsheet production modelling with the

[1] http://www.cosewic.gc.ca/eng/sct2/sct2_5_e.cfm

provided survey indices over the whole east coast area, there were counter trends between some indices while others showed very little signal. These patterns in survey indices means that there is no overall image of the population and suggests either that the indices are not indices of stock size or that perhaps they represent different populations showing different trends. If one assumes that the surveys do not reflect population abundance at all then the modelling is impossible, we assumed instead that the surveys represented different populations. As such, we broke up the Atlantic wide DU into the largest contiguous areas where indices provide similar trends or could be combined meaningfully given other information. We derived three stocks for *S. fasciatus* in this manner that collectively made up the Atlantic DU: (1) Unit 3 (2) Unit 1 + Unit 2 + 3LNO (3) 2J3K (Figure 7).

Since the status of *S. fasciatus* is provided at the population level, overall DU level results need to be some collective of these three fittings. Perhaps the simplest way to do this is to examine the relative biomass contribution of each population to the DU collective and appropriately weight population status in each sub area summing them to get the total.

The DUs for *Sebastes mentella* appeared to form coherent population units which could be meaningfully modelled to derive DU level estimates of biomass and project populations under various scenarios (Figure 7).

SURPLUS PRODUCTION MODEL EQUATIONS

We applied a Bayesian surplus production model that utilized Sampling Importance Resampling (Rubin 1987, 1988) to assess redfish stock status within each of the five species-stocks. Analyses were conducted using a previously developed Bayesian Surplus Production model program (BSP; McAllister and Babcock 2006). The version of the BSP model applied in this assessment is the Bayesian surplus production model developed for and applied to the recent Pacific region Bocaccio assessment (Prager 1994; McAllister et al. 2001; Stanley et al. 2009), inside waters yelloweye rockfish assessment (Lynne Yamanaka, Pers Comm), and offshore lingcod assessments (Jackie King Pers Comm). Required inputs for the program were catch and at least one catch rate (CPUE) index of abundance with coefficients of variation (CV) for each year obtained from survey data analysis. Estimated parameters included carrying capacity (K), the maximum intrinsic rate of population growth (r), the biomass in the first modeled year defined as a ratio of K (p_0), variance parameters for each CPUE series, and constant of proportionality (q) for each CPUE series. Prior probability distributions (priors) were specified for all of the estimated parameters.

DETERMINISTIC MODEL COMPONENTS

The surplus production model used is Prager's instantaneous F version of the Schaefer production model (Schaefer 1954; Prager 1994). State dynamics are modelled by assuming that biomass in a given year is a function of biomass in the previous year, the instantaneous fishing mortality rate, and two parameters that describe the impact of earlier biomass in growth, *r* and *K*:

$$B_{y+1} = B_y + rB_y\left(1 - \frac{B_y}{\mathrm{K}}\right) - F_y B_y \quad \text{(F1)}$$

where *y* is the year, B_y the stock biomass at the start of year *y*, *r* the intrinsic rate of increase, K the carrying capacity and F_y the instantaneous fishing mortality rate during year *y*. For the initial year, an additional parameter, p_0, is estimated which gives the ratio of initial stock biomass to carrying capacity ($p_0 = B_{1960}/K$).

Abundance indices are assumed to be directly proportional to stock biomass. The deterministic observation equation is:

(F2) $$\hat{I}_{j,y} = q_j B_y$$

where q_j is the constant of proportionality for the abundance index j, $I_{j,y}$ the observed abundance index j in year y and $\hat{I}_{j,y}$ is the model predicted value for $I_{j,y}$.

STOCHASTIC MODEL COMPONENTS

The state-space approach allows for deviations from model predictions (i.e., random variability) in both (i) the data (e.g., relative biomass indices) and (ii) the unobserved state of the system of interest (e.g., annual population biomass) (Millar and Meyer, 2000). These two components of the system are modelled within a single probabilistic framework that can be highly flexible (Rivot *et al.*, 2004). Fisheries modellers tend to choose multiplicative lognormal errors (Millar and Meyer, 2000), which is what we use in our model. The abundance index data are assumed to be lognormally distributed:

(F3) $$I_{j,y} \sim \text{lognormal}\left(\ln\left(\hat{I}_{j,y}\right), \sigma^2_{\text{obs},j}\right)$$

where $I_{j,y}$ is the observed index of abundance for series j in year y, q_j is the constant of proportionality for series j and $\sigma_{\text{obs},j}$ is the standard deviation in the error deviation between the log predicted index and the log observed index j.

The stochastic form equation F1 (i.e., the process equation) is:

(F4a) $$\log\left(B_{y+1}\right) = \log\left(B_y + rB_y\left(1 - \frac{B_y}{\text{K}}\right) - F_y B_y\right) + \varepsilon_{process,y} - \frac{\sigma^2_{process}}{2},$$

where, $\varepsilon_{process,\,y} \sim \text{Normal}\left(0, \sigma^2_{process}\right)$.

Given these equations, the posterior mean for is:

(F4b) $$E\left(B_{y+1}\right) = B_y + rB_y\left(1 - \frac{B_y}{\text{K}}\right) - F_y B_y$$

Also, under unfished conditions the posterior mean of B_y is K and under the maximum sustainable harvest rate the posterior mean of B_y is $K/2$.

The stochastic form of equation F2-a (i.e., the observation equation) is:

(F5) $$\log\left(I_{j,y}\right) = \log\left(q_j\right) + \log\left(B_y\right) + \varepsilon_{obs,j}$$

where $\varepsilon_{obs,j} \sim \text{Norma}\left(0, \sigma^2_{\text{obs},j}\right)$.

Both $\varepsilon_{process}$ and $\varepsilon_{obs,j}$ are i.d.d. random variables in all modelled years up to 2009. For each future year in the projections, we have modelled $\varepsilon_{process}$ to be positively autocorrelated with a correlation coefficient, ρ (see Stanley et al. (2009) for details on the autocorrelation equations). There were too few years in which it was possible to estimate the correlation in process error deviates because non-zero estimates of process error only became non-zero after 2000. We therefore applied the commonly applied default value for ρ of 0.5. The sensitivity of results to different values for ρ was evaluated in the BSP application to bocaccio (Stanley et al. 2009) and projection results were found to be relatively insensitive to values between 0.5 and 0.7 but more pessimistic than assuming that $\rho = 0$.

A summary of key parameters estimated in the surplus production model is provided in Table 10. A summary of derived management parameters is provided in Table 11.

A summary of prior distributions for estimated parameters is given in Table 12. A more detailed description of the methods used to determine each prior is provided below.

COMPUTING A PRIOR DENSITY FUNCTION FOR THE MAXIMUM INTRINSIC RATE OF INCREASE (*R*)

The methodology developed in the 2008 B.C. bocaccio stock assessment (Stanley et al. 2009) to compute a prior density function for *r* is extended similarly as in the B.C. 2009 lingcod assessment (Cuif et al. 2009) to include additional sources of uncertainty. Prior probability distributions were computed for each of the five assessed redfish stocks. Previously these included only the stock-recruit steepness (*h*) parameter and the rate of natural mortality (*M*). In this redfish assessment, uncertainty was included in all of the input parameters for this Monte Carlo algorithm. The program uses the prior means and variances for the female growth parameter estimates (Table 7a,b), the length to weight conversion factors (Table 7c), and parameters for the fraction maturity-at-age schedule (Table 8) (the prior covariances in parameter values are assumed to be zero). As in Cuif et al. (2009) cumulative normalized lognormal distribution function was applied to describe the fraction mature at age with the standard deviation in the natural logarithm of maturity at age (SD in ln(age maturity)) set at 0.5. A coefficient of variation of 5% was applied for both of these parameters to account for uncertainty in them in the stochastic demographic analysis.

A total of 10,000 Monte Carlo simulations are carried out and values less than 0.005 are excluded from the results to avoid the application of values that are biologically implausible. The maximum age was truncated at 50 years. As usual, the form of the density function is very well approximated by a log normal density function. The prior mean for *r* based on B-H steepness that resulted from the Monte Carlo simulation ranged from 0.104 with a SD of 0.046 for *S. mentella* in the Northern DU to 0.153 with a SD of 0.073 for *S. fasciatus* in Unit 3 (Table 9).

CARRYING CAPACITY (*K*)

The prior for *K* in each assessment area was first assumed uniform over a large range of values between 10,000 tonnes and 10,000,000 tons in order to enable equal credibility for small and large possible values for *K*. The upper bound for each assessment area was set at about the highest unfished stock size of any groundfish stock worldwide. However, this uniform prior on *K* appeared unsuitable because posterior distributions for some assessed stock units were very flat. This problem has previously been noted by Millar and Meyer (2000). We therefore chose an alternative approach in which we applied a uniform prior over the log of *K* with the same upper and lower bounds (Jackie King, unpub data). This alternative tended to reduce the very flat tail in posteriors for *K* and initial stock size, but had relatively little influence on posterior median results. The uniform prior over the log of *K* was used in the reference case.

RATIO OF INITIAL BIOMASS TO CARRYING CAPACITY (P_0)

The first year of the total catch time series considered is 1960. Our prior distribution for p_o suggested the redfish stock biomass in 1960 (B_{1960}) was at lightly fished conditions since the deepwater trawl fishery was not widely developed at this time. The prior for p_0 was assumed to be log-normal with a prior mean of 0.8 and a SD in log(p_0) of 0.2.

PROCESS ERROR VARIANCE

The standard deviation of $\varepsilon_{process}$, $\sigma_{\mathrm{process}}$, was set at 0.05 (to account for potentially large interannual variability in stock biomass due to variability in stock dynamics processes that were not explicitly modeled (e.g. movement between areas, recruitment, variation in growth). We did not test the sensitivity of results to this parameter. This was done in the bocaccio assessment with values of up to 0.15 applied and it made no different to the assessment of stock status and very little different in the median results and probability results obtained from the projections. The main effect was to widen the distributions in the projections of stock biomass and make the posterior integration much less efficient.

OBSERVATION ERROR VARIANCE

Values for $\sigma_{\mathrm{obs},j}$ (i.e., the standard deviation of $\varepsilon_{obs,j}$, from equation F-5) were obtained by iterative reweighting for each model run. Even then, the values obtained tended to be quite stable across different model runs for the same stock (Table 13 for reference case values). We presumed that values for $\sigma^2_{\mathrm{obs},j}$ were the sum of (i) the variance for each index j, determined from the construction of the survey indices ($\sigma^2_{\mathrm{ind},j}$) and (ii) the variance presumably due to interannual processes ($\sigma^2_{\mathrm{int},j}$) (e.g., variation in the spatial distribution, $\sigma^2_{\mathrm{obs},j} = \sigma^2_{\mathrm{ind},j} + \sigma^2_{\mathrm{int},j}$). Thus in the iterative reweighting, the values for $\sigma^2_{\mathrm{ind},j}$ were set to be the sum of the analytical variances and the values for $\sigma^2_{\mathrm{int},j}$ were adjusted to match (rounding up to the nearest 0.05 or 0.1) the values for $\sigma^2_{\mathrm{obs},j}$ that were outputted from the stock assessment model.

CONSTANT OF PROPORTIONALITY (*Q*)

The prior *pdf* for q_j is uniform over the log of q_j over the interval [-20,200]. This prior is the same for each abundance index *j*.

POSTERIOR APPROXIMATION

The SIR algorithm was used to compute marginal posterior distributions for BSP model parameters and quantities of interest (McAllister et al. 1994; Stanley et al. 2009). The key output statistics computed include marginal posterior distributions of current stock biomass (B_{2010}), current stock biomass to carrying capacity (B_{2010}/K), the ratio of current stock biomass to stock biomass at MSY (B_{2010}/B_{MSY}), the replacement yield in 2010 ($RepY_{2010}$), the ratio of the replacement yield in 2010 to the catch biomass in 2009 ($RepY_{2010}/C_{2010}$), and the ratio of fishing mortality rate in 2009 to fishing mortality rate at *MSY* (F_{2010}/F_{MSY}).

Due to extreme high variability in some time series, sampling was relatively inefficient and for some areas runs with up to 36 million draws from the importance function were carried out (approximately 7-9 hours of computing on 2 GHz IBM PCs). The marginal posteriors for the quantities of interest were reliably estimated with the maximum importance ratio for any one draw taking no more than about 2% in each of the runs conducted. Runs using alternative importance functions, (e.g., with different variances in the key parameters), yielded practically identical marginal posterior estimates. The marginal prior and posterior *pdf*s of *r* and *K* are plotted below to show the extent to which priors have been updated. SIR was also applied to compute Bayes factors when comparing the credibility of alternative model settings to the reference case runs (see below).

DEFINITION OF REFERENCE CASE

We develop and present results for each of the five assessed stocks using a reference case set of inputs and assumptions. For the reference case runs, all inputs, assumptions and settings were formulated based on the best available information and scientific judgment. Prior distributions used in the reference case have been described above. The following list summarizes the key settings:

Prior mean *r* formulated for each of the four stocks using the Beverton-Holt steepness prior distribution and life history parameter estimates for each stock

All stock trend indices used for each stock

Likelihood function for catch data follows a lognormal distribution

Schaefer surplus production function ($B_{MSY}/K=0.5$)

Prior mean $B_{1960}/K = 0.8$

Uninformative priors for *q*

Lag 1 autocorrelation with the autocorrelation coefficient, ρ, set at 0.5 starts in 2010 (see Stanley et al. 2009 for the equations)

CVs for stock trend indices obtained by iterative reweighting, with fixed observation error from survey imprecision and process error components determined by fitting the BSP model to the data

We allowed for the possibility of updating the reference case settings based on results obtained after fitting the model to the data in the different sensitivity analyses. We applied conservative criteria for updating the reference case settings to reduce the possibility of making excessively frequent and numerous changes or poorly justified changes that could result from random variation in the data when reference case settings are actually better approximations than the alternative settings. We would consider revising reference case settings only if there was a very strong weight of evidence (e.g., a Bayes factor of less than 1/10 (see below)) against the reference case setting compared to the most credible alternative setting for some model component) in the posterior results and this held for all four stocks.

SENSITIVITY ANALYSES

Sensitivity tests were conducted to evaluate the effect of stock assessment model assumptions on stock status and projection results, though sensitivity runs for projections are shown only for the runs with alternative priors for r. A summary of these analyses is provided in Table 14, and a brief description of each analysis is provided below.

Prior distribution on r - To evaluate the sensitivity of model results to the informative prior distribution for r, two additional runs were conducted for each of the four assessment areas: one with high r and one with low r (Table 14). The low r prior was obtained by applying a prior mean for r that was two thirds of the reference case prior mean, while the high r value was obtained by using a prior mean that was one third higher than the reference case prior mean. In contrast, the prior CVs were held constant.

Prior distribution on B_{1960}/K (or p_0 B_{init}/K) - p_0 typically cannot be estimated from available data and it is commonly assumed that Binit/K falls at 90-100% of K, in Schaefer surplus production model applications, when the model starts near or at the beginning of the fishery. It has been found that if the catch series is more than a few decades, the final results are insensitive to the value assumed for p_0, provided it is over about 50%. In the BSP model, we considered alternative prior means of 0.6 and 1.0.

Uncertainty in catch estimates - The influence of uncertainty in historic catch is evaluated by conducting runs where annual fixed catch values for all fisheries combined are set at 50% and then 200% (i.e., 0.5 and 2.0 times higher) of the originally estimated time series of combined fixed catch values. There is large uncertainty over the historic catches for both species because the species composition of landings of Canadian redfish have not been ascertained historically due to the lack of a reliable, quick and inexpensive method to distinguish between the two main species and the fact that we applied the survey swept area biomass estimates by species to split the historical commercial landings by species. The four fold range of catch values by species we believe is sufficient to evaluate the sensitivity of results to alternative plausible assumptions about the magnitude of historic landings of each species in the different areas.

EVALUATION OF CREDIBILITY OF SENSITIVITY ANALYSIS SCENARIOS

To compare the credibility of each model given the data in sensitivity analyses, we computed Bayes factors (Kass and Raftery 1995) for the reference case and for each of the related sensitivity runs. Bayes factors account for both the relative goodness of fit of the model to the data and the parsimony for each of the alternative models. They are calculated as the ratio of the marginal probability of the data for one model to that for another model. Bayes factors were computed by approximating the marginal posterior probability of the data given the model using the average value of the importance weights obtained from each model run (Kass and Raftery 1995; McAllister and Kirchner 2002). In all instances we referenced Bayes factors to our reference case model settings, i.e., the probability of the data for the reference case model was placed in the denominator and that for the model to which it was compared in the numerator. It is commonly held that nothing should be made of Bayes factor unless the value for it departs substantially from 1. Even fairly large or small Bayes factors can come from random chance in the data and possible misspecification of probability models for the data, e.g., treating errors for each observed index value as independent when they may not be independent. Thus, while a factor of 1/10 may appear to provide strong evidence against a model, the difference in fits of the model to the data could still have resulted from random chance in the data. Intermediate values for Bayes factor (e.g., between about 1/100 and 100) should be interpreted with restraint. Models with Bayes factors of about 1/100 could be interpreted as unlikely but not discredited. When Bayes factor is less than 1/1000, the model with lower credibility can be viewed as highly unlikely relative to the other.

MODEL RESULTS

STOCK STATUS IN 2010

S. fasciatus in Unit 3

Results for the full suite of parameters estimated from the reference case run for *S. fasciatus* in Unit 3 are summarized in Table 15. Predicted posterior median biomass levels from the surplus production model between 1960 and 2010, as well as catch and observed stock trend indices, are shown in Figure 8.

The posterior distributions for carrying capacity (*K*), stock biomass in 2010, and most other quantities of interest are imprecise (Table 15, Figures 8, 13, 14). This result is mainly due to the extreme high interannual variability in the stock trend index and lack of apparent decline in the indices in the 1970s when catches were largest (Tables 1, 13, Figure 8). The posterior for the intrinsic rate of increase *r* was only slightly updated to slightly higher values (Figure 13, Tables 9, 15). The posterior correlation between r and K was 0.05 (Fig. 13g). See McAllister et al. (2001) for plots of the joint posterior density function for *r* and *K* that can be obtained in applications of the BSP model to abundance index data when an informative prior for r is also used. The lack of trend in the survey biomass series indicates that this stock remains only very lightly exploited with a 99% probability that stock biomass in 2010 is greater than 0.8 of B_{msy}.

Estimates of process error terms for *S. fasciatus* in Unit 3 were zero up to the year 2000 but were updated to deviate from zero for most years since 2000 (Figure 23). In the last few years, process error deviate estimates are positive.

S. fasciatus in Units 1 and 2, and 3LNO

Results for the full suite of parameters estimated from the reference case run for *S. fasciatus* in Units 1 and 2, and 3LNO are summarized in Table 16. Predicted posterior median biomass levels from the surplus production model between 1960 and 2010, as well as catch and observed stock trend indices, are shown in Figure 9.

The posterior distributions for carrying capacity (*K*), stock biomass in 2010, and most other quantities of interest are imprecise (Table 16, Figures 9, 15, 16). However, some of the posterior distributions, e.g., for B_{2010}/ K and B_{2010}/ B_{msy} are strongly bimodal with peaks at low and high values (Figure 16). The large uncertainty in estimates of variables of interest results mainly from the moderately high interannual variability in the stock trend indices and lack of apparent net decline in the indices in the 1990s when catches decreased from high to low values in the 1990s (Tables 2, 13, Figure 9). The posterior for the intrinsic rate of increase *r* was not noticeably updated (Figure 15, Tables 9, 16). The posterior correlation between *r* and *K* was -0.014 (Fig. 15g). The lack of trend in the survey biomass series indicates that this stock remains only very lightly exploited with a 64% probability that stock biomass in 2010 is greater than 0.8 of B_{msy}.

As with the other areas, estimates of process error terms for *S. fasciatus* in Units 1 and 2, and 3LNO were zero up to the year 2000 but were updated to deviate from zero for most years since 2000 (Figure 23). In the last few years, process error deviate estimates are negative.

S. fasciatus in Area 2J3K

Results for the full suite of parameters estimated from the reference case run for *S. fasciatus* in Area 2J3K are summarized in Table 17. Predicted posterior median biomass levels from the surplus production model between 1960 and 2010, as well as catch and observed stock trend indices, are shown in Figure 10.

The posterior distributions for carrying capacity (*K*), stock biomass in 2010, and most other quantities of interest are quite precise (Table 17, Figures 10, 17, 18). The precision in estimates of variables of interest results mainly from the strong decline in the 1980s in the stock trend indices when catches decreased from high to low values, despite the large imprecision in the indices (Tables 3, 13, Figure 10). The posterior for the intrinsic rate of increase *r* was strongly updated to rest over lower values (Figure 17, Tables 9, 17). The posterior correlation between *r* and *K* was -0.85 (Fig. 17g). The strong early decline in the survey biomass series and continuance of relatively low values indicates that this stock remains depleted with a 4% probability that stock biomass in 2010 is greater than 0.8 of B_{msy} and 37% probability that stock biomass in 2010 is greater than 0.4 of $B_{msy.}$

Estimates of process error terms for *S. fasciatus* in Area 2J3K were zero for all years (Figure 23).

***S. mentella* in Units 1 and 2**

Results for the full suite of parameters estimated from the reference case run for *S. mentella* in Units 1 and 2 are summarized in Table 18. Predicted posterior median biomass levels from the surplus production model between 1960 and 2010, as well as catch and observed stock trend indices, are shown in Figure 11.

The posterior distributions for carrying capacity (*K*), stock biomass in 2010, and most other quantities of interest are quite precise (Table 18, Figures 11, 19, 20). The precision in estimates of variables of interest results mainly from the strong decline in the 1990s in the stock trend indices when catches decreased from high to low values, and was facilitated by the moderate imprecision in the indices (Tables 4, 13, Figure 11). The posterior median for B_{2010}/ B_{msy} was very low at 0.032 with a posterior CV of 32% (Table 18). The posterior for the intrinsic rate of increase *r* was strongly updated to rest over lower values (Figure 19, Tables 9, 18). The posterior correlation between *r* and *K* was -0.63 (Fig. 19g). The strong early decline in the survey biomass series and continuance of relatively low values indicates that this stock remains depleted with a 0% probability that stock biomass in 2010 is greater than 0.8 of B_{msy} and 0% probability that stock biomass in 2010 is greater than 0.4 of $B_{msy.}$

As with the other areas, estimates of process error terms for *S. mentella* in Units 1 and 2 were zero up to the year 2000 but were updated to deviate from zero for most years since 2000 (Figure 23). In the last few years, process error deviate estimates are negative.

***S. mentella* in Areas 2J3K and 3LNO**

Results for the full suite of parameters estimated from the reference case run for Northern *S. mentella* are summarized in Table 19. Predicted posterior median biomass levels from the surplus production model between 1960 and 2010, as well as catch and observed stock trend indices, are shown in Figure 12.

The posterior distributions for carrying capacity (*K*), stock biomass in 2010, and most other quantities of interest are quite precise (Table 19, Figures 12, 21, 22). The precision in estimates of variables of interest results mainly from the strong decline in the 1980s and 1990s in the stock trend indices when catches decreased from high to low values, and despite the high imprecision in all of the indices (Tables 5, 13, Figure 12). The posterior for the intrinsic rate of increase *r* was strongly updated to rest over lower values (Figure 21, Tables 9, 19). The posterior correlation between r and K was -0.72 (Fig. 21g). The strong early decline in the survey biomass series and continuance of relatively low values indicates that this stock remains depleted with a 0.4% probability that stock biomass in 2010 is greater than 0.8 of B_{msy} and 10% probability that stock biomass in 2010 is greater than 0.4 of $B_{msy.}$

As with the other areas, estimates of process error terms for *S. mentella* in Units 1 and 2 were zero up to the year 2000 but were updated to deviate from zero for most years since 2000 (Figure 23). In the last few years, process error deviate estimates are slightly positive.

STOCK PROJECTIONS TO EVALUATE THE POTENTIAL FUTURE STOCK TRENDS UNDER ALTERNATIVE POLICY OPTIONS

Decision tables for constant Total Allowable Catch (TAC) policies based on 5, 20, and 60 year projections (the latter being approximately three generations for both species) are summarized by assessment area in Table 20 to Table 24. The range of constant TAC policies considered ranged from 0 to either 3, 6 or 9 kilotons (000t), depending on the area. Larger TAC quota policies were considered for *S. fasciatus* in Unit 3 and the central region (Units 1, 2 and 3LNO combined) since the ratio of current biomass estimates to B_{MSY} was estimated to be larger in these areas. For all areas where the posterior median for ratio of stock biomass in 2010 to Bmsy was estimated to be less than 1, upward median trajectories of B_{FINAL}/B_{MSY} occur for TACs policy options of 1000 tonnes and lower.

Constant effort policies were also evaluated in which the effort equivalent to some fixed quota in 2011 was applied in future years. The results for these projections in all instances were similar to those for the analogous constant quota policies. Results are thus not shown for these TAC referenced effort policies.

SENSITIVITY ANALYSES

Model assumptions and input data

Estimates of parameters and key variables of interest obtained from sensitivity runs for each individual assessed stock are provided in Table 25 to Table 29. For all of the assessed stocks, stock status results were largely insensitive to the alternative settings for the prior mean for r, smaller and larger catch time series and prior means for the ratio of initial stock size to carrying capacity. In some instances, the estimates of absolute quantities such as Bmsy and current stock size varied considerably with the changes in stock assessment model settings. For example, B_{2010}, Bmsy and replacement yield in 2010 varied about four fold for *S. fasciatus* in 2J3K and *S. mentella* in Units 1 and 2, and the north when historic catches ranged from half to double the reference case (Tables 27, 28 and 29). However, in all instances the stock status results, e.g. B_{2010}/B_{msy} varied much less due to the scaling in the stock trends given by the large observed decreases in the stock trend data.

In contrast, stock projection results showed some sensitivity to the lower and higher prior means for r only for Northern *S. fasciatus* (Table 33). Under the low prior mean for r for example the 1 kt quota policy option gave about a 6% $P(B_{2030} > 0.4\ B_{msy})$. In contrast, the reference case and high policy options gave 14% and 25% for $P(B_{2030} > 0.4\ B_{msy})$. The very large jump (i.e., about 12 fold) in the 2J3K survey index for *S. fasciatus* after 2005 appears to have been the chief source of this poor ability of the model to fit the data when the 2J3K survey catchability was assumed to be constant from 1994-2009. For such a long-lived fish, it is highly unlikely that there could be a recruitment event from a single or a few large cohorts that could cause the mature population biomass to increase as much as 12 fold in a given year. We thus revised the reference case to allow for a change in 2J3K catchability for both species in 2005. For the four other assessed stocks, the projection results showed little sensitivity to the prior mean specified for r (Tables 31, 32, 34 and 35). Projection results however for *S. fasciatus* in 2J3K were also sensitive to the two alternative scenarios for historic catches in 2J3K (Tables 38).

For nearly all sets of comparable sensitivity runs for a given stock, the Bayes factors suggested that all of the options considered remained credible, i.e., in nearly all instances, Bayes factors for the alternative runs were 2 or less and much less than the threshold value (i.e., a Bayes factor of about 100) at which a hypothesis or run could be discredited (Table 30). The only two instances in which Bayes factors for the original alternative runs were markedly higher than the reference case run were where the 2J3K survey biomass series was split to create an additional series for 2005-2009. This was for both *S. fasciatus* (Bayes factor for splitting = 2002) and *S. mentella* (Bayes factor for splitting = 637). In both instances when the 2J3K survey series was split after 2004, the stock status results were less optimistic than the reference case, particularly for *S. fasciatus* where the posterior median for B_{2010}/ B_{msy} was at 9% under the split series and 32% under the reference case. The very large Bayes factors in favour of the run in which the 2J3K series was split to create an additional series from 2005-2009 for both *S. fasciatus* and *S. mentella* strongly support the creation of an additional survey index with a different catchability coefficient for 2005-2009. While there appears to be no obvious reason for why the 2J3K survey index jumped several-fold for both species and stayed consistently higher after 2005, this could occur if the spatial distribution of both species simultaneously shifted further into the 2J3K survey area in 2005 and this change in geographic distribution continued or if there happened to be some unknown change in the survey protocol in 2005 that increased the catching power of the survey gear or the vulnerability of both fish species to capture by the survey gear in 2J3K. A change in the reference case definitions for *S. fasciatus* and *S. mentella* in the northern region encompassing the 2J3K survey was thus applied in which the 2J3K survey series for both species was split to create an additional survey series with their own catchabilities.

DISCUSSION

An assessment of past and current population state and 60-year projections is provided for three populations of Acadian redfish, *Sebastes fasciatus*, and two populations of deepwater redfish, *Sebastes mentella*, in eastern Canadian waters. The population assessment and projections were conducted in the context of a Fisheries and Oceans commissioned recovery potential assessment (RPA) for these two *Sebastes* species following from a 2010 COSEWIC evaluation of some populations of these species being classified as of Special Concern, Threatened or Endangered.

The results presented here neither correspond to the Designatable Units (DU) used by COSEWIC in all cases nor the management units used by DFO. The purpose of this modelling work was to inform the minister of the potential for recovery at an ecologically meaningful scale of aggregation closest to the DU level. For *Sebastes mentella* this corresponded to the DU level while for *Sebastes fasciatus*, the Atlantic DU was broken up into three sub areas. The purpose of this work was not to provide a stock assessment for redfish for the purposes of direct fisheries management in the sense of providing advice on next year's catch. The work here does however, provide a means of assessing redfish populations and if the method is deemed appropriate through a peer reviewed DFO assessment process then it may be useful to attempt a model fitting at the DFO management unit scale with the caveat that management units that do not properly correspond to population units do not form a good basis for either modelling or management.

WHY APPLY A STATE-SPACE SURPLUS PRODUCTION MODEL FOR REDFISH?

Age-structured models are considered by many to be the desired modelling approach for populations should the available data and knowledge permit reliable estimation of model parameters and population abundance (Hilborn and Walters 1992). Indeed age-structured models can permit the characterisation of recruitment events, the formulation of a stock-recruit relationship and identification of associated reference points. For many data-poor species (e.g., for which only sparse or no catch-age data exist) or for species which are difficult to age or track cohorts in length, it may not be possible to develop useful age structured models, especially if fishery vulnerability at age is poorly known (e.g., the fish population's median age of recruitment and vulnerability-at-age to each fishing fleet is poorly known). Such is the case for many *Sebastes* species where age-discriminated survey and catch data are not available. This often occurs because it may be impractical to distinguish between co-occurring Sebastes species on the boat deck and records of the catch-at-length or catch-at-age by species of co-occurring *Sebastes* species have not been kept (Stanley et al. 2009; COSEWIC 2010).

When reliable time series of catch-at-age data are not available and fishery vulnerability-at-age is poorly known for a given fish population, a variety of other modelling approaches could be applied such as delay-difference models (Deriso 1980; Schnute 1987) or length-based methods (Fournier et al. 1998). However, each alternative approach has its limitations. For example the delay-difference approach is dependent upon the assumption of knife-edged recruitment and maturity at the same size/age. And while delay-difference models include a stock-recruit function, it is often not possible to reliably estimate annual recruitment events or stock-recruit model parameters from the data to which such models are commonly fitted (i.e., total stock biomass abundance indices) (Ludwig and Walters 1985, 1989). Length-based methods require up-to-date historic records of length-based data by species and for redfish in several of the regions, full time series to the present of commercial catch-at-length data by species are not available.

We chose to apply a state-space surplus production model because it requires relatively simple data (i.e., stock trend indices and catch biomass time series that could be separated by species) which were available for all of the regions of interest within the DUs. In addition, the state-space modelling approach which estimates annual process error deviates from population dynamics model predictions allows the model to implicitly capture some complexity which would be explicitly modelled in some of the other approaches. The explicit modelling of that complexity may not be worth the effort even if data had permitted it given the unknown but potentially large uncertainty related to splitting catch between species -- “you can’t make a silk purse out of a sow’s ear”. Moreover, results from simulations of age-structured and non-age structured data using age-structured population dynamics models have commonly shown that surplus production models can provide better estimation performance and more reliable management recommendations than could be provided by age-structured models, even when the data themselves are generated from age-structured models (Ludwig and Walters 1985; Punt 1993; Horbowy in press).

INTERPRETATION OF MODEL RESULTS AT THE DESIGNATABLE UNIT (DU) SCALE

As modelling for *S. mentella* could be done at the DU level and results are directly available in tables and figures, we will discuss only *S. fasciatus* in this section.

S. fasciatus potential populations in Unit 3 and Unit 1+ Unit 2 + 3LNO are considerably larger than in zone 2+3K with median estimated carrying capacities of 2290 kt, 2372 kt and 145 kt, respectively. The Unit 3 estimate of stock size is very imprecise but there is a 0.99 probability that the stock was in the healthy zone in 2010. For Unit 1 + Unit 2 + 3LNO there was a 0.64

probability that the stock was in the healthy zone and 0.84 probability it was larger than the limit reference point. To the contrary, there was a very low probability that the stock in 2+J3K was above the limit reference point. Taken collectively, it would appear that the Atlantic wide DU would place the stock somewhere in the cautious zone with quite high probability. A not-invalid exercise for combining these population level results at the DU level would be to weight the probabilities of being above certain common points by the median estimated K of the stocks. These data are all available in Tables 15-17. Likewise, scenario related to fishing allowable harm for the base runs could be estimated in the same manner.

A BIMODAL POSTERIOR: CORRECT INTERPRETATION OF MID-REGION *S. FASCIATUS* POPULATION STATUS

Special note must be made of the bimodal posterior distribution of current stock state (i.e., B_{2010}/ B_{msy}) for Unit 1 + Unit 2 + 3LNO. Multimodal posteriors are problematic because they suggest two or more much more plausible hypothesis of stock state, and for this population, these states are about equally likely. One of the states would place the stock at about 40% Bmsy while the other would put it near virgin biomass. The biomodality in current stock status (i.e., B_{2010}/ B_{msy}) has occurred mainly because of the slight declines seen in one of the two stock trend data sets (the combined one that starts in 1991) despite large catches that decreased to low levels by about 1994. This small decline and moderately high variability in the stock trend data (CV=40%) results in a fat tail in the posterior distribution for current stock size in 2010 (B_{2010}) that extends credibility to very high stock sizes (i.e., up to over 8 million tons) with some concentration of posterior probability at smaller stock sizes. The fat tail in the distribution for B_{2010} results in probability accumulating at values larger than 1 for B_{2010}/ B_{msy}. This together with the concentration of posterior probability at low values for B_{2010} results in the bimodal posterior distribution seen for B_{2010}/B_{msy}. What it does demand is prudence in assuming a very large stock size and managing according to that optimistic outlook. It would be prudent to view the stock as being in the lower mode of the posterior.

BAYESIAN PROBABILITY AND INTERPRETATION OF STOCK SIZE, THE CASE OF UNIT 3

Bayesian methods treat parameter values and variables (e.g., on stock status) in a model as alternative hypotheses rather than as point estimates and it is important to remember this distinction when interpreting model output. In many cases where most hypothesis are implausible, the distinction is not so important as the most plausible state corresponds to the best estimate of state; however in cases where the plausibility of hypotheses is not that different, then the most likely hypothesis does not equate to a good estimate of state. Such is the case for the Unit 3 model fitting for *S. fasciatus* where the median hypothesis on biomass in 2010 was 2254 kt, which is a value that most would consider to be far too large. In reality the range was from 325 kt to 8642 kt thus the probability surface was very flat. The prior on carrying capacity was uniform in log space from 10 to 10000 kt and when the prior was confronted with data mediated through the production model, there was so little contrast in the data that it did not allow much update of the prior which defined the range of hypotheses on maximum stock size.

Given the lack of cause-effect signal between catches and the survey index in Unit 3, it would be in grave error to assume that the stock biomass in Unit 3 in 2010 was 2.2 million tonnes even though that was the median estimate. All we can say is that we cannot rule out that the stock biomass is between 325,000 t and 8,642, 000 t. There certainly appears to be latitude for increased catches in Unit 3 but it should be prudent and account for the possibility that the stock size is much lower than the median value.

CONCLUSIONS

The BSP stock assessment results provide consistent precise estimates of very high levels of depletion for *S. mentella* in Units 1 and 2. The posterior median values for B_{2010}/ B_{msy} for this stock were all consistently very low at about 3 % with 90% probability intervals ranging between about 2% and 6%. Quota policies of no more than 1 kt resulted in projected stock increases to the critical-cautious zone boundary but this was very slow with there being only about a 46% chance of the stock exceeding 40% of B_{msy} in three generations. Stock status results were relatively uncertain for *S. fasciatus* in Unit 3, and the central region (Units 1, 2 and Area 3LNO) but the posterior medians for B_{2010}/ B_{msy} were no less than about 50% larger than B_{msy} for both stocks . Maintaining the quotas at present day levels presented no risks of depleting either stock. *S. fasciatus* and *S.mentella* in their northern most stocks, showed strong levels of depletion with posterior median biomass ranging from 10-30% of B_{msy} in 2010. However, for Northern *S. mentella*, a quota policy of no more than 1 kt (close to the recent annual catch) had a high chance of leading to increases in stock size and no less than an 80% probability of the stock exceeding 80% of B_{msy} by 2030. For *S. fasciatus* in 2J3K, catches have been very low (recently at about 50 tons) and the stock has been trending upwards.

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Table 1. Swept Area Mature Biomass Estimates (in kt) and Coefficients of Variation (CVs) for S. fasciatus in Unit 3, the southern most management unit. Individual CVs were not available; thus the CV for the time series was computed from the average and standard deviation in values and rounded up to 0.70.

Year	Index	Coefficient of Variation
1970	55	0.700
1971	71	0.700
1972	133	0.700
1973	133	0.700
1974	31	0.700
1975	209	0.700
1976	26	0.700
1977	100	0.700
1978	169	0.700
1979	26	0.700
1980	15	0.700
1981	34	0.700
1982	71	0.700
1983	123	0.700
1984	96	0.700
1985	15	0.700
1986	79	0.700
1987	59	0.700
1988	79	0.700
1989	25	0.700
1990	56	0.700
1991	22	0.700
1992	107	0.700
1993	69	0.700
1994	47	0.700
1995	38	0.700
1996	42	0.700
1997	67	0.700
1998	17	0.700
1999	61	0.700
2000	48	0.700
2001	94	0.700
2002	32	0.700
2003	50	0.700
2004	33	0.700
2005	116	0.700
2006	96	0.700
2007	33	0.700
2008	146	0.700
2009	147	0.700

Table 2. Swept Area Mature Biomass Estimates (in kt) and Coefficients of Variation (CVs) for S. fasciatus in central management units, i.e., Units 1 and 2 and 3LNO. The CV for the time series was computed from log(upper 97.5th CI/ Swept Area Estimate)/ 1.96. This was because some of the computed lower CI bounds were zero. CVs are shown only for the indices that were used in the stock assessment. The combined index was computed from swept area methodology, first by averaging the 3LNO fall and spring swept area estimates and summing the result with the U1 swept area index.

Year	3LNO fall	3LNO spring	U1	U2	CV	U1, 3LNO combined	CV
1990	NA	NA	267	NA	NA	NA	NA
1991	25	10	189	NA	NA	206	0.402
1992	84	10	209	NA	NA	256	0.478
1993	37	63	109	NA	NA	159	0.396
1994	37	75	71	NA	NA	127	0.316
1995	66	53	11	NA	NA	71	0.592
1996	19	49	10	NA	NA	44	0.420
1997	121	14	26	NA	NA	94	0.534
1998	127	135	48	NA	NA	179	0.601
1999	64	138	13	NA	NA	114	0.235
2000	107	109	19	119	0.498	127	0.344
2001	105	40	22	177	0.700	94	0.430
2002	39	28	13	NA	NA	47	0.396
2003	42	33	72	69	0.144	110	0.408
2004	41	112	14	NA	NA	91	0.394
2005	56	79	24	168	0.277	92	0.222
2006	98	NA	38	NA	NA	NA	0.381
2007	105	175	24	158	0.145	164	0.171
2008	127	124	53	NA	NA	178	0.380
2009	100	102	19	128	0.694	120	0.390

Table 3. Swept Area Mature Biomass Estimates (in kt) and Coefficients of Variation (CVs) for S. fasciatus in northern management units, i.e., 2J 3K. The CV for the time series was computed from log(upper 97.5th CI/ Swept Area Estimate)/ 1.96. This was because some of the computed lower CI bounds were zero. The values up to 1994 and from 1995 onwards were treated as two separate stock trend indices each with their own proportionality constants because the survey net changed in 1995.

Year	2J3K fall	CV
1978	438.2	0.477
1979	178.3	1.032
1980	552.1	1.073
1981	711.4	0.490
1982	120.0	0.377
1983	1064.3	0.421
1984	91.9	0.246
1985	72.9	0.248
1986	62.2	0.586
1987	17.3	0.254
1988	61.8	0.527
1989	15.7	0.526
1990	40.8	1.084
1991	5.7	0.350
1992	0.7	0.384
1993	0.5	0.106
1994	0.4	0.201
1995	0.4	0.086
1996	1.6	0.208
1997	1.3	0.915
1998	3.1	0.309
1999	1.8	0.166
2000	0.9	0.217
2001	1.5	0.179
2002	1.2	0.665
2003	0.6	0.105
2004	1.9	0.941
2005	10.6	0.287
2006	20.4	0.685
2007	14.5	0.223
2008	16.3	0.214
2009	27.6	0.277

Table 4. Swept Area Mature Biomass Estimates (in kt) and Coefficie nts of Variation (CVs) for S. mentella in central management units, i.e., Units 1 and 2. The CV for the time series was computed from log(upper 97.5th CI/ Swept Area Estimate)/ 1.96. This was because some of the computed lower CI bounds were zero.

Year	Unit 1	CV	Unit 2	CV
1990	443.012	0.272	NA	NA
1991	208.702	0.209	NA	NA
1992	147.726	0.206	NA	NA
1993	93.656	0.37	NA	NA
1994	55.785	0.185	NA	NA
1995	73.626	0.112	NA	NA
1996	59.242	0.175	NA	NA
1997	52.723	0.131	NA	NA
1998	26.391	0.186	NA	NA
1999	47.859	0.235	NA	NA
2000	49.549	0.122	223.464	0.233
2001	43.549	0.139	151.356	0.14
2002	67.468	0.797	NA	NA
2003	95.821	0.609	100.795	0.196
2004	23.963	0.219	NA	NA
2005	46.166	0.106	90.993	0.118
2006	25.042	0.125	NA	NA
2007	28.034	0.094	76.633	0.185
2008	79.371	0.462	NA	NA
2009	11.55	0.147	103.86	0.164

Table 5. Swept Area Mature Biomass Estimates (in kt) and Coefficients of Variation (CVs) for S. mentella in Central and northern management units, i.e., 3LNO and 2J 3KL. The CV for the time series was computed from log(upper 97.5th CI/ Swept Area Estimate)/ 1.96. This was because some of the computed lower CI bounds were zero. The values up to 1994 and from 1995 onwards for each survey were treated as two separate stock trend indices each with their own proportionality constants because the survey net changed in 1995.

year	2J3K fall	CV	3LNO fall	CV	3LNO spring	CV
1978	1617	0.477	NA	NA	NA	NA
1979	437	1.032	NA	NA	NA	NA
1980	616	1.073	NA	NA	NA	NA
1981	497	0.49	NA	NA	NA	NA
1982	423	0.377	NA	NA	NA	NA
1983	1155	0.421	NA	NA	NA	NA
1984	273	0.246	NA	NA	NA	NA
1985	326	0.248	NA	NA	NA	NA
1986	262	0.586	NA	NA	NA	NA
1987	107	0.254	NA	NA	NA	NA
1988	281	0.527	NA	NA	NA	NA
1989	68	0.526	NA	NA	NA	NA
1990	177	1.084	NA	NA	NA	NA
1991	29	0.35	11	0.894	7	0.857
1992	8	0.384	15	1.035	5	0.852
1993	5	0.106	17	0.687	12	0.505
1994	5	0.201	21	0.491	10	0.717
1995	4	0.086	43	0.877	5	0.236
1996	16	0.208	11	0.613	11	1.104
1997	26	0.915	35	0.767	7	1.174
1998	31	0.309	37	0.808	25	1.048
1999	31	0.166	42	0.281	26	0.303
2000	11	0.217	36	0.507	45	0.187
2001	26	0.179	33	0.605	21	0.188
2002	17	0.665	23	0.500	12	0.219
2003	11	0.105	20	0.491	8	0.383
2004	32	0.941	26	0.568	40	0.543
2005	29	0.287	26	0.302	20	0.692
2006	88	0.685	27	0.554	NA	NA
2007	72	0.223	34	0.240	82	0.635
2008	94	0.214	43	0.525	28	0.216
2009	120	0.277	52	0.572	25	0.272

Table 6. Catch in kt for S. fasciatus and S. mentella in the assessed management units. Catches for 2010 are filled in presuming the catch for 2009 where no catch values for 2010 are available.

	S. fasciatus			*S. mentella*	
Year	Unit 3	Unit 1, 2, 3LNO	2J3KL	Unit 1, 2	3LNO, 2J3KL
1960	20.1	36	32.9999	19	119
1961	19.6	37	20.0299	15	58
1962	24	34	9.2952	14	25
1963	23.5	43	3.3619	23	37
1964	10.8	44	5.1182	29	54
1965	11	59	9.6047	42	53
1966	25.9	64	7.1255	54	37
1967	6.6	83	5.5401	63	36
1968	2.9	65	4.1344	67	23
1969	5.4	91	3.1662	78	31
1970	15.7	83	4.2881	78	25
1971	25.6	100	3.7118	77	33
1972	24.4	89	3.3508	71	29
1973	17.3	100	3.3475	97	45
1974	14.2	67	6.9321	57	37
1975	10.5	72	5.673	61	30
1976	7	52	4.7263	38	35
1977	4.8	38	5.3684	24	25
1978	3.7	32	4.3305	22	28
1979	2.8	39	8.006	19	31
1980	4	40	8.9324	17	19
1981	4.4	44	4.6621	24	25
1982	4.7	41	5.876	24	23
1983	4.9	34	5.7611	21	21
1984	5.2	42	4.8443	26	25
1985	5.6	41	6.9962	23	31
1986	6.6	49	7.8802	27	46
1987	6.1	92	6.324	32	54
1988	3.9	86	3.826	35	36
1989	3.3	58	1.3976	37	23
1990	2.3	60	0.6672	41	20
1991	2	62	0.4861	49	15
1992	2.5	69	0.0992	53	16
1993	5.2	59	0.0502	43	13
1994	5.2	28	0.0202	23	4
1995	4.8	10	0.0108	6	1
1996	4.8	14	0.0002	5	2
1997	6.4	10	0.0003	5	1
1998	5.8	18	0.0003	5	3
1999	4.5	22	0.0131	9	3
2000	4.8	16	0.0125	6	3
2001	4.3	23	0.0079	5	4
2002	4.8	19	0.0063	4	3

2003	3	20	0.0117	4	3
2004	2.1	7	0.0237	3	1
2005	3.1	14	0.032	4	2
2006	2.7	15	0.0547	3	2
2007	2.9	8	0.0723	2	1
2008	3.6	6	0.0569	2	1
2009	4.6	9	0.0487	3	1
2010	5.2	9	0.0487	3	1

Table 7. Life History Parameters for S. mentella and S. fasciatus in the different management units.

a. Growth parameters for female S. fasciatus (Saborido-Rey et al. 2004).

	Mean	CV	SD
Linf	440.4	0.1	44.04
K	0.103	0.2	0.0206
t0	-1.19	0.2	0.238

b. Growth parameters for female S. mentella (Saborido-Rey et al. 2004).

	Mean	CV	SD
Linf	458.2	0.1	45.82
K	0.096	0.2	0.0192
t0	-1.28	0.2	0.256

c. Length-weight conversion factors for female Canadian redfish.

		mean	CV	SD
S. fasciatus	ln(a)	-18.320	0.0050	0.0909
	b	3.080	0.0058	0.0178
S. mentella	ln(a)	-18.478	0.0029	0.0536
	b	3.107	0.0032	0.0101

d. Natural mortality rate prior probability distributions (units in yr^{-1}). The lognormal density function was truncated and the lower and upper bounds provided.

	median	SD(log(M))	lower	upper
S. mentella	0.100	0.25	0.050	0.150
S. fasciatus	0.125	0.25	0.075	0.175

e. Prior probability distribution for the Beverton-Holt steepness parameter (h) used to formulate a prior for the maximum rate of increase parameter. The prior for h is given by parameters of the beta density function where by h = 0.2 + 0.8 x (B) where B is a beta(a,b) random variable. The mean and standard deviation (SD) in h obtained from Forrest et al. (2010) are provided also.

	a	b
Beta parameters	2.6	1.8
	mean	SD
steepness (h)	0.67	0.17

Table 8. Median age at maturity for female redfish in each of the five assessed areas. The standard deviation in the natural logarithm of age at maturity (SD in ln(age maturity)) is presumed to be 0.5 for all management units and a coefficient of variation of 5% was applied to the median age at maturity and the SD in ln(age maturity).

	Geographic Area	Unit	Age at Maturity females
S. mentella	Gulf of St. Lawrence	1	10.36
Gulf of St. Lawrence and Laurentian Channel	Laurentian Channel	2	10.6
		average 1,2	10.48
		3M	Not available
S. mentella	Grand Banks	3O	15.08
Northern Population	Labrador Shelf	2, 2K, 2GH	Not available
	Davis Strait	3 LN	Not available
	Baffin Bay		
S. fasciatus	Gulf of St. Lawrence and Laurentian Channel	Unit 1	7.67
Canadian Atlantic		Unit 2	10.31
		Unit 3	8.03
		3O	10.31
		3LN	Not available
		2J3K	Not available
		2GH	Not available
		3M	Not available
		Average all	9.08
		Average Unit 1, 2	8.99
		Average Unit 1, 2, 3LNO	9.43
		Assumed for 2J3K	10.31

Table 9. Prior probability distributions for the maximum rate of increase (r) for redfish in each of the five assessed management areas.

Species	Management Unit	Mean r	Median r	SD	CV	SD(log(r))
S. fasciatus	U3	0.153	0.135	0.073	0.480	0.525
S. fasciatus	3LNO, U1,U2	0.142	0.126	0.067	0.468	0.514
S. fasciatus	2J 3K	0.136	0.121	0.063	0.461	0.508
S. mentella	U1, U2	0.124	0.110	0.058	0.467	0.509
S. mentella	Northern	0.104	0.094	0.046	0.440	0.484

Table 10. Summary of estimated parameters.

Parameter	Description
r	Intrinsic rate of increase
K	Carrying Capacity
p_0	Ratio of initial stock biomass in first year to carrying capacity
$\{q_{j=1}, q_{j=2}, \ldots\ q_{j=J}\}$	Vector of catchability parameters for J abundance indices (where, J is Area-specific as described in Table 1 of main document)

Table 11. Summary of derived management parameters of interest for the Schaefer model.

Maximum Sustainable Yield (MSY)	$rK/4$
Stock size for MSY (B_{msy})	K/2
Rate of exploitation at MSY	$r/2$
Replacement yield	$rB_y\left(1-\frac{B_y}{K}\right) \quad for \quad B_y < K$ $0 \quad for \quad B_y \geq K$
Maximum rate of exploitation	r

Table 12 Prior distributions for surplus production model parameters. Biomass values are shown in kt.

Parameter	Prior density function
ln(K)	Uniform(log(5),log(10,000))
ln(q_j)	Uniform(-20,200)
p_0	Lognormal(log(0.8),0.2^2)
r (*S. fasciatus*, Unit 3)	logNormal(log(0.135),0.525^2)
r (*S. fasciatus*, Units 1, 2, 3LNO)	logNormal(log(0.126),0.514^2)
r (*S. fasciatus*, 2J3K)	logNormal(log(0.121),0.508^2)
r (*S. mentella*, Units 1 and 2)	logNormal(log(0.110),0.509^2)
r (*S. mentella*, Northern (3LNO, 2J3K))	logNormal(log(0.094),0.509^2)
$\varepsilon_{process,y}$	Normal(0, 0.05^2)

Table 13. Standard deviation of the observation error for each abundance indices j, $\sigma_{obs,j}$, per area, obtained from the preliminary analysis and used in the assessment models. j=U3 is for the unit 3 survey index, j=U1 is for the Unit 1 survey index, j=U2 is for the Unit 2 survey index, j=U1, 3LNO is for the index for S. fasciatus obtained from summing the average of the spring and fall index for 3LNO and the Unit 1 index for S. fasciatus, j = 3LNOf/s,1 is for the fall/spring index in NAFO area 3LNO from 1991 to 1994, j=2J3K, j = 3LNOf/s,2 is for the fall/spring index for NAFO area 3LNO from 1995-2009, j=2J3K,1 is for the 2J3K fall index from 1978 to 1994, j=2J3K,2 is for the 2J3K fall index from 1995 to 2009.

	$\sigma_{obs,U3}$	$\sigma_{obs,U1}$	$\sigma_{obs,U2}$	$\sigma_{obs,U1,3LNO}$	$\sigma_{obs,3LNOs,1}$	$\sigma_{obs,3LNOs,2}$	$\sigma_{obs,3LNOf,1}$	$\sigma_{obs,3LNOf,2}$	$\sigma_{obs,2J3K,1}$	$\sigma_{obs,2J3K,2}$
S. fasciatus Unit 3	0.700									
S. fasciatus Unit 1, 2, 3LNO	--		0.410	0.395						
S. fasciatus, 2J3K	--			--					1.51	0.911
S. mentella, Unit 1, 2	--	0.531	0.266	--	--					
S. mentella, 3LNO, 2J3K	--	--	--	--	0.794	0.703	0.777	0.547	1.14	0.652

Table 14. Summary of sensitivity runs in the redfish stock assessment, including their categorization. S stands for stock, where S=1 is S. fasciatus in Unit 3, S=2 is S. fasciatus in the central management units 1, 2, 3LNO, S=3 is S. fasciatus in 2J3K (2J3K 1995-2009 series split 95-04, 05-09), S=4 is S. mentella in Units 1,2 and S = 5 is S. mentella in 3LNO and 2J3K (2J3K 1995-2009 series split 95-04, 05-09).

Category code	Category Description	Table Code	Run Description
Ref	Reference run	Ref.S.1	Reference run
A	r prior mean	A.S.1	low r (mean = 0.67 reference run mean)
		A.S.2	high r (mean = 1.33 reference run mean)
B	Initial stock size assumptions	B.S.1	prior mean B1960/ K0 = 0.6
		B.S.2	prior mean B1960/ K0 = 1.0
C	Uncertainty over catch records	C.S.1	fixed catches are 50% of the reference case
		C.S.2	fixed catches are twice the reference case
D	Alternative ways to treat the survey data	D.2.1	Unit 1, 3LNO fall and spring are treated as separate
		D.3.1	*S. fasciatus* 2J3K 1995-2009 as a single index
		D.5.1	*S. mentella* 2J3K 1995-2009 as a singe index

Table 15. Parameter estimates and stock status indicators for S. fasciatus in Unit 3. Posterior means, standard deviations (SDs), coefficients of variation (CVs) medians, 90% probability intervals (5th and 95th percentiles of posterior distribution), and are provided for all parameter estimates. K is carrying capacity, r is the maximum rate of increase, F is fishing mortality rate, MSY is maximum sustainable yield, B_{msy} is the stock biomass that gives MSY, B is stock biomass, REPY is the replacement yield in 2010. The two quantiles represent the probability that biomass in 2010 is above the critical zone [$P(B_{2010} > 0.4B_{MSY})$] and the probability that biomass in 2010 is in the healthy zone [$P(B_{2010} > 0.8B_{MSY})$]. All biomass and yield values are in kilotons.

Estimated Variables						
Variable	Mean	SD	CV	5th Percentile	Median	95th Percentile
r	0.168	0.08	0.477	0.062	0.153	0.324
K	3133	2574	0.822	388	2290	8450
MSY	131	134	1.02	11	83	412
B_{msy}	1567	1287	0.822	194	1145	4225
B_{1960}	2575	2181	0.847	309	1891	7221
B_{2010}	3145	2670	0.849	325	2254	8642
B_{2010}/B_{msy}	1.95	0.29	0.15	1.469	1.98	2.33
B_{2010}/B_{1960}	1.21	0.29	0.24	0.784	1.19	1.69
B_{2010}/K	0.97	0.15	0.15	0.73	0.99	1.17
F_{MSY}	0.084	0.040	0.477	0.03	0.08	0.16
F_{2010}	0.0048	0.008	1.66	0.0006	0.0023	0.0161
F_{2010}/F_{msy}	0.0814	0.1728	2.123	0.006	0.032	0.296
$REPY$	16	31.9	2.0	0	2.6	79.7
$Catch_{2010}/REPY$	0.73	9.29	12.65	0	0.05	1.55
Estimated quantiles						
$P(B_{2010} > 0.4B_{msy})$	0.999					
$P(B_{2010} > 0.8B_{msy})$	0.99					

Table 16. Parameter estimates and stock status indicators for S. fasciatus in Unit 1, 2 and areas 3LNO. Posterior means, standard deviations (SDs), coefficients of variation (CVs) medians, 90% probability intervals (5th and 95th percentiles of posterior distribution), and are provided for all parameter estimates. K is carrying capacity, r is the maximum rate of increase, F is fishing mortality rate, MSY is maximum sustainable yield, B_{msy} is the stock biomass that gives MSY, B is stock biomass, REPY is the replacement yield in 2010. The two quantiles represent the probability that biomass in 2010 is above the critical zone [$P(B_{2010}> 0.4B_{MSY})$] and the probability that biomass in 2010 is in the healthy zone [$P(B_{2010}> 0.8B_{MSY})$]. All biomass and yield values are in kilotons.

Estimated Variables						
Variable	Mean	SD	CV	5th Percentile	Median	95th Percentile
r	0.140	0.066	0.47	0.055	0.128	0.268
K	3346	2449	0.73	941	2372	8662
MSY	116	114	0.98	31	60	355
B_{msy}	1673	1225	0.73	471	1186	4331
B_{1960}	2685	2004	0.75	742	1887	7214
B_{2010}	2832	2829	1.00	175	1876	8778
B_{2010}/B_{msy}	1.329	0.729	0.55	0.303	1.615	2.248
B_{2010}/B_{1960}	0.843	0.497	0.59	0.18	0.941	1.607
B_{2010}/K	0.664	0.365	0.55	0.1516	0.8076	1.124
F_{MSY}	0.070	0.033	0.47	0.028	0.064	0.134
F_{2010}	0.0152	0.0184	1.21	0.001	0.0048	0.0528
F_{2010}/F_{msy}	0.240	0.2616	1.09	0.012	0.089	0.737
$REPY$	27	26.8	0.99	0	25.5	71.9
$Catch_{2010}/REPY$	0.419	2.4182	5.78	0	0.267	0.826
Estimated quantiles						
$P(B_{2010}> 0.4B_{msy})$	0.842					
$P(B_{2010}> 0.8B_{msy})$	0.639					

Table 17. Parameter estimates and stock status indicators for S. fasciatus in 2J3K. Posterior means, standard deviations (SDs), coefficients of variation (CVs) medians, 90% probability intervals (5th and 95th percentiles of posterior distribution), and are provided for all parameter estimates. K is carrying capacity, r is the maximum rate of increase, F is fishing mortality rate, MSY is maximum sustainable yield, B_{msy} is the stock biomass that gives MSY, B is stock biomass, REPY is the replacement yield in 2010. The two quantiles represent the probability that biomass in 2010 is above the critical zone [$P(B_{2010} > 0.4B_{MSY})$] and the probability that biomass in 2010 is in the healthy zone [$P(B_{2010} > 0.8B_{MSY})$]. All biomass and yield values are in kilotons.

Estimated Variables						
Variable	Mean	SD	CV	5th Percentile	Median	95th Percentile
r	0.087	0.033	0.38	0.045	0.080	0.147
K	151	28	0.188	109	145	206
MSY	3	1	0.274	2	3	5
B_{msy}	76	14	0.188	54	73	103
B_{1960}	137	23	0.167	63	104	142
B_{2010}	8	5	0.599	3	8	23
B_{2010}/B_{msy}	0.12	0.092	0.767	0.042	0.091	0.318
B_{2010}/B_{1960}	0.079	0.07	0.879	0.022	0.06	0.276
B_{2010}/K	0.060	0.046	0.767	0.0208	0.0457	0.159
F_{MSY}	0.0434	0.0165	0.38	0.0227	0.0399	0.0733
F_{2010}	0.0076	0.0039	0.505	0.0022	0.0065	0.0152
F_{2010}/F_{msy}	0.225	0.188	0.835	0.032	0.169	0.565
REPY	0.700	0.700	0.943	0.2	0.5	2.4
$Catch_{2010}/REPY$	0.12	0.096	0.799	0.020	0.092	0.294
Estimated quantiles						
$P(B_{2010} > 0.4B_{msy})$	0.029					
$P(B_{2010} > 0.8B_{msy})$	0.000					

Table 18. Parameter estimates and stock status indicators for S. mentella in Units 1, 2. Posterior means, standard deviations (SDs), coefficients of variation (CVs) medians, 90% probability intervals (5th and 95th percentiles of posterior distribution), and are provided for all parameter estimates. K is carrying capacity, r is the maximum rate of increase, F is fishing mortality rate, MSY is maximum sustainable yield, B_{msy} is the stock biomass that gives MSY, B is stock biomass, REPY is the replacement yield in 2010. The two quantiles represent the probability that biomass in 2010 is above the critical zone [$P(B_{2010} > 0.4B_{MSY})$] and the probability that biomass in 2010 is in the healthy zone [$P(B_{2010} > 0.8B_{MSY})$]. All biomass and yield values are in kilotons.

Estimated Variables						
Variable	Mean	SD	CV	5th Percentile	Median	95th Percentile
r	0.073	0.029	0.40	0.033	0.069	0.130
K	1213	277	0.23	841	1168	1722
MSY	21	6	0.28	11	21	31
B_{msy}	606	139	0.23	420	584	861
B_{1960}	987	212	0.21	677	962	1339
B_{2010}	21	7	0.35	11	19	35
B_{2010}/B_{msy}	0.035	0.011	0.32	0.023	0.032	0.058
B_{2010}/B_{1960}	0.022	0.007	0.34	0.013	0.020	0.035
B_{2010}/K	0.018	0.006	0.32	0.011	0.016	0.029
F_{MSY}	0.037	0.015	0.40	0.02	0.03	0.07
F_{2010}	0.158	0.049	0.31	0.085	0.153	0.247
F_{2010}/F_{msy}	4.78	1.94	0.41	2.43	4.42	8.43
$REPY$	1.50	0.50	0.35	0.70	1.40	2.40
$Catch_{2010}/REPY$	2.32	0.90	0.39	1.2394	2.14	4.03
Estimated quantiles						
$P(B_{2010} > 0.4B_{msy})$	0.000					
$P(B_{2010} > 0.8B_{msy})$	0.000					

Table 19. Parameter estimates and stock status indicators for S. mentella in 3LNO and 2J3K. Posterior means, standard deviations (SDs), coefficients of variation (CVs) medians, 90% probability intervals (5th and 95th percentiles of posterior distribution), and are provided for all parameter estimates. K is carrying capacity, r is the maximum rate of increase, F is fishing mortality rate, MSY is maximum sustainable yield, B_{msy} is the stock biomass that gives MSY, B is stock biomass, REPY is the replacement yield in 2010. The two quantiles represent the probability that biomass in 2010 is above the critical zone [$P(B_{2010} > 0.4B_{MSY})$] and the probability that biomass in 2010 is in the healthy zone [$P(B_{2010} > 0.8B_{MSY})$]. All biomass and yield values are in kilotons.

Estimated Variables						
Variable	Mean	SD	CV	5th Percentile	Median	95th Percentile
r	0.123	0.035	0.29	0.074	0.120	0.189
K	763	176	0.23	528	727	1106
MSY	22	4	0.19	16	22	29
B_{msy}	382	88	0.23	264	363	553
B_{1960}	630	126	0.20	355	515	736
B_{2010}	58	28	0.49	27	54	118
B_{2010}/B_{msy}	0.154	0.074	0.48	0.07	0.139	0.291
B_{2010}/B_{1960}	0.102	0.049	0.48	0.048	0.09	0.193
B_{2010}/K	0.077	0.037	0.48	0.035	0.0697	0.1455
F_{MSY}	0.0617	0.0177	0.29	0.0368	0.0601	0.0947
F_{2010}	0.021	0.0091	0.44	0.0088	0.0198	0.0385
F_{2010}/F_{msy}	0.355	0.155	0.44	0.156	0.332	0.646
$REPY$	5.9	2.5	0.42	2.9	5.4	10.5
$Catch_{2010}/REPY$	0.1978	0.080	0.40	0.095	0.186	0.347
Estimated quantiles						
$P(B_{2010} > 0.4B_{msy})$	0.011					
$P(B_{2010} > 0.8B_{msy})$	0.000					

Table 20. Decision table for S. fasciatus in Unit 3 with median posterior estimates of biomass after five twenty and sixty years (up to three generations) ($B_{2016,}$ B_{2030}, and B_{2070}) in relation to the target biomass (B_{MSY}) at various levels of constant annual total allowable catch (TAC). Probabilities (P) are presented for 4 stock status indicators: B_{fin} will be above the Limit Reference Point (40% of B_{MSY}), B_{fin} will be above the Upper Stock Reference (80% of B_{MSY}), B_{fin} will be above the target biomass of B_{MSY}, and B_{fin} will be above the current biomass (B_{2010}).

Horizon	TAC (kt)	Median(B_{fin}/B_{msy})	P(B_{fin}>0.4 B_{msy})	P(B_{fin}>0.8 B_{msy})	P(B_{fin}>B_{msy})	P(B_{fin}>B_{cur})
5 -year	0	1.966	1	0.993	0.987	0.516
	2	1.959	1	0.993	0.987	0.497
	4	1.951	0.999	0.992	0.986	0.481
	6	1.944	0.999	0.99	0.985	0.457
20-year	0	1.968	1	0.999	0.997	0.495
	2	1.952	1	0.998	0.994	0.477
	4	1.936	0.999	0.994	0.99	0.453
	6	1.918	0.996	0.989	0.982	0.428
60-year	0	1.964	1	1	0.998	0.489
	2	1.946	1	0.999	0.997	0.471
	4	1.925	0.999	0.997	0.993	0.447
	6	1.905	0.992	0.988	0.981	0.415

Table 21. Decision table for S. fasciatus in Unit 1, 2 and 3LNO with median posterior estimates of biomass after five twenty and sixty years (up to three generations) ($B_{2016,}$ B_{2030}, and B_{2070}) in relation to the target biomass (B_{MSY}) at various levels of constant annual total allowable catch (TAC). Probabilities (P) are presented for 4 stock status indicators: B_{fin} will be above the Limit Reference Point (40% of B_{MSY}), B_{fin} will be above the Upper Stock Reference (80% of B_{MSY}), B_{fin} will be above the target biomass of B_{MSY}, and B_{fin} will be above the current biomass (B_{2010}).

Horizon	TAC (kt)	Median(B_{fin}/B_{msy})	P(B_{fin}>0.4 B_{msy})	P(B_{fin}>0.8 B_{msy})	P(B_{fin}>B_{msy})	P(B_{fin}>B_{cur})
5 -year	0	1.589	0.969	0.720	0.649	0.682
	3	1.596	0.968	0.725	0.652	0.681
	6	1.591	0.957	0.715	0.646	0.670
	9	1.583	0.947	0.705	0.641	0.654
20-year	0	1.809	0.999	0.968	0.934	0.731
	3	1.794	0.997	0.961	0.924	0.722
	6	1.768	0.996	0.951	0.902	0.711
	9	1.736	0.990	0.934	0.885	0.688
60-year	0	1.934	1.000	0.999	0.997	0.721
	3	1.914	1.000	0.997	0.994	0.710
	6	1.888	0.999	0.995	0.989	0.700
	9	1.864	0.997	0.992	0.981	0.690

Table 22. Decision table for S. fasciatus in 2J3K with median posterior estimates of biomass after five twenty and sixty years (up to three generations) (B_{2016}, B_{2030}, and B_{2070}) in relation to the target biomass (B_{MSY}) at various levels of constant annual total allowable catch (TAC). Probabilities (P) are presented for 4 stock status indicators: B_{fin} will be above the Limit Reference Point (40% of B_{MSY}), B_{fin} will be above the Upper Stock Reference (80% of B_{MSY}), B_{fin} will be above the target biomass of B_{MSY}, and B_{fin} will be above the current biomass (B_{2010}).

Horizon	TAC (kt)	Median(B_{fin}/B_{msy})	P(B_{fin}>0.4 B_{msy})	P(B_{fin}>0.8 B_{msy})	P(B_{fin}>B_{msy})	P(B_{fin}>B_{cur})
5 -year	0	0.127	0.101	0.027	0.003	0.969
	0.025	0.131	0.104	0.027	0.003	0.969
	0.050	0.130	0.104	0.027	0.003	0.961
	0.075	0.128	0.104	0.027	0.003	0.951
20-year	0	0.338	0.464	0.162	0.137	0.996
	0.025	0.337	0.466	0.163	0.137	0.995
	0.050	0.326	0.461	0.162	0.137	0.990
	0.075	0.311	0.439	0.162	0.136	0.985
60-year	0	1.503	0.954	0.862	0.789	1.000
	0.025	1.475	0.945	0.851	0.761	0.999
	0.050	1.428	0.931	0.831	0.746	0.997
	0.075	1.377	0.915	0.821	0.736	0.991

Table 23. Decision table for S. mentella in Units 1 and 2 with median posterior estimates of biomass after five twenty and sixty years (up to three generations) (B_{2016}, B_{2030}, and B_{2070}) in relation to the target biomass (B_{MSY}) at various levels of constant annual total allowable catch (TAC). Probabilities (P) are presented for 4 stock status indicators: B_{fin} will be above the Limit Reference Point (40% of B_{MSY}), B_{fin} will be above the Upper Stock Reference (80% of B_{MSY}), B_{fin} will be above the target biomass of B_{MSY}, and B_{fin} will be above the current biomass (B_{2010}).

Horizon	TAC (kt)	Median(B_{fin}/B_{msy})	P(B_{fin}>0.4 B_{msy})	P(B_{fin}>0.8 B_{msy})	P(B_{fin}>B_{msy})	P(B_{fin}>B_{cur})
5 -year	0	0.042	0	0	0	0.903
	1	0.034	0	0	0	0.575
	2	0.025	0	0	0	0.172
	3	0.016	0	0	0	0.045
20-year	0	0.117	0.039	0.002	0.001	0.989
	1	0.053	0.013	0.001	0.001	0.673
	2	0	0.003	0	0	0.146
	3	0	0	0	0	0.022
60-year	0	0.98	0.786	0.578	0.49	0.998
	1	0.311	0.457	0.301	0.25	0.698
	2	0	0.095	0.065	0.058	0.129
	3	0	0.012	0.01	0.008	0.016

Table 24. Decision table for S. mentella in 3LNO and 2J3K with median posterior estimates of biomass after five twenty and sixty years (up to three generations) ($B_{2016,}$ B_{2030}, and B_{2070}) in relation to the target biomass (B_{MSY}) at various levels of constant annual total allowable catch (TAC). Probabilities (P) are presented for 4 stock status indicators: B_{fin} will be above the Limit Reference Point (40% of B_{MSY}), B_{fin} will be above the Upper Stock Reference (80% of B_{MSY}), B_{fin} will be above the target biomass of B_{MSY}, and B_{fin} will be above the current biomass (B_{2010}).

Horizon	TAC (kt)	Median(B_{fin}/B_{msy})	P(B_{fin}>0.4 B_{msy})	P(B_{fin}>0.8 B_{msy})	P(B_{fin}>B_{msy})	P(B_{fin}>B_{cur})
5 -year	0	0.230	0.123	0.004	0.001	0.995
	1	0.226	0.124	0.004	0.001	0.990
	2	0.211	0.106	0.004	0.001	0.935
	3	0.193	0.088	0.003	0.001	0.876
20-year	0	0.870	0.903	0.563	0.404	1.000
	1	0.798	0.835	0.498	0.346	0.998
	2	0.683	0.738	0.428	0.272	0.983
	3	0.557	0.634	0.329	0.211	0.931
60-year	0	1.877	1.000	0.997	0.987	1.000
	1	1.842	0.999	0.986	0.977	1.000
	2	1.788	0.981	0.960	0.940	0.990
	3	1.731	0.899	0.867	0.854	0.936

Table 25. Stock assessment results for alternative settings to the Bayesian surplus production (BSP) stock assessment model for S. fasciatus in Unit 3. B_{2010} refers to the stock size in 2010, $RepY_{2010}$ refers to the replacement yield in 2010. F_{2010} refers to the fishing mortality rate in 2010. All biomass values are in tons. The posterior 5th, 50th (median) and 95th percentiles are shown for each estimated quantity. See Table 11 for a description of each sensitivity run.

	r			***B_{msy}***			***B_{2010}***			***$RepY_{2010}$***			***B_{2010}/B_{msy}***			***F_{2010}/F_{msy}***			***$Catch_{2010}/RepY_{2010}$***		
	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Code	Reference run																				
Ref.1.1	0.062	0.153	0.324	194	1145	4225	325	2254	8642	0	2.6	79.7	1.469	1.979	2.333	0.006	0.032	0.296	0	0.054	1.548
	r prior mean 33% lower and 33% higher																				
A.1.1	0.042	0.101	0.251	186	1047	4277	213	2005	8575	0	5.2	69	1.044	1.919	2.352	0.009	0.05	0.711	0	0.136	1.863
A.1.2	0.083	0.2	0.363	186	1095	4220	332	2211	8604	0	0.7	88.6	1.625	1.992	2.326	0.005	0.024	0.191	0	0.026	1.598
	Initial stock size, 0.6 K and 1.0 K																				
B.1.1	0.063	0.171	0.338	223	1217	4324	341	2420	8785	0	2.7	88	1.397	1.979	2.318	0.006	0.027	0.286	0	0.045	1.268
B.1.2	0.062	0.146	0.325	167	962	4017	272	1908	8177	0	3.1	68.7	1.473	1.967	2.338	0.007	0.038	0.371	0	0.082	1.833
	Catches half or double																				
C.1.1	0.062	0.155	0.329	104	820	4206	180	1663	8496	0	1.3	73.4	1.511	1.982	2.348	0.003	0.021	0.272	0	0.026	1.291
C.1.2	0.061	0.151	0.331	348	1465	4393	507	2889	9021	0	5.9	96.8	1.293	1.962	2.324	0.011	0.049	0.476	0	0.115	2.059

Table 26. Stock assessment results for alternative settings to the Bayesian surplus production (BSP) stock assessment model for S. fasciatus in Unit 1, 2, 3LNO. B_{2010} refers to the stock size in 2010, $RepY_{2010}$ refers to the replacement yield in 2010. F_{2010} refers to the fishing mortality rate in 2010. All biomass values are in tons. The posterior 5^{th}, 50^{th} (median) and 95^{th} percentiles are shown for each estimated quantity. See Table 11 for a description of each sensitivity run.

	r			B_{msy}			B_{2010}			$RepY_{2010}$			B_{2010}/B_{msy}			F_{2010}/F_{msy}			$Catch_{2010}/RepY_{2010}$		
	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Code	Reference run																				
Ref.2.1	0.055	0.128	0.268	471	1186	4331	175	1876	8778	0	25.5	71.9	0.303	1.615	2.248	0.012	0.089	0.736	0	0.267	0.826
	r prior mean 33% lower and 33% higher																				
A.2.1	0.035	0.088	0.194	550	1370	4251	210	1881	8514	0	27	69.4	0.315	1.334	2.219	0.017	0.144	0.795	0	0.277	0.769
A.2.2	0.074	0.163	0.323	432	1154	4363	161	2050	8859	0	24.5	79.1	0.3	1.791	2.266	0.009	0.055	0.669	0	0.246	0.739
	Initial stock size, 0.6 K and 1.0 K																				
B.2.1	0.056	0.134	0.276	501	1413	4336	171	2334	8702	0	25	84.7	0.278	1.702	2.241	0.011	0.064	0.709	0	0.235	0.632
B.2.2	0.061	0.133	0.264	436	937	4071	166	1325	8263	0	24.8	66.6	0.314	1.435	2.245	0.013	0.133	0.743	0	0.287	0.783
	Catches half or double																				
C.2.1	0.053	0.126	0.268	244	1057	4509	92	1980	9820	0	11.7	51.7	0.326	1.88	2.313	0.006	0.036	0.674	0	0.183	0.655
C.2.2	0.055	0.129	0.265	879	1758	4441	312	1684	8725	0	52.6	104.6	0.283	0.903	2.179	0.024	0.276	0.766	0	0.298	0.687
	Unit 1, 3LNO spring and fall treated as separate time series as opposed to combined																				
D.2.1	0.055	0.13	0.293	593	1513	4433	403	2703	8957	0	26.9	86	0.534	1.837	2.272	0.011	0.051	0.457	0	0.197	0.892

Table 27. Stock assessment results for alternative settings to the Bayesian surplus production (BSP) stock assessment model for S. fasciatus in 2J3K. B_{2010} refers to the stock size in 2010, $RepY_{2010}$ refers to the replacement yield in 2010. F_{2010} refers to the fishing mortality rate in 2010. All biomass values are in tons. The posterior 5th, 50th (median) and 95th percentiles are shown for each estimated quantity. See Table 11 for a description of each sensitivity run.

	r			***B_{msy}***			***B_{2010}***			***$RepY_{2010}$***			***B_{2010}/B_{msy}***			***F_{2010}/F_{msy}***			***$Catch_{2010}/RepY_{2010}$***		
	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Code	Reference run																				
Ref.3.1	0.045	0.08	0.147	54	73	103	3	8	23	0.2	0.5	2.4	0.042	0.091	0.318	0.032	0.169	0.565	0.02	0.092	0.294
	r prior mean 33% lower and 33% higher																				
A.3.1	0.035	0.068	0.115	60.54	76.3	108.3	3	6	14	0.11	0.35	1.35	0.034	0.069	0.214	0.061	0.263	0.889	0.035	0.141	0.458
A.3.2	0.053	0.097	0.203	46.47	70.3	96.1	4	9	24	0.2	0.73	3.25	0.048	0.119	0.478	0.022	0.121	0.455	0.015	0.067	0.239
	Initial stock size, 0.6 K and 1.0 K																				
B.3.1	0.049	0.088	0.139	66.14	86.3	121.5	4	10	24	0.21	0.81	2.42	0.042	0.108	0.318	0.032	0.109	0.445	0.02	0.06	0.231
B.3.2	0.043	0.077	0.141	51.38	69.2	88.9	3	6	16	0.12	0.35	1.6	0.039	0.074	0.243	0.051	0.263	0.785	0.031	0.141	0.405
	Catches half or double																				
C.3.1	0.046	0.081	0.114	30.41	35.7	50.8	2	4	10	0.1	0.28	0.84	0.05	0.099	0.257	0.048	0.161	0.465	0.029	0.087	0.243
C.3.2	0.047	0.082	0.142	82.39	140.4	197.4	6	13	31	0.36	0.89	3.25	0.043	0.081	0.23	0.051	0.203	0.521	0.03	0.109	0.273
	2J3K for 1995-2009 a single series.																				
D.3.1	0.067	0.143	0.2	43	55	98	7	22	38	0.4	2.1	4	0.07	0.323	0.664	0.015	0.036	0.23	0.012	0.023	0.122

Table 28. Stock assessment results for alternative settings to the Bayesian surplus production (BSP) stock assessment model for S. mentella in Units 1 and 2. B_{2010} refers to the stock size in 2010, $RepY_{2010}$ refers to the replacement yield in 2010. F_{2010} refers to the fishing mortality rate in 2010. All biomass values are in tons. The posterior 5^{th}, 50^{th} (median) and 95^{th} percentiles are shown for each estimated quantity. See Table 11 for a description of each sensitivity run.

	r			***B_{msy}***			***B_{2010}***			***$RepY_{2010}$***			***B_{2010}/B_{msy}***			***F_{2010}/F_{msy}***			***$Catch_{2010}/RepY_{2010}$***		
	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Code	Reference run																				
Ref.4.1	0.033	0.069	0.13	420	584	861	11	19	35	0.7	1.4	2.4	0.023	0.032	0.058	2.433	4.419	8.425	1.239	2.144	4.027
	r prior mean 33% lower and 33% higher																				
A.4.1	0.024	0.052	0.102	458	648	948	13	21	39	0.6	1.2	2.1	0.023	0.033	0.06	2.782	5.283	10.605	1.401	2.565	5.113
A.4.2	0.042	0.082	0.149	397	547	794	11	18	32	0.9	1.5	2.6	0.023	0.032	0.056	2.285	4.027	7.047	1.164	1.955	3.35
	Initial stock size, 0.6 K and 1.0 K																				
B.4.1	0.032	0.072	0.135	458	668	1013	12	20	35	0.8	1.5	2.7	0.022	0.029	0.05	2.211	4.093	7.368	1.118	1.986	3.532
B.4.2	0.033	0.071	0.134	376	523	746	11	18	33	0.7	1.4	2.3	0.024	0.035	0.064	2.537	4.543	8.697	1.279	2.204	4.09
	Catches half or double																				
C.4.1	0.034	0.069	0.122	209	292	428	6	9	17	0.4	0.7	1.2	0.023	0.033	0.056	2.489	4.473	8.032	1.258	2.175	3.844
C.4.2	0.034	0.069	0.122	832	1168	1686	23	38	68	1.6	2.8	4.8	0.023	0.033	0.057	2.48	4.422	8.024	1.255	2.149	3.802

Table 29. Stock assessment results for alternative settings to the Bayesian surplus production (BSP) stock assessment model for S. mentella in 2J3K. B_{2010} refers to the stock size in 2010, $RepY_{2010}$ refers to the replacement yield in 2010. F_{2010} refers to the fishing mortality rate in 2010. All biomass values are in tons. The posterior 5th, 50th (median) and 95th percentiles are shown for each estimated quantity. See Table 11 for a description of each sensitivity run.

	r			B_{msy}			B_{2010}			$RepY_{2010}$			B_{2010}/B_{msy}			F_{2010}/F_{msy}			$Catch_{2010}/RepY_{2010}$		
	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Code	Reference run																				
Ref.5.1	0.074	0.12	0.189	264	363	553	27	54	118	2.9	5.4	10.5	0.07	0.139	0.291	0.156	0.332	0.646	0.095	0.186	0.347
	r prior mean 33% lower and 33% higher																				
A.5.1	0.053	0.103	0.168	282	395	584	28	56	125	2.6	4.9	9.9	0.069	0.134	0.291	0.166	0.368	0.735	0.101	0.205	0.391
A.5.2	0.082	0.132	0.201	251	348	527	26	50	110	3.1	5.7	10.6	0.072	0.141	0.283	0.156	0.308	0.599	0.094	0.174	0.324
	Initial stock size, 0.6 K and 1.0 K																				
B.5.1	0.075	0.112	0.173	311	481	689	28	48	109	2.5	4.9	9.9	0.044	0.107	0.229	0.17	0.374	0.76	0.101	0.205	0.399
B.5.2	0.073	0.126	0.191	245	328	463	27	53	115	3	5.5	10.3	0.08	0.149	0.329	0.155	0.322	0.626	0.097	0.183	0.337
	Catches half or double																				
C.5.1	0.074	0.121	0.191	131	181	276	13	27	59	1.4	2.7	5.2	0.071	0.139	0.286	0.16	0.334	0.659	0.097	0.187	0.351
C.5.2	0.073	0.121	0.19	528	726	1106	51	105	240	5.5	10.5	21.3	0.07	0.137	0.296	0.156	0.339	0.673	0.094	0.191	0.361
	2J3K for 1995-2009 a single series.																				
D.5.1	0.091	0.142	0.216	247	339	460	43	82	168	5.4	9	16.5	0.129	0.222	0.471	0.089	0.188	0.332	0.061	0.112	0.187

Table 30. Relative credibility of alternative model runs as indicated by Bayes factors which give the ratio of the probability of the data for the run to the probability of the data under the reference case run. See Table 11 for a description of each sensitivity run.

Category Code	Category description	Run description	Code	*S. fasciatus* Unit 3	*S. fasciatus* Units 1,2 3LNO	*S. fasciatus* 2J3K	*S. mentella* Units 1,2	S mentella 3LNO, 2J3K
A	r prior mean	low	A.S.1	1.2	1.2	1.9	2.0	0.6
		reference	Ref.S.1	1.0	1.0	1.0	1.0	1.0
		high	A.S.3	1.1	0.9	0.5	0.6	1.0
B	Initial stock size uncertainty	low	B.S.1	0.8	0.8	0.3	0.8	0.8
		reference	Ref.S.1	1.0	1.0	1.0	1.0	1.0
		high	B.S.2	1.4	1.1	1.9	1.3	1.4
C	Catch history uncertainty	low	C.S.1	1.1	1.3	0.3	1.0	1.1
		reference	Ref.S.1	1.0	1.0	1.0	1.0	1.0
		high	C.S.2	1.0	0.7	0.9	1.1	1.1
D	Data series	reference	Ref.S.1	NA	NA	1	NA	1
		vary aggregation of data	D.S.1	NA	NA	1 /9848	NA	1/637

Table 31. Decision table for alternative quota policies for S. fasciatus in Unit 3 when alternative priors for r are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

prior mean for r	low	reference	high
Bayes factor	1.2	1.0	1.1
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	1	1	1
2	0.999	1	1
4	0.996	0.999	0.999
6	0.986	0.996	0.998

Table 32. Decision table for alternative quota policies for S. fasciatus in Unit 1, 2, 3LNO when alternative priors for r are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

prior mean for r	low	reference	high
Bayes factor	1.2	1.0	0.9
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.998	0.999	0.999
3	0.995	0.997	0.999
6	0.989	0.996	0.998
9	0.981	0.99	0.995

Table 33. Decision table for alternative quota policies for S. fasciatus in 2J3K when alternative priors for r are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

prior mean for r	low	reference	high
Bayes factor	1.9	1.0	0.5
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.283	0.464	0.620
0.025	0.285	0.466	0.622
0.050	0.280	0.461	0.618
0.075	0.262	0.439	0.597

Table 34. Decision table for alternative quota policies for S. mentella in Units 1 and 2 when alternative priors for r are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

prior mean for r	low	reference	high
Bayes factor	2.0	1.0	0.6
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.017	0.039	0.088
1	0.006	0.013	0.032
2	0.001	0.003	0.006
3	0.000	0.000	0.001

Table 35. Decision table for alternative quota policies for S. mentella in 2J3K and 3LNO when alternative priors for r are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

prior mean for r	low	reference	high
Bayes factor	0.4	1.0	1.4
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.819	0.903	0.948
1	0.734	0.835	0.884
2	0.618	0.738	0.809
3	0.514	0.634	0.725

Table 36. Decision table for alternative quota policies for S. fasciatus in Unit 3 when alternative historic catch scenarios (half or double the reference case catches) are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

Historic catch	half	reference	double
Bayes factor	1.1	1.0	1.0
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	1	1	1
2	0.999	1	1
4	0.993	0.999	0.999
6	0.983	0.996	0.999

Table 37. Decision table for alternative quota policies for S. fasciatus in Unit 1, 2, 3LNO when alternative historic catch scenarios (half or double the reference case catches) (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

Historic catch	half	reference	double
Bayes factor	1.3	1.0	0.7
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.999	0.999	0.999
3	0.996	0.997	0.998
6	0.987	0.996	0.998
9	0.963	0.99	0.997

Table 38. Decision table for alternative quota policies for S. fasciatus in 2J3K when alternative historic catch scenarios (half or double the reference case catches) are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

Historic catch	half	reference	double
Bayes factor	0.3	1.0	0.9
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.431	0.464	0.469
0.025	0.430	0.466	0.469
0.050	0.418	0.461	0.469
0.075	0.413	0.439	0.464

Table 39. Decision table for alternative quota policies for S. mentella in Units 1 and 2 when alternative historic catch scenarios (half or double the reference case catches) are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

Historic catch	half	reference	double
Bayes factor	1.0	1.0	1.1
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.037	0.039	0.039
1	0.001	0.013	0.023
2	0	0.003	0.012
3	0	0	0.005

Table 40. Decision table for alternative quota policies for S. mentella in 2J3K and 3LNO when alternative historic catch scenarios (half or double the reference case catches) are applied (see Table 11 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2030 exceeds 40% of stock biomass at MSY. Bayes factors are computed for the alternative runs with the ratio of the probability of the data for each scenario divided by the probability of the data for the reference case.

Historic catch	half	reference	double
Bayes factor	1.1	1.0	1.1
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.911	0.903	0.905
1	0.733	0.835	0.892
2	0.508	0.738	0.84
3	0.313	0.634	0.781

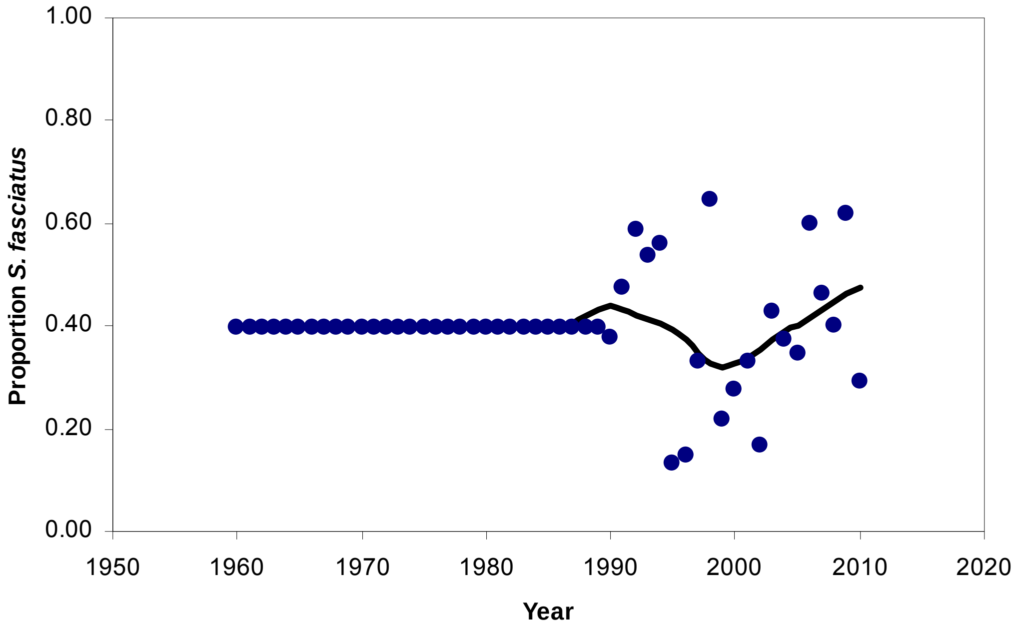


Figure 1: proportion of mature S. fasciatus in the survey for unit 1 (Gulf of St. Lawrence) summer survey. The survey data (points) were available from 1990 onward and a mean proportion applied in earlier years. A loess smooth (line) was run through the points and applied to aggregated Sebastes spp catch data to determine the S. fasciatus and S. mentella (1-S. fasciatus proportion) catch for each year.

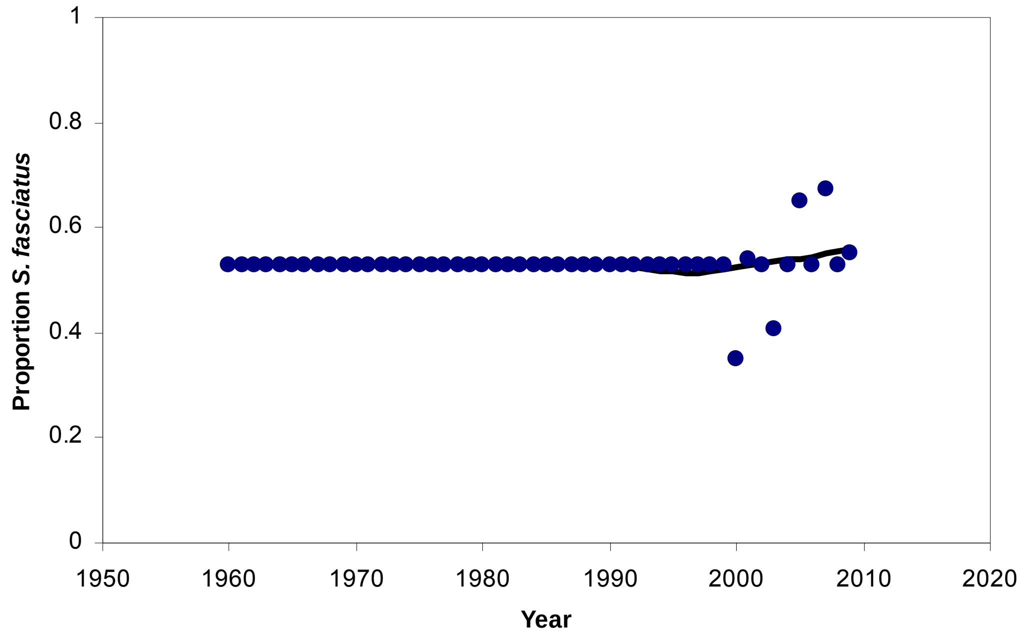


Figure 2: proportion of mature S. fasciatus in the survey for unit 2 summer survey. The survey data (points) were available every other year from 2000 onward and a mean proportion applied in other years. A loess smooth (line) was run through the points and applied to aggregated Sebastes spp. catch data to determine the S. fasciatus and S. mentella (1-S. fasciatus proportion) catch for each year.

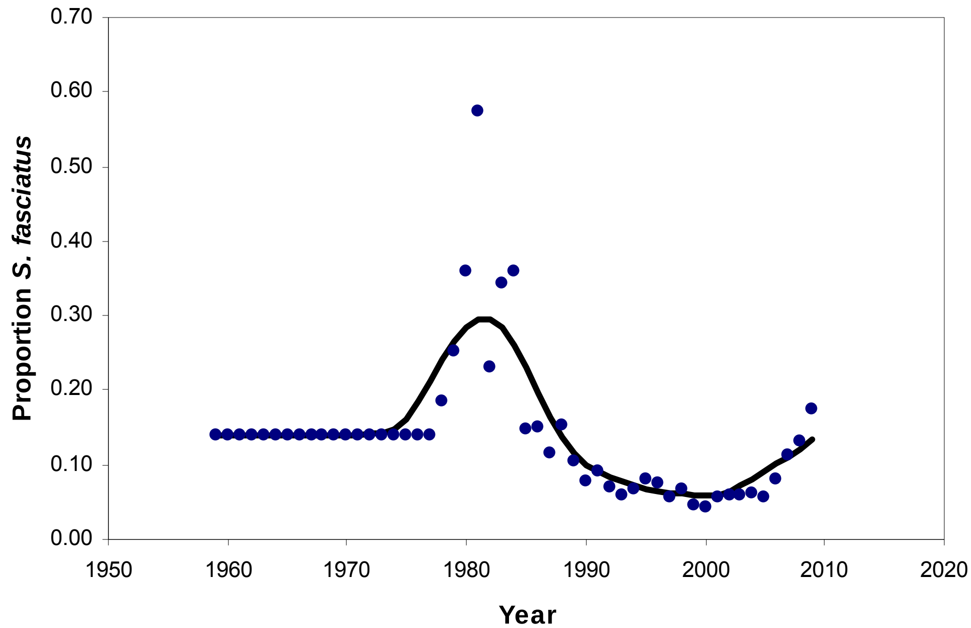


Figure 3: proportion of mature S. fasciatus in the survey for 2GHJ fall survey. A loess smooth (line) was run through the points and applied to aggregated Sebastes spp. catch data to determine the S. fasciatus and S. mentella (1-S. fasciatus proportion) catch for each year.

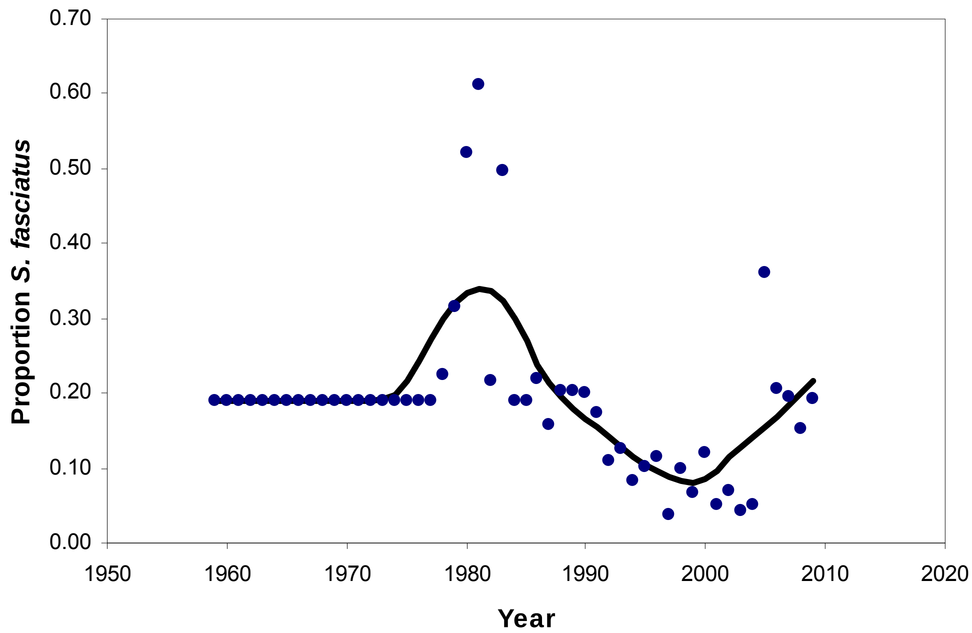


Figure 4: proportion of mature S. fasciatus in the survey for the 3K fall survey. A loess smooth (line) was run through the points and applied to aggregated Sebastes spp. catch data to determine the S. fasciatus and S. mentella (1-S. fasciatus proportion) catch for each year.

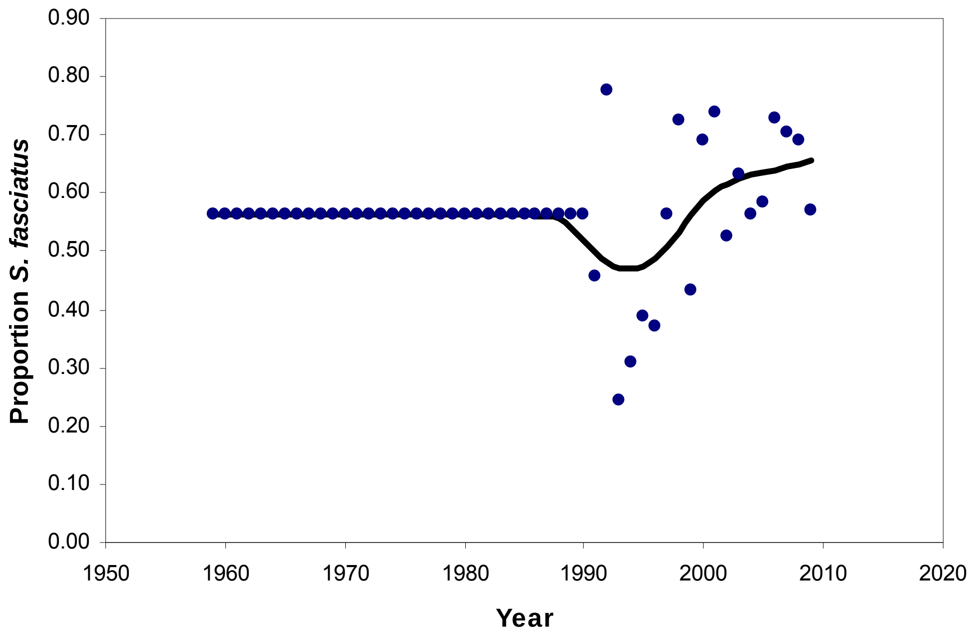


Figure 5: proportion of mature S. fasciatus in the survey for the 3LN fall survey. A loess smooth (line) was run through the points and applied to aggregated Sebastes spp. catch data to determine the S. fasciatus and S. mentella (1-S. fasciatus proportion) catch for each year.

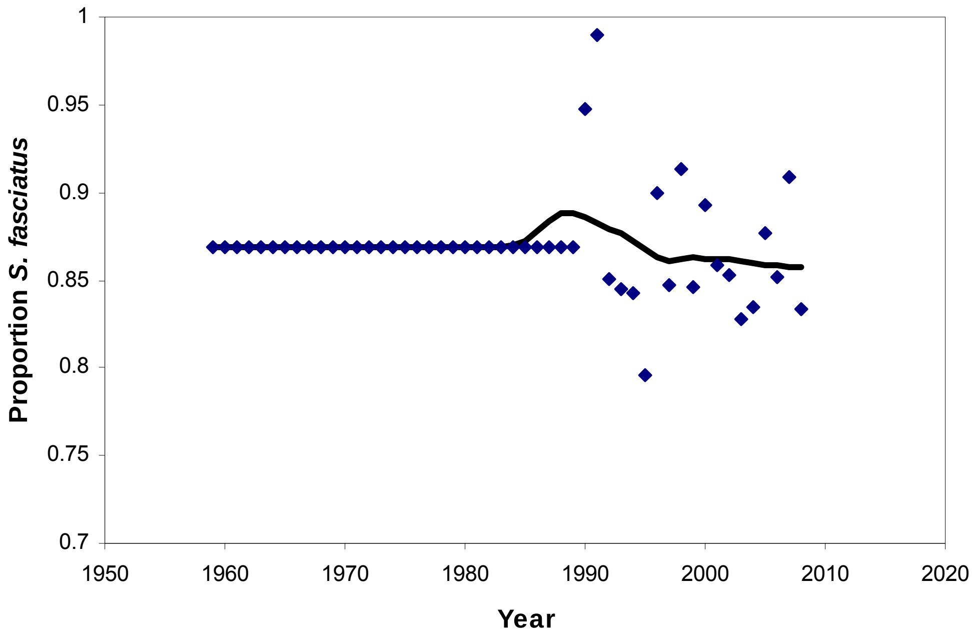


Figure 6: proportion of mature S. fasciatus in the survey for the 3O fall survey. A loess smooth (line) was run through the points and applied to aggregated Sebastes spp. catch data to determine the S. fasciatus and S. mentella (1-S. fasciatus proportion) catch for each year.

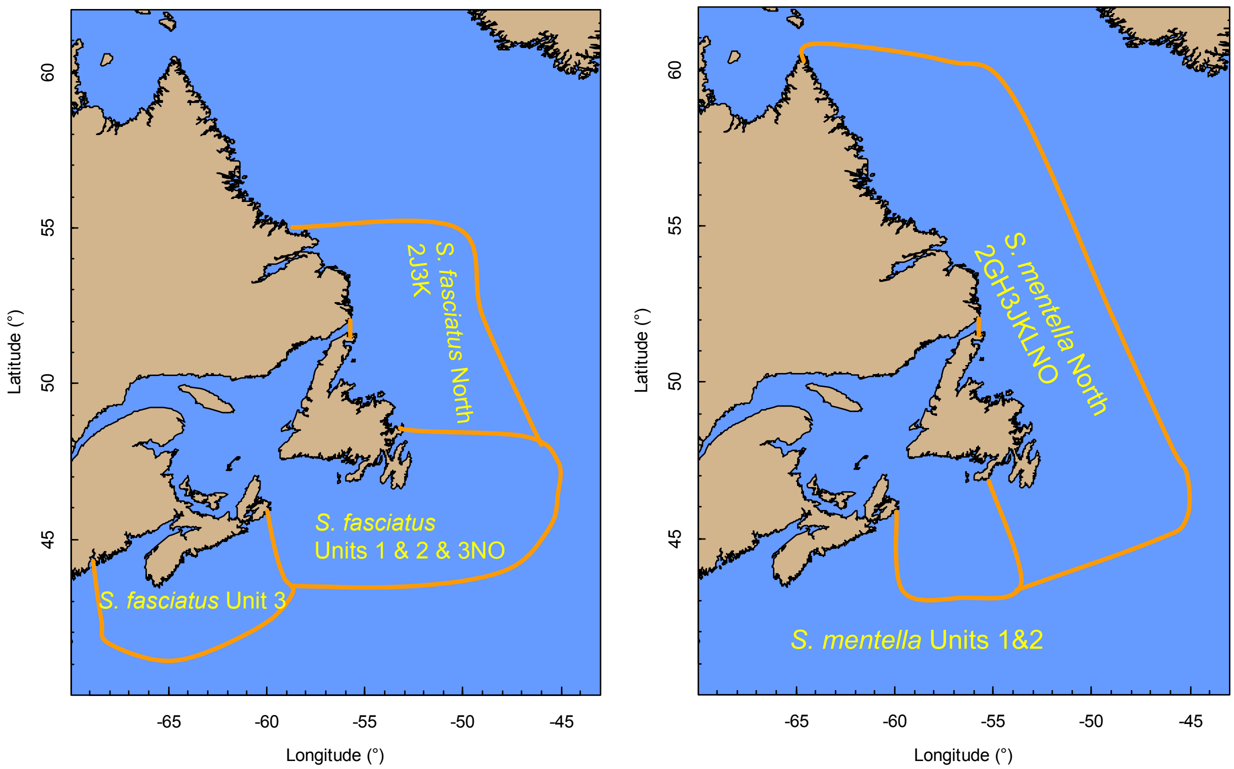


Figure 7: maps showing the rough geographic areas corresponding to the populations modelled for the purposes of the RPA. The modelled populations for S. mentella correspond to the designated units used by COSEWIC while COSEWIC used the entire area as the designated unit for S. fasciatus but contradictory survey trends made modelling results nonsensical at this level thus the DU was disaggregated into three sub-areas.

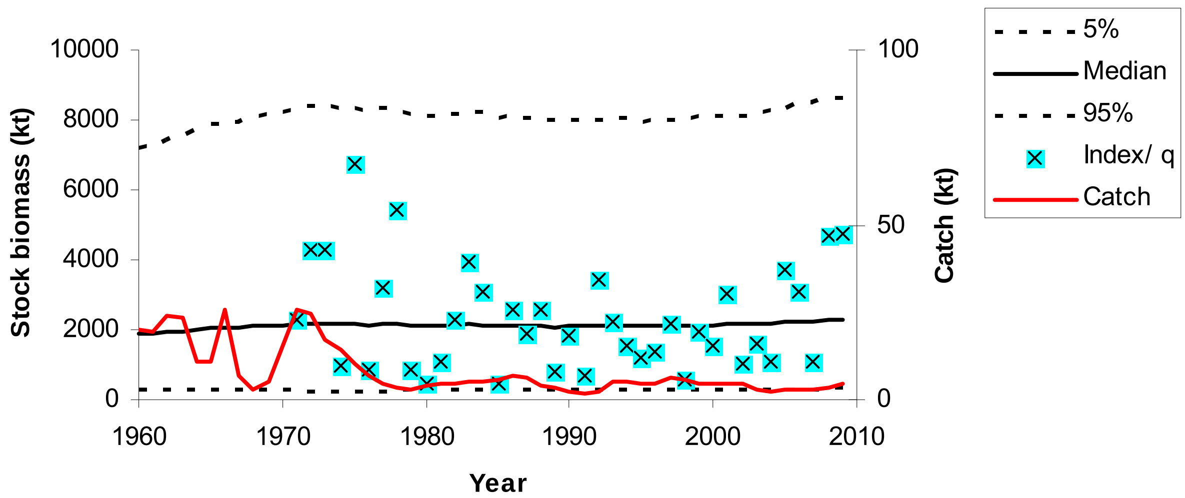


Figure 8. Plots of catch biomass (kt), and 5th,median and 95% percentiles for mature stock biomass of S. fasciatus in Unit 3. The survey biomass indices divided by the median estimates of q are also shown.

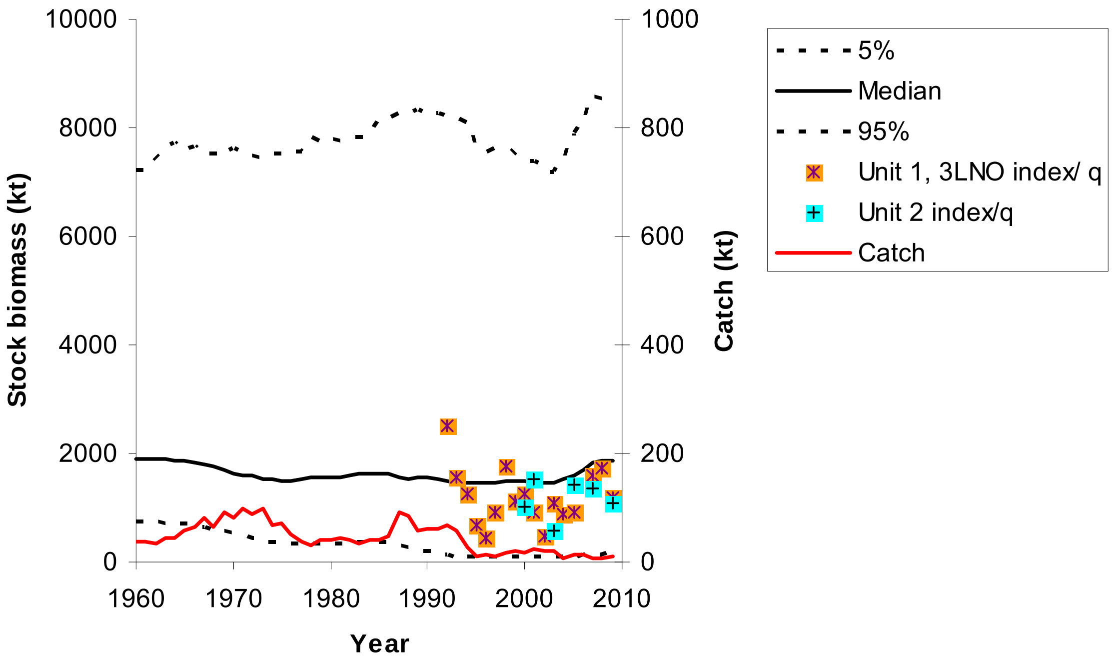
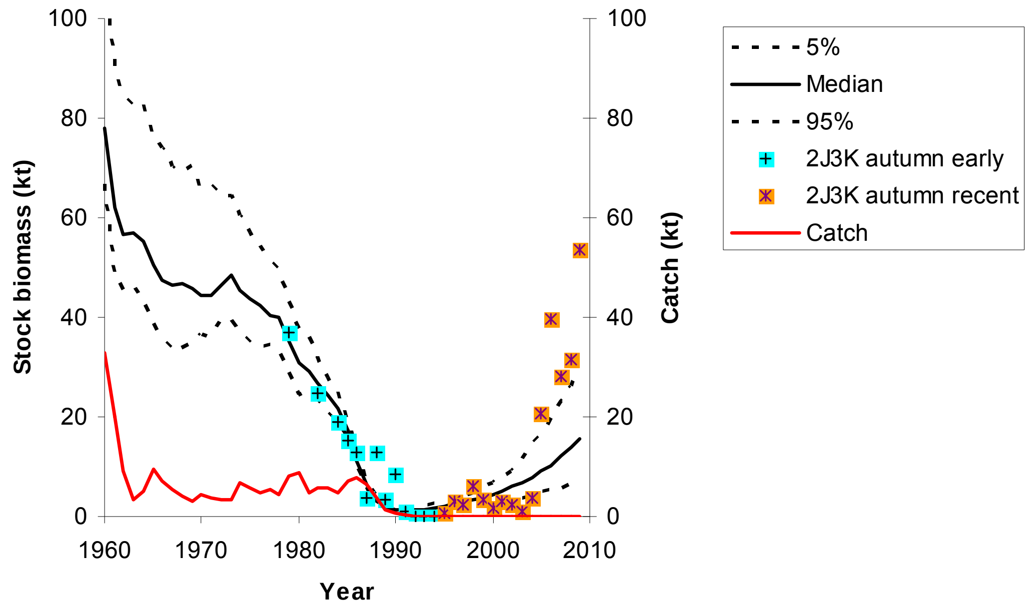


Figure 9. Plots of catch biomass (kt), and 5th,median and 95% percentiles for mature stock biomass of S. fasciatus in Unit 1, 2, 3LNO. The survey biomass indices divided by the median estimates of q are also shown.

a.



b.

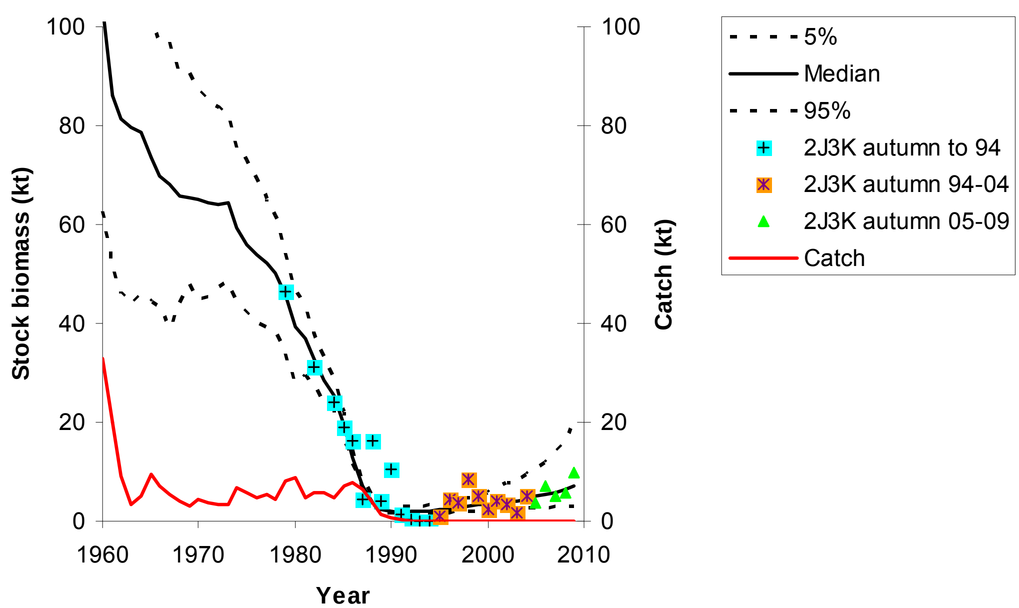


Figure 10. Plots of catch biomass (kt), and 5th,median and 95% percentiles for mature stock biomass of S. fasciatus in 2J3K. The survey biomass indices divided by the median estimates of q are also shown. a. 2J3K series from 1995-2009 is kept as a single series. b. 2J3K series from 1995-2004 and 2005-2009 are split as separate series.

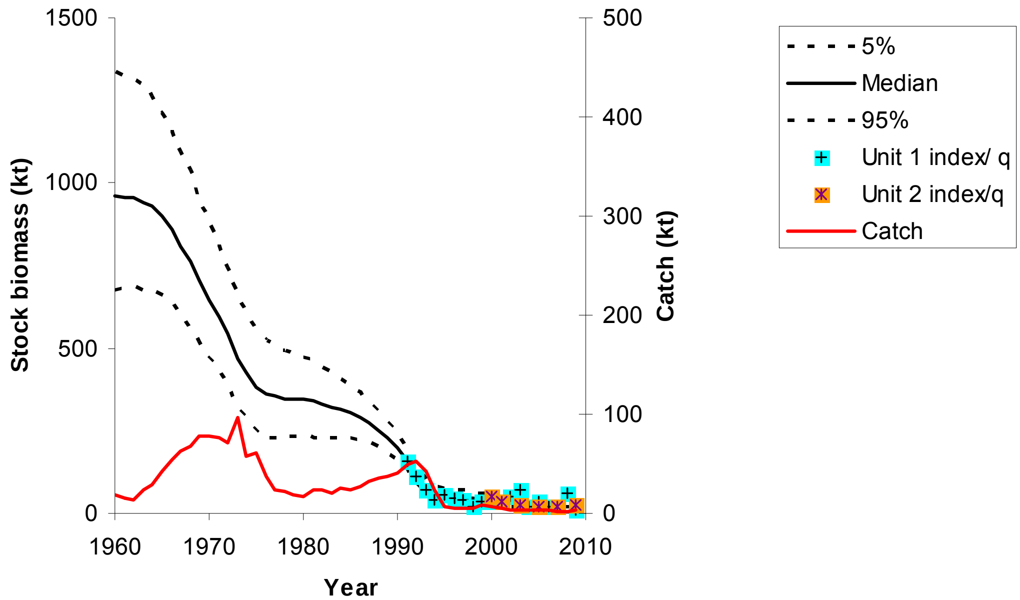
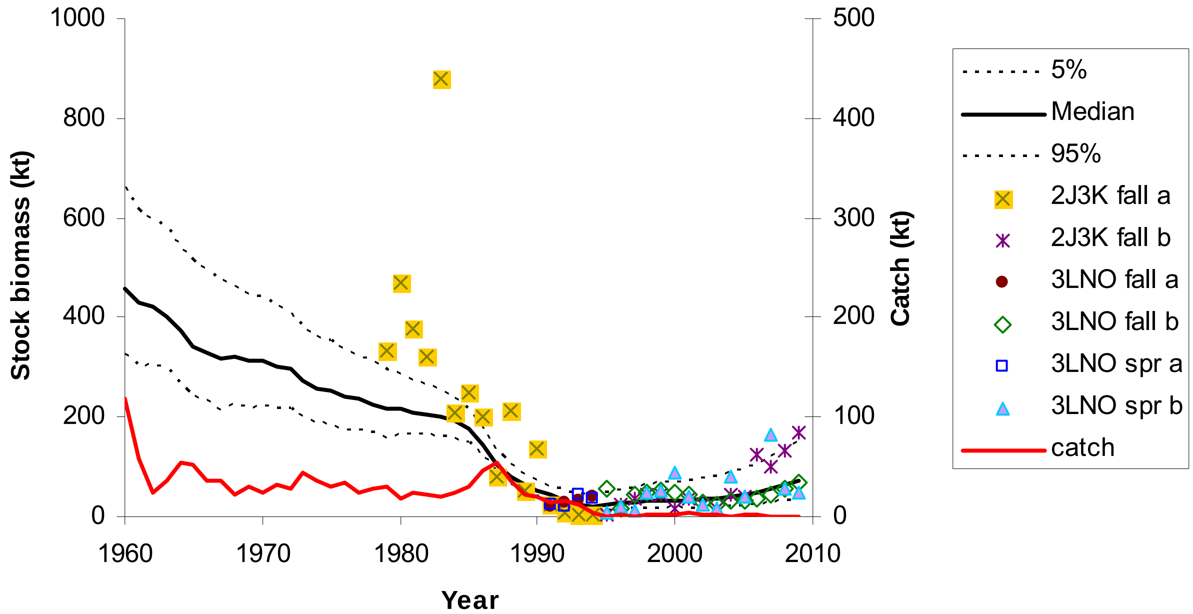


Figure 11. Plots of catch biomass (kt), and 5th,median and 95% percentiles for mature stock biomass of S. mentella in Unit 1, 2. The survey biomass indices divided by the median estimates of q are also shown.

a.



b.

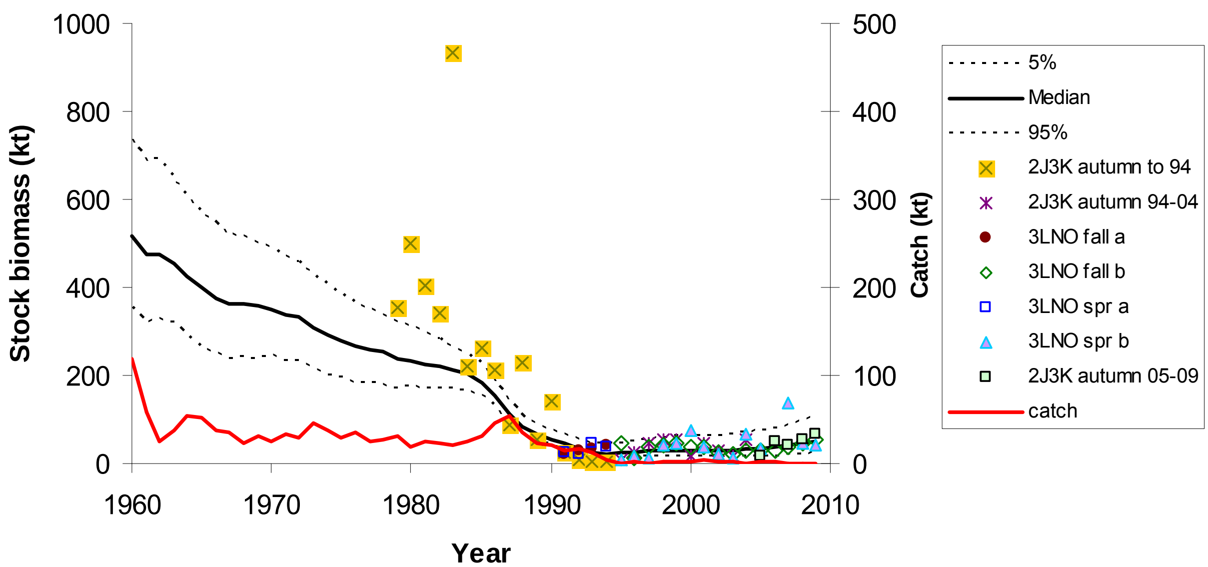


Figure 12. Plots of catch biomass (kt), and 5th,median and 95% percentiles for mature stock biomass of S. mentella in 3LNO and 2J3K. The survey biomass indices divided by the median estimates of q are also shown. a. 2J3K series from 1995-2009 is kept as a single series. b. 2J3K series from 1995-2004 and 2005-2009 are split as separate series.

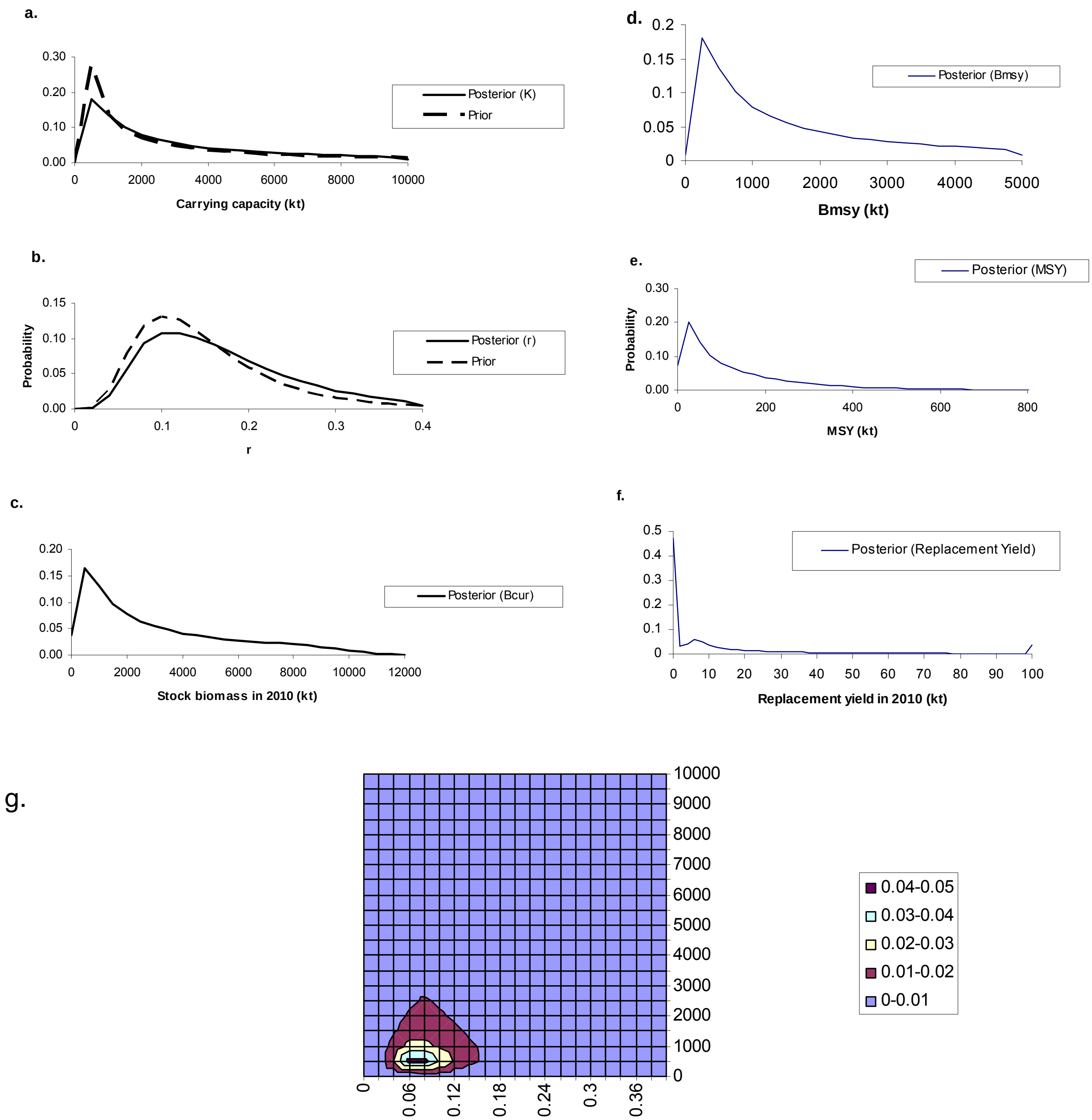


Figure 13. Parameter estimates and stock status outputs for S. fasciatus in Unit 3. Marginal posterior distributions for a) carrying capacity (K), b) maximum rate of increase (r), c) mature stock biomass in 2010, d) stock biomass that gives the maximum sustainable yield (Bmsy), e) MSY, f) the replacement yield. g) Joint posterior distribution for r and K. Biomass values are in kt and prior probability distributions are also shown for K and r.

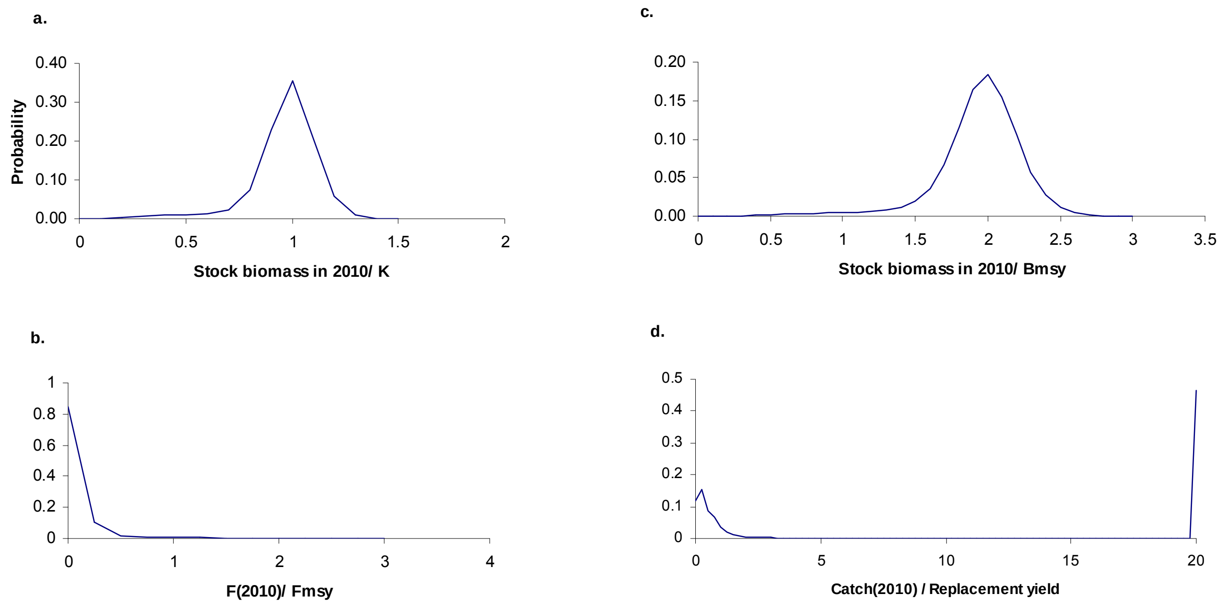


Figure 14. Stock status outputs for S. fasciatus in Unit 3. Marginal posterior distributions for the ratios of a) stock biomass in 2010 to carrying capacity (K), b) fishing mortality rate in 2010 to Fmsy, c) mature stock biomass in 2010 to stock biomass that gives MSY, and d) catch biomass in 2010 to the replacement yield.

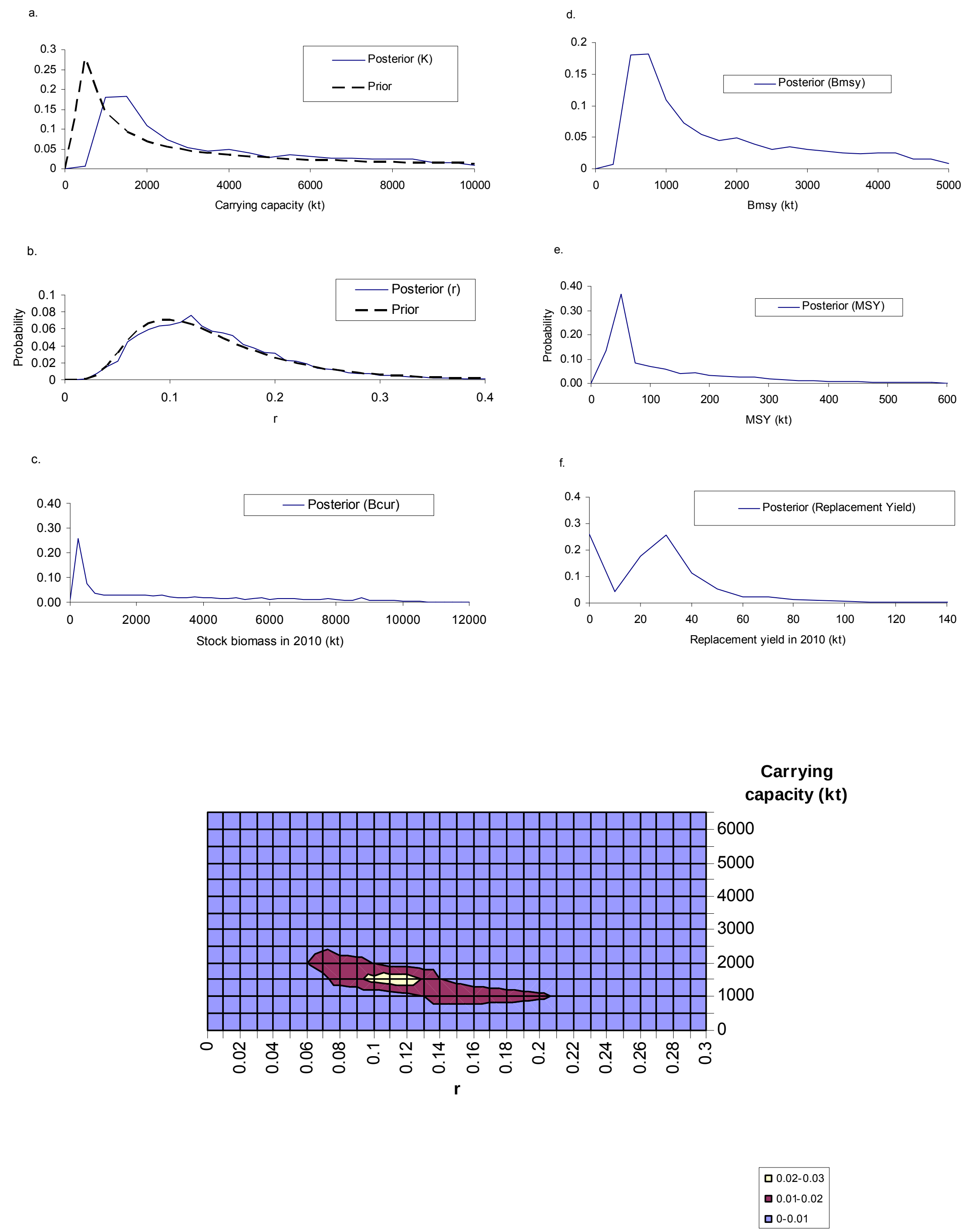


Figure 15. Parameter estimates and stock status outputs for S. fasciatus in Units 1, 2 and 3LNO. Marginal posterior distributions for a) carrying capacity (K), b) maximum rate of increase (r), c) mature stock biomass in 2010, d) stock biomass that gives the maximum sustainable yield (Bmsy), e) MSY , and f) the replacement yield. g) Joint posterior distribution for r and K. Biomass values are in kt and prior probability distributions are also shown for K and r.

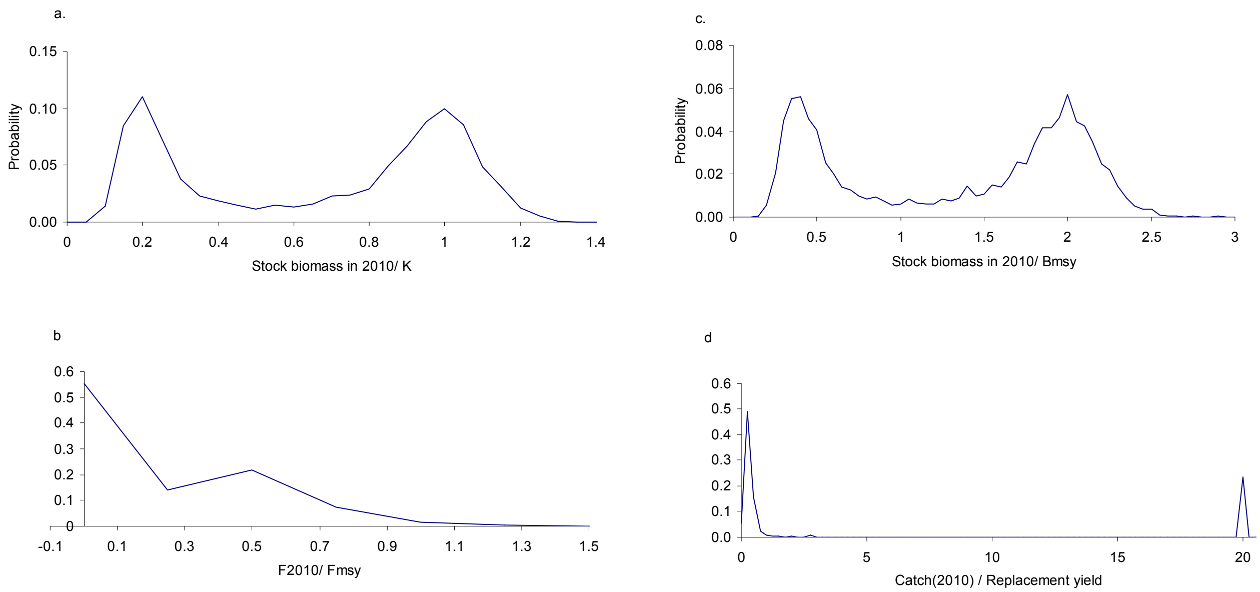


Figure 16. Stock status outputs for S. fasciatus in Units 1, 2 and 3LNO. Marginal posterior distributions for the ratios of a) stock biomass in 2010 to carrying capacity (K), b) fishing mortality rate in 2010 to Fmsy, c) mature stock biomass in 2010 to stock biomass that gives MSY, and d) catch biomass in 2010 to the replacement yield.

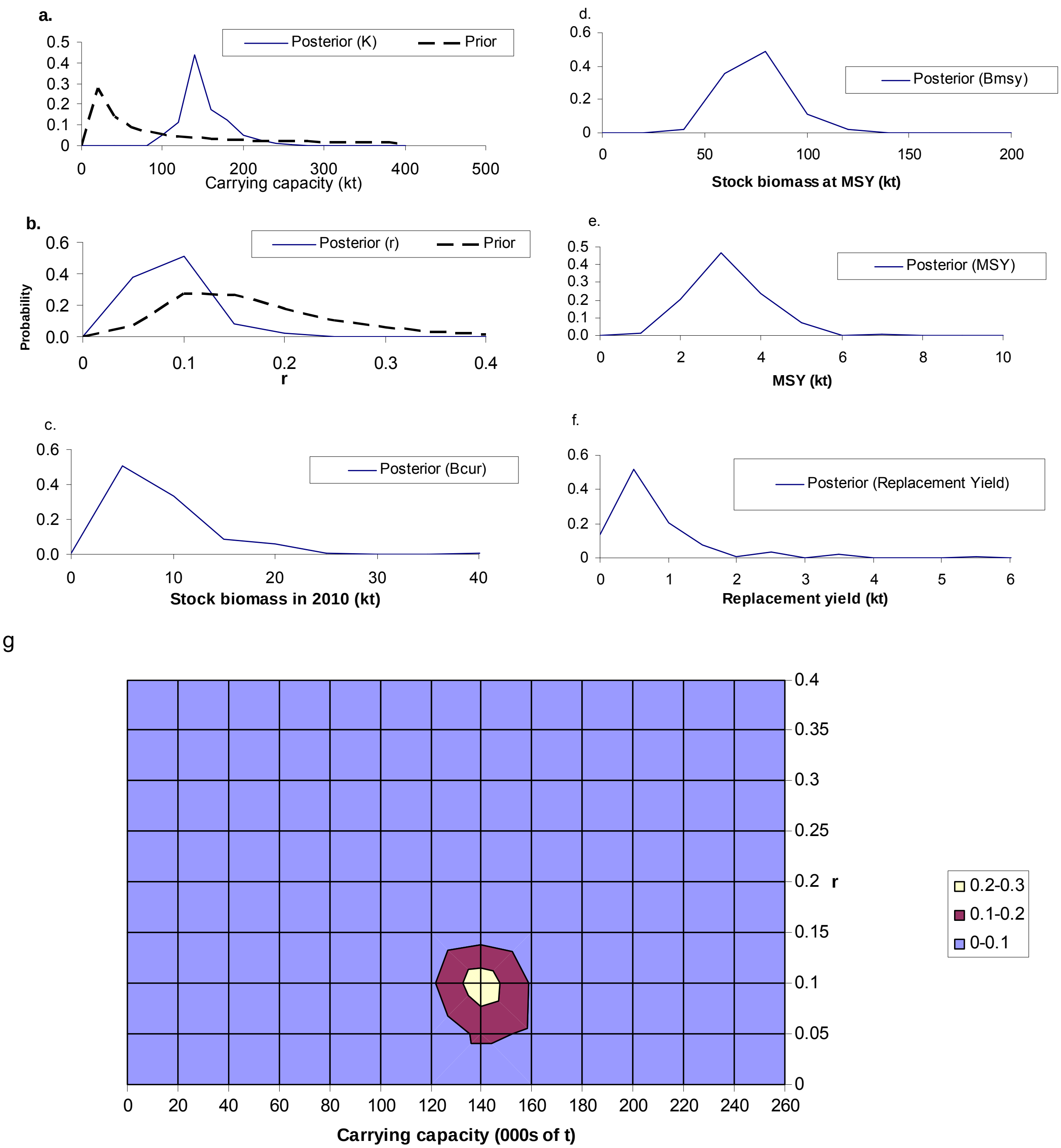


Figure 17. Parameter estimates and stock status outputs for S. fasciatus in 2J3K. Marginal posterior distributions for a) carrying capacity (K), b) maximum rate of increase (r), c) mature stock biomass in 2010, d) stock biomass that gives the maximum sustainable yield (Bmsy), e) MSY, and f) the replacement yield. g) Joint posterior distribution for r and K. Biomass values are in kt and prior probability distributions are also shown for K and r.

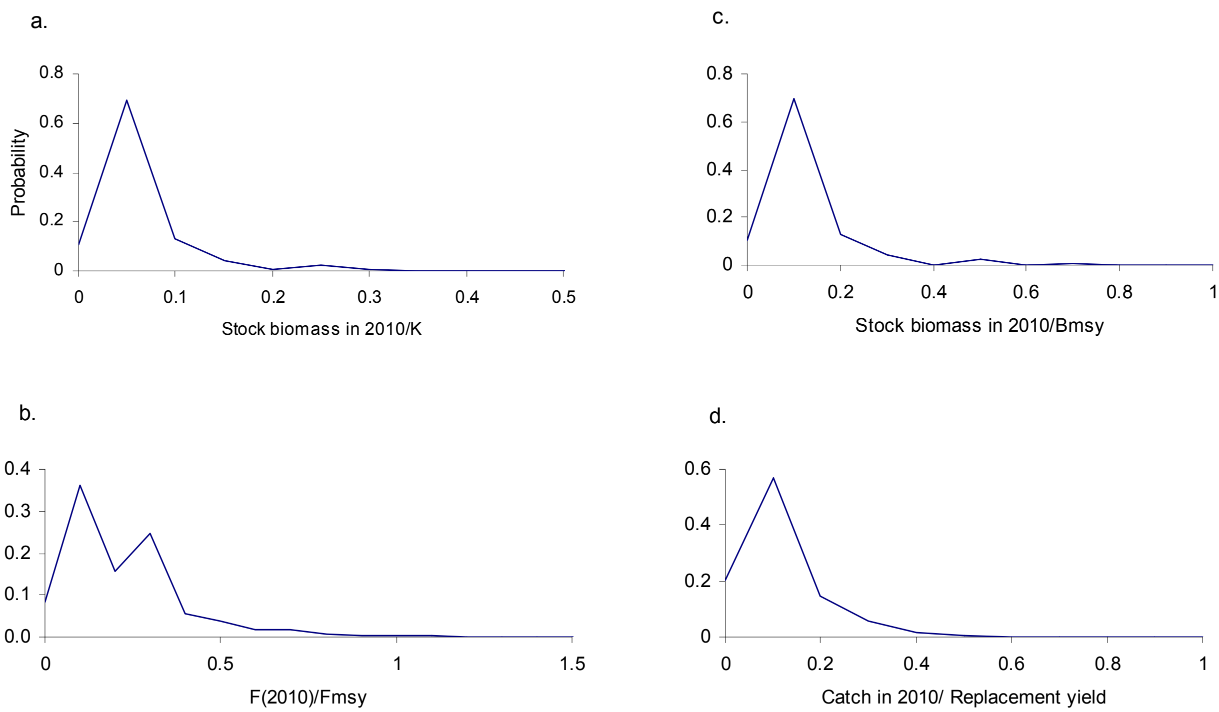


Figure 18. Stock status outputs for S. fasciatus in 2J3K. Marginal posterior distributions for the ratios of a) stock biomass in 2010 to carrying capacity (K), b) fishing mortality rate in 2010 to Fmsy, c) mature stock biomass in 2010 to stock biomass that gives MSY, and d) catch biomass in 2010 to the replacement yield.

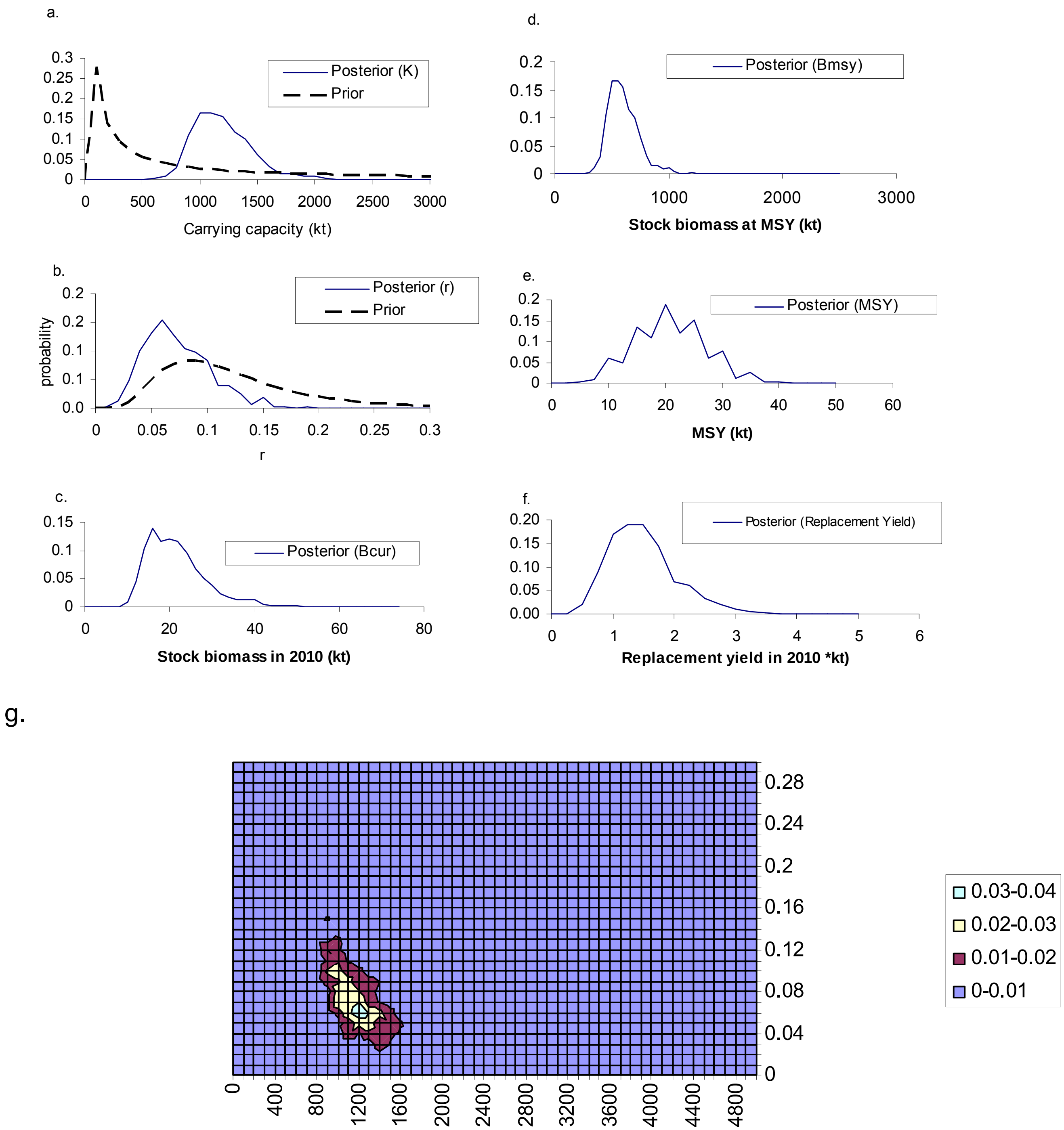


Figure 19. Parameter estimates and stock status outputs for S. mentella in Units 1 and 2. Marginal posterior distributions for a) carrying capacity (K), b) maximum rate of increase (r), c) mature stock biomass in 2010, d) stock biomass that gives the maximum sustainable yield (Bmsy), e) MSY , and f) the replacement yield. g) Joint posterior distribution for r and K. Biomass values are in kt and prior probability distributions are also shown for K and r.

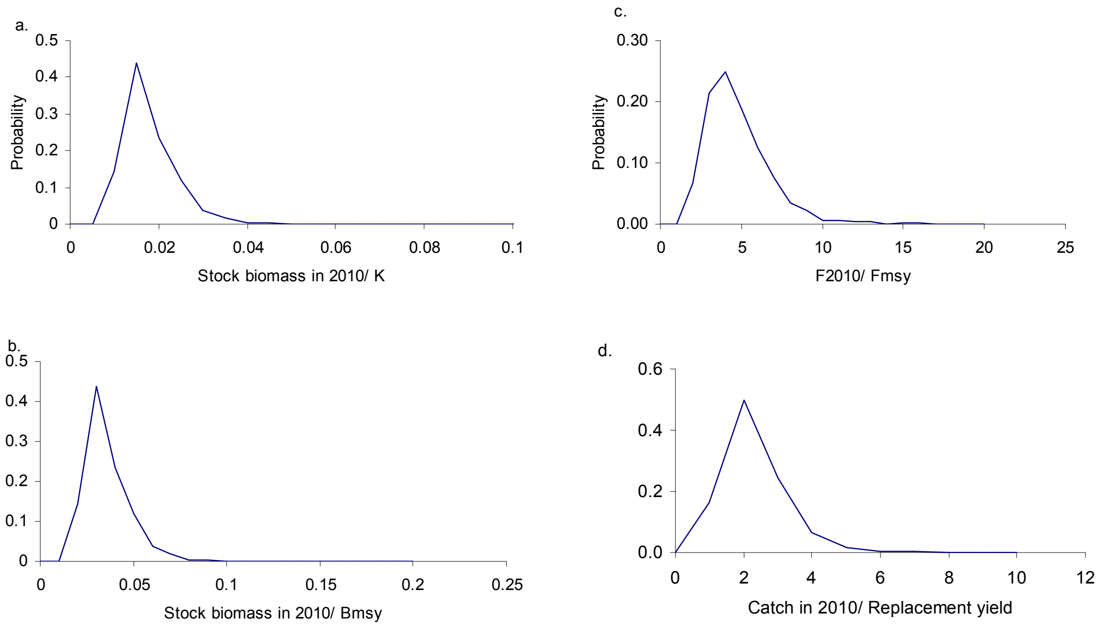


Figure 20. Stock status outputs for S. mentella in Units 1 and 2. Marginal posterior distributions for the ratios of a) stock biomass in 2010 to carrying capacity (K), b) fishing mortality rate in 2010 to Fmsy, c) mature stock biomass in 2010 to stock biomass that gives MSY, and d) catch biomass in 2010 to the replacement yield.

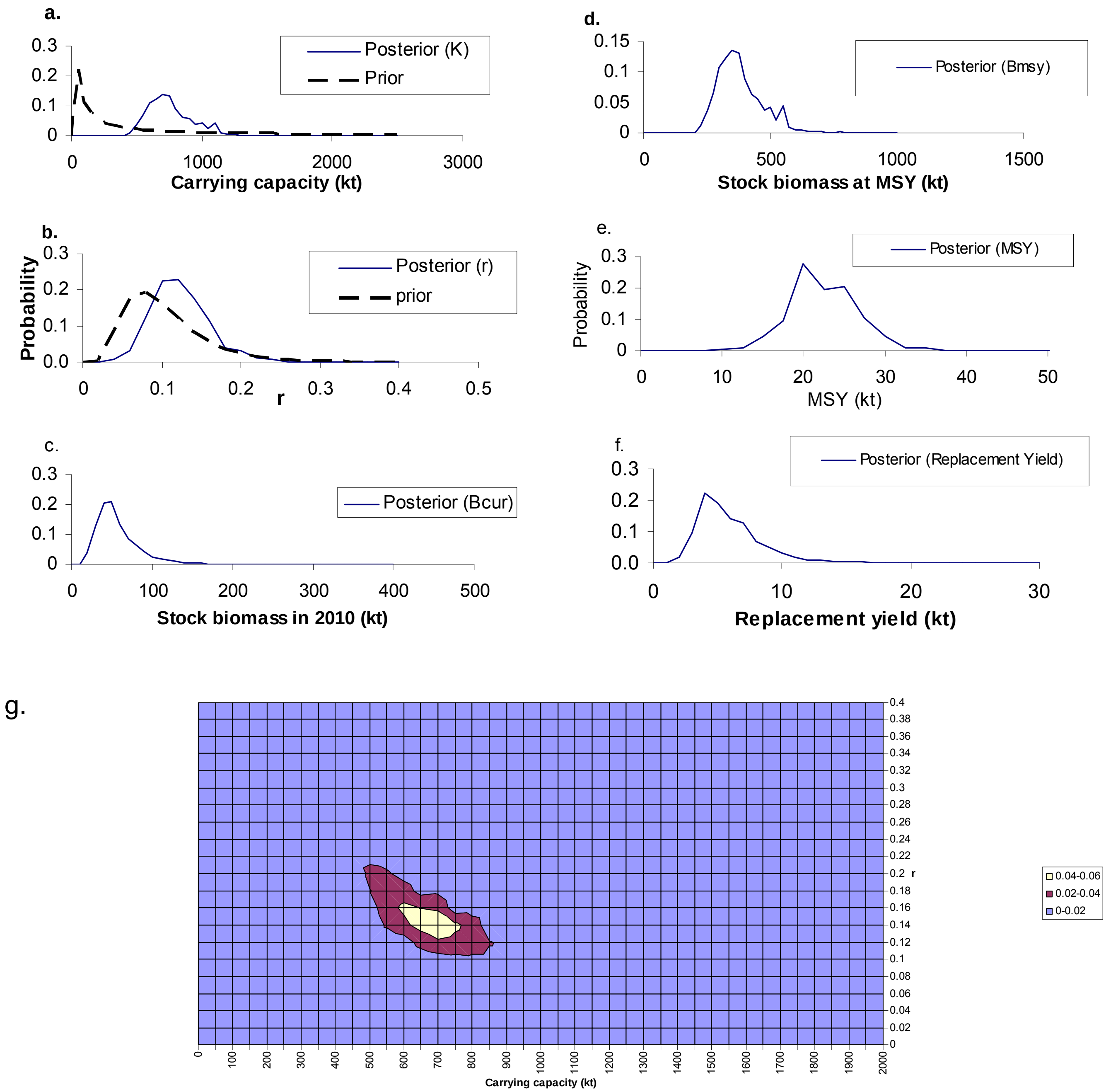


Figure 21. Parameter estimates and stock status outputs for S. mentella in 3LNO and 2J3K. Marginal posterior distributions for a) carrying capacity (K), b) maximum rate of increase (r), c) mature stock biomass in 2010, d) stock biomass that gives the maximum sustainable yield (Bmsy), e) MSY, and f) the replacement yield. g) Joint posterior distribution for r and K. Biomass values are in kt and prior probability distributions are also shown for K and r.

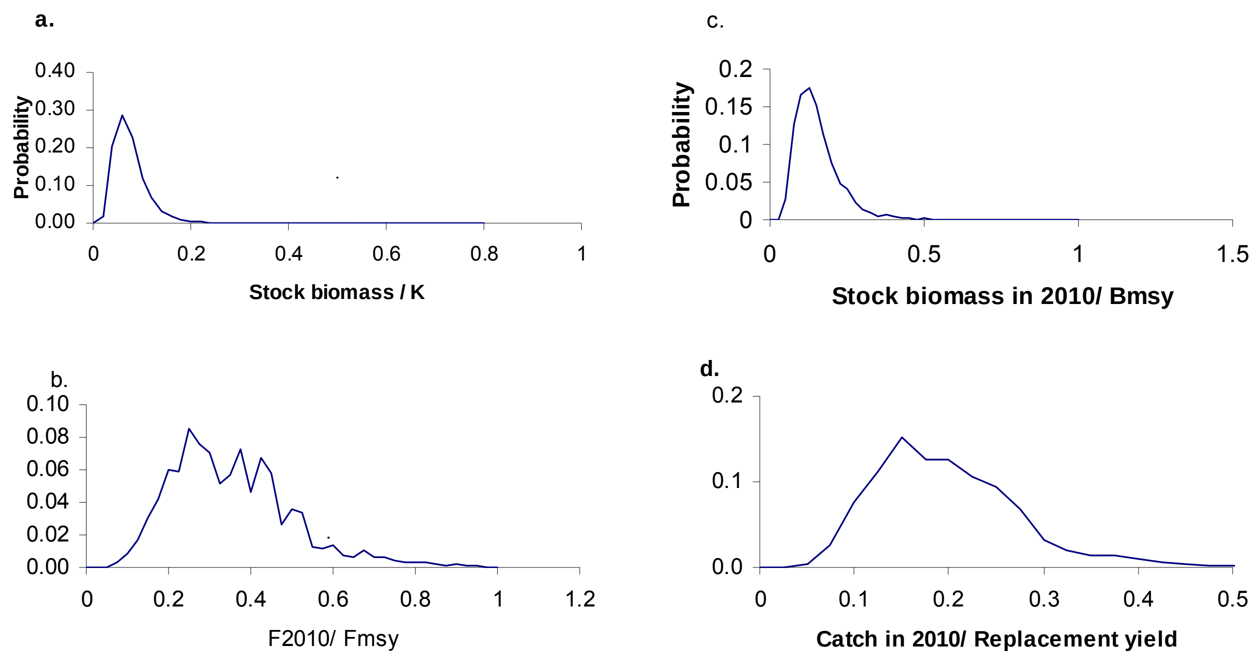


Figure 22. Stock status outputs for S. mentella in 3LNO and 2J3K. Marginal posterior distributions for the ratios of a) stock biomass in 2010 to carrying capacity (K), b) fishing mortality rate in 2010 to Fmsy, c) mature stock biomass in 2010 to stock biomass that gives MSY, and d) catch biomass in 2010 to the replacement yield.

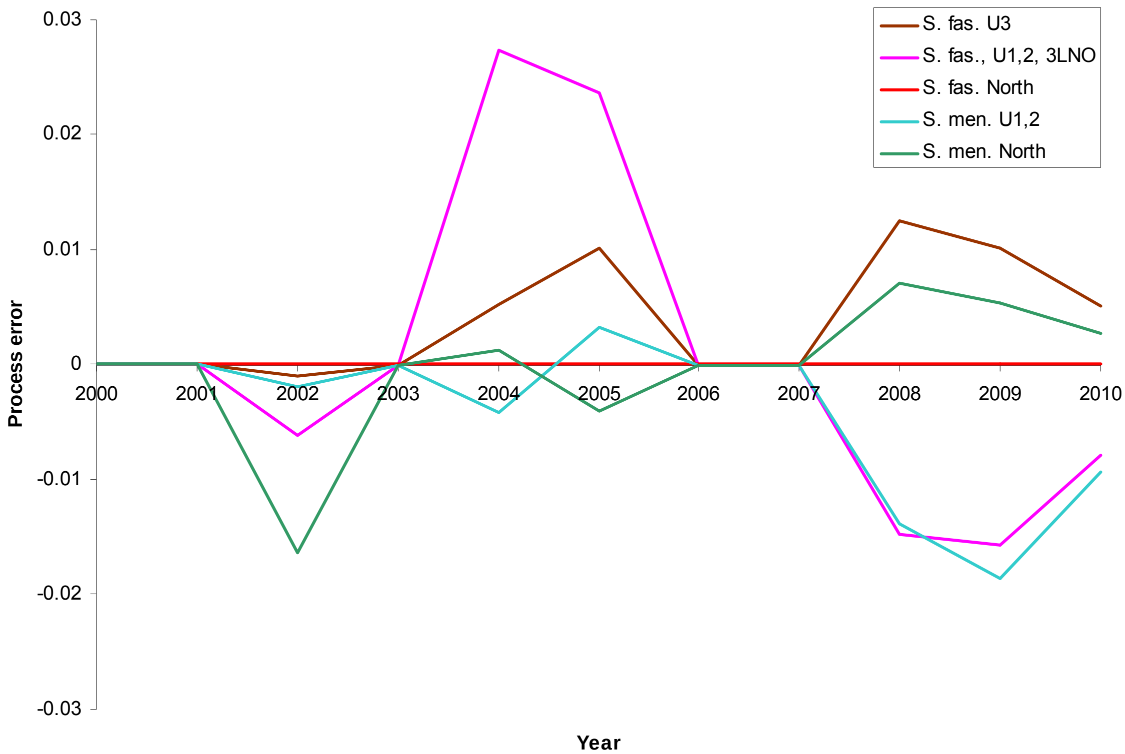


Figure 23. Posterior mode estimates of process error for the five assessed redfish stocks. S. fas. is short for Sebastes fasciatus and S. men. is short of Sebastes mentella.