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Production model fitting and projection for Acadian redfish (*Sebastes fasciatus*) in Units 1 and 2

Ajustement du modèle de production et projection pour le sébaste d'Acadie (*Sebastes fasciatus*) dans les unités 1 et 2

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ABSTRACT

A state-space Schaefer surplus production model was fitted to trawl survey biomass estimates considered as relative indices of abundance for the Laurentian Channel (Unit 1+2) *Sebastes fasciatus*. Bayesian methods were applied for parameter estimation, evaluation of stock status and stock projections for the purpose of assessing recovery potential. This methodology has been previously applied to Atlantic Acadian and deepwater (*S. mentella*) redfish in an RPA of stocks in five Atlantic east areas and 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.

Results suggest that the Laurentian Channel population of *S. fasciatus* is presently in a low biomass state with a 7% chance of being above 40% of the most productive stock biomass level (0.4 B_{msy}) in 2011. There appears to have been an increasing trend in stock size in recent years and the 2011 catch of 1,250 tons is well below the posterior median estimate of replacement yield of about 6,500 tons.

Results suggest the Laurentian Channel population of *S. fasciatus* is well into the critical zone (assuming a lower reference point (LRP) of 0.4 B_{msy}) though it is able to support the current fishery and see continued increases in abundance when considered as a unit stock. Other work indicates that the Unit 1 and Unit 2 area may have important substock structure and some components of the stock (Unit 1) appear to be more depleted than others. Fishing or allowable by-catch on this stock should account for its overall status as well as that of sub-components.

RÉSUMÉ

Un modèle de surplus de production d'espace d'état de Schaefer a été adapté aux estimations de la biomasse obtenues à partir des relevés au chalut, lesquelles sont considérées comme des indices relatifs de l'abondance du sébaste d'Acadie *Sebastes fasciatus* dans le chenal Laurentien (unités 1 et 2). Des méthodes bayésiennes ont été utilisées pour l'estimation des paramètres, l'évaluation de l'état des stocks et les projections de stocks aux fins de l'évaluation du potentiel de rétablissement. Cette méthodologie a déjà été appliquée au sébaste d'Acadie et au sébaste atlantique (*Sebastes mentella*) dans le cadre d'une évaluation du potentiel de rétablissement (EPR) des stocks dans cinq zones de l'est de l'Atlantique et d'autres espèces de sébastes sur la côte du Pacifique au Canada. L'utilisation de la version de type espace d'état de ce modèle permettait l'inclusion de l'erreur de traitement qui peut entraîner des écarts dans la dynamique des hypothèses de production excédentaire.

Les résultats laissent supposer que la population de sébaste d'Acadie (*Sebastes fasciatus*) dans le chenal Laurentien est actuellement dans un état de faible biomasse et n'a qu'une possibilité de 7 % d'atteindre un seuil supérieur à 40 % du niveau de biomasse le plus productif (0,4 B_{rms}) en 2011. Il semble y avoir une tendance à la hausse de la taille des stocks au cours des dernières années et la capture réalisée en 2011 représentant 1 250 tonnes est bien inférieure à l'estimation médiane de production de remplacement d'environ 6 500 tonnes.

Les résultats laissent supposer que la population de *Sebastes fasciatus* du chenal Laurentien est bel et bien dans la zone critique (en supposant que le point de référence limite (PRL) = 40 % B_{rms}) même si elle est en mesure de supporter la pêche actuelle et de continuer de croître en abondance, si on la considère comme un stock indépendant. D'autres travaux indiquent que la zone de l'unité 1 et de l'unité 2 peut avoir une importante sous-structure de stock et que certains éléments du stock (unité 1) semblent être plus décimés que d'autres. La pêche ou le total autorisé de prises accessoires pour ce stock devraient tenir compte de son état global ainsi que de l'état de ses sous-composants.

INTRODUCTION

Following the recovery potential assessment (RPA) for redfish (DFO 2011), reference point estimation for the Atlantic *Sebastes* stocks became the pre-occupation to fulfil management needs. Unfortunately, the production model fitting done for the RPA did not necessarily correspond to the biological stock and was conducted at an aggregated stock scale as close to the Designatable Unit (DU) scale as possible. For this reason, the RPA results could not always be used to derive reference points on a stock by stock basis. Because Acadian redfish in the Unit 1+2 area supports a fairly substantial commercial fishery, it was considered necessary to re-fit the production model at a scale corresponding to the biological stock so as to drive reference points and current stock state.

This document presents a stock assessment and long-term projections over 60 years, approximately three generations, for the Unit 1 and 2 Acadian redfish population. It reports on the use of a state-space Schaefer surplus production modelling approach fitted with Bayesian methods. This approach has previously been applied to Pacific *Sebastes* species for assessment and projection (Stanley et al. 2009, Yamanaka *et al.* 2011). Population trajectories are determined under different fishing scenarios including status quo. The sensitivity of these results was examined in relation to priors and deviations from reported historical catch.

DATA AND METHODS

SURVEY INDICES

Population size indices used for model fitting came primarily from DFO groundfish trawl surveys in summer and fall period (Table 1). 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.

CATCH DATA

Catch data for Units 1 and 2 extend back to 1960 (Table 2). 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 and 2).

LIFE HISTORY PARAMETERS FOR *S. FASCIATUS*.

The growth parameters for *S. fasciatus* 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 Table 3a. The length-weight conversion factors for females of *S. fasciatus* in Canadian waters were obtained from Don Power (pers. commn) (Table 3b). 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 higher for *S. fasciatus* than *S. mentella*. 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}. (NAFO 2000, NAFO 2005) We've presumed that the median for *S. fasciatus* is slightly higher at 0.125 yr^{-1}. 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 3c).

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 in Canadian waters. 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*. 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 3d for details).

Estimates of the median age at maturity for *S. fasciatus* are available for a number of management units (COSEWIC 2010). For *S. fasciatus* in Units 1 and 2 we've used for the estimate of median age at maturity the average of the estimates for Units 1 and 2 (Table 4). This came to 8.99 years.

SURPLUS PRODUCTION MODEL EQUATIONS

We applied a Bayesian surplus production model that utilized Sampling Importance Resampling (Rubin 1987, 1988) to assess *S. fasciatus* stock status within Units 1 and 2. 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 (Yamanaka et al. 2011, in rev.), offshore lingcod assessments (King et al. 2011, in prep.) and the recent Atlantic redfish RPA (McAllister and Duplisea 2011). 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*:

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

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

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

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

Given these equations, the expected value for B_{y+1} is:

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

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 (i.e., the observation equation) is:

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

where $\varepsilon_{obs,j} \sim \mathrm{Normal}(0, \sigma^2_{\mathrm{obs},j})$.

Both $\varepsilon_{process}$ and $\varepsilon_{obs,j}$ are i.i.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 ρ = 0.

A summary of key parameters estimated in the surplus production model is provided in Table 6. A summary of derived management parameters is provided in Table 7.

A summary of prior distributions for estimated parameters is given in Table 8. 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 the Unit 1 and 2 *S. fasciatus* stock. 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 3a), the length to weight conversion factors (Table 3b), and parameters for the fraction maturity-at-age schedule (Table 4) (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 were carried out and values less than 0.005 were excluded from the results to avoid the application of values that were 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 median for *r* based on B-H steepness that resulted from the Monte Carlo simulation was 0.145 with a SD of 0.069 (Table 5).

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, in the recent redfish RPA (McAllister and Duplisea 2011) 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 (see King et al. 2011, in prep.). 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 unfished 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 1 and a SD in log(p_0) of 0.2.

PROCESS ERROR VARIANCE

The standard deviation of $\varepsilon_{process}$, σ_{process}, was set at 0.1 (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). This would result in interannual changes in total recruited stock biomass of about 10% on average and of up to about 20% once every 20 years. As in Stanley et al. (2009), we tested the sensitivity of results to this parameter. As was done in the bocaccio assessment, we applied lower and higher values of 0.05 to 0.15.

OBSERVATION ERROR VARIANCE

Values for $\sigma_{\text{obs},j}$ (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 $\sigma^2_{\text{obs},j}$ were the sum of (i) the variance for each index j, determined from the construction of the survey indices ($\sigma^2_{\text{ind},j}$) and (ii) the variance presumably due to interannual processes ($\sigma^2_{\text{int},j}$) (e.g., variation in the spatial distribution, $\sigma^2_{\text{obs},j} = \sigma^2_{\text{ind},j} + \sigma^2_{\text{int},j}$). Thus in the iterative reweighting, the values for $\sigma^2_{\text{ind},j}$ were set to be the sum of the analytical variances and the values for $\sigma^2_{\text{int},j}$ were adjusted to match (rounding up to the nearest 0.05 or 0.1) the values for $\sigma^2_{\text{obs},j}$ 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*. Due to the lack of availability of information about key features of redfish behaviour and specific aspects of trawl survey protocol that would be required to formulate an informative prior for q, we considered q as a random variable that could take on a wide range of values including values less than and above one. Where attempts have been made to formulate informative priors for the constant of proportionality for trawl surveys, it has been common for up to about 10 different factors to be formulated that work mostly independently of each other to scale the total stock biomass to the expected value for the trawl survey swept area index. While it is often naively held that this constant of proportionality should be equal to one and fixed at one or approximately equal to one, careful inspection of the various factors by experts and experiments have found that the range of values for the contributing factors can range from values much smaller than one to values much larger than one (McAllister and Ianelli 1997; Boyer et al. 2001; McAllister et al. 2010). McAllister and Ianelli (1997) found that herding of yellowfin sole by the trawl doors could cause the value for q to exceed one and range between one to three Boyer et al. (2001) found that where there was a non-random element to the determination of trawl locations, the fish density estimates could exceed the area wide fish density estimates by factors ranging much larger than one. Moreover it is common for the factors to be modeled to work multiplicatively with each other. Thus it is conceivable that if there were more than one factor whose value is less than one, the expected value for q could be much less than one. Likewise, if there were more than one factor whose values were larger than one, the expected value of q could be much larger than one.

Thus, we treated the prior for q as non-informative over a wide range of potential values above and below the value of one and allowed the data to speak for themselves in the determination of the constant of proportionality for the trawl survey indices for *S. fasciatus* in units 1 and 2. This assumption does not preclude potential future research that may be aimed at formulating rigorously determined informative priors for the constant of proportionality for redfish trawl survey q. However, when there's been no scientific research devoted to formulating and informative prior for q, it is commonly accepted that the most defensible prior for q is a non-informative one that ranges from values less than one to values well above one (McAllister et al. 1994). For marine groundfish stocks that occupy extraordinarily large geographic regions, are found at a wide range of depths, especially in deeper waters and have complex movements and behaviours, and where trawl locations may not necessarily be randomly determined over the full range of the surveyed fish population (i.e., where each fish in the population would have an equal chance of being surveyed) it would be presumptuous to assert that the value for trawl survey q must be close to the value of one and certainly not larger than it.

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_{2011}), current stock biomass to carrying capacity (B_{2011}/K), the ratio of current stock biomass to stock biomass at MSY (B_{2011}/B_{MSY}), the replacement yield in 2011 ($RepY_{2011}$), the ratio of the replacement yield in 2011 to the catch biomass in 2011 ($RepY_{2011}/C_{2011}$), and the ratio of fishing mortality rate in 2011 to fishing mortality rate at *MSY* (F_{2011}/F_{MSY}).

Sampling was relatively inefficient and runs with up to several million draws from the importance function carried out (several 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 1% 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 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 this stocks using the Beverton-Holt steepness prior distribution for Pacific Sebastes species (Forrest et al. 2010) and life history parameter estimates for this stock (see McAllister and Duplisea 2011)

- Stock trend indices obtained from (1) the DFO survey in the northern Gulf of St. Lawrence from 1990 and the GEAC trawl survey in this same area starting in 2001

- Likelihood function for catch data follows a lognormal distribution

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

- Prior mean $B_{1960}/K = 1$

- Uninformative priors for *q*

- Lag 1 autocorrelation with the autocorrelation coefficient, ρ, set at 0.5 starts in 2011 (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. Due to the lengthy time it takes to carry out an individual stock assessment run, i.e., overnight, it was not possible in the time available for the stock assessment to carry out an exhaustive set of sensitivity runs and time permitted only relatively few sensitivity analyses to be carried out. A summary of the additional model runs carried out in this assessment is provided in Table 10, 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 a high prior mean for r and one with a low prior mean for r. 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 prior 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 B_{init}/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 0.75 and 1.25.

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) of the originally estimated time series of combined fixed catch values. There is large uncertainty over the historic catches for both the deepwater and Acadian redfish 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. In addition, 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 Units 1 and 2.

Uncertainty in the standard deviation (SD) in process error (σ_p) deviates in annual stock biomass – Due to the few years of overlap for the abundance indices and having only time series of abundance, it is not possible to jointly estimate σ_p and the standard deviation in observation error deviates for the different abundance indices (σ_o). We thus evaluated the sensitivity of results to applying a lower and higher value for σ_p. The values applied in this sensitivity analysis were 0.05 and 0.15.

EVALUATION OF CREDIBILITY OF ALTERNATIVE 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 annual 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 2011

Results for the full suite of parameters estimated from the reference case run for *S. fasciatus* in Unit 1 and 2 are summarized in Table 11. Predicted posterior median biomass levels from the surplus production model between 1960 and 2011, as well as catch and observed stock trend indices, are shown in Figure 4.

The posterior distributions for carrying capacity (*K*), stock biomass in 2011, and most other quantities of interest are fairly precise (Table 11, Figures 5, 6). This result is mainly due to the apparent decline in the indices in the 1990s when catches were fairly large (Tables 1, 2, Figure 4). The posterior for the intrinsic rate of increase *r* was only slightly updated to slightly lower values (Figure 5). The posterior correlation between r and K was -0.48 (Fig. 5g). The strong drop in the Unit 1 survey biomass series in the 1990s followed by a relatively small increase indicates that this stock remains depleted with a 7% probability that stock biomass in 2011 is greater than 0.4 of B_{msy}.

Estimates of process error terms for *S. fasciatus* 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 7). In the last few years, process error deviate estimates are negative.

The posterior median estimates for the trawl survey constants of proportionality for the surveys in units 1 and 2 were 0.64 and 2.53 (Table 11) which are within the range of values estimated for other trawl surveys in other studies (e.g., McAllister and Ianelli 1997). The 90% probability intervals for these parameter estimates were quite wide (i.e., about 0.3-1.2 for Unit 1 and 1.2 to 5.2 for Unit 2) and indicate considerable uncertainty over these values based on the available stock assessment data for *S. fasciatus* in units 1 and 2 (Table 11).

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 the species) are summarized in Table 12. The range of constant TAC policies considered ranged from 0 to 7 kilotons (000t). Upward median trajectories of B_{FINAL}/B_{MSY} occur for TACs policy options of 6 kilotons and lower.

SENSITIVITY ANALYSES

<u>Model assumptions and input data</u>

Estimates of parameters and key variables of interest obtained from sensitivity runs are provided in Table 13. Stock status results were largely insensitive to the alternative settings for the prior mean for r, the historic catch time series, prior means for the ratio of initial stock size to carrying capacity and the standard deviation in process error terms. In some instances, the estimates of absolute quantities such as B_{msy} and current stock size varied considerably with the changes in stock assessment model settings. For example, B_{2011}, B_{msy} and replacement yield in 2011 varied from about two to four fold, when historic catches ranged from half to double the reference case (Table 13). However, in all instances the stock status results, e.g. B_{2011}/ 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 some instances, however, the B_{2011} and B_{msy} distributions as referenced by the 90% PIs in Table 13 were considerably wider when higher values for some of the inputs were applied, e.g., for the high r, high prior mean for B_{1960}/B_0 and high process error SD scenarios.

The estimated probability values showed some sensitivity to different settings for model inputs (Table 14). For example under the high process error SD run, P(B_{2031}> 0.4 B_{msy}) was 0.22, compared to 0.07 under the reference case and 0.02 under the low process error runs.

Stock projection results showed some sensitivity to the lower and higher prior means for r and the low and high scenarios for historic catches (Tables 15, 17). Under the low prior mean for r for example the 4 kt quota policy option gave about a 47% P(B_{2031}> 0.4 B_{msy}). In contrast, the reference case and high prior r mean options gave 61% and 73% for P(B_{2031}> 0.4 B_{msy}). Projection results were less sensitive to the low and high prior means for the ratio of initial stock size to K (Table 16) and low and high process error SD runs (Table 18).

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 all instances, Bayes factors for the alternative runs ranged between 0.6 and 4.8 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 14).

DISCUSSION

An assessment of past and current population state and 60-year projections is provided for Acadian redfish, *Sebastes fasciatus* in Units 1 and 2. The population assessment and projections were conducted in the context of a Fisheries and Oceans commissioned recovery potential assessment (RPA) for this stock following from a 2010 COSEWIC evaluation of the Canadian Atlantic population of this species being classified as of Threatened.

The stock status results for *S. fasciatus* in Units 1 and 2 are quite similar to the stock status results for *S. mentella* in this same area (McAllister and Duplisea 2011). This is not very surprising since the Unit 1 index for *S. mentella* in Unit 1 showed a similar strong decline in the 1990s while catches were relatively large. As the catch is mixed species, it is also not surprising that the history of fishing pressure on both species has been similar.

Estimates of stock status were relatively insensitive to the different prior mean values for r, different prior means for initial stock size, high and low catch series and different settings for the process error standard deviation. These findings are consistent with results obtained in evaluations of the sensitivity of BSP model results in its application in stock assessments of other Sebastes species (Stanley et al. 2009, 2012, McAllister and Duplisea 2011; Yamanaka et al. 2011, 2012). This is because the life histories and configurations in the catch and abundance index data are similar for the different Sebastes stocks that have been assessed using BSP.

For all of these assessed Sebastes stocks, the life history parameters have resulted in relatively low prior means for r and the catch values applied were relatively high in the 1970s to the early 1990s and have since dropped considerably. It has also been common for at least some of the abundance indices for these stocks to show very substantial declines during the periods of intense exploitation and then either no recovery or very slow rates of recovery following the much lowered rates of exploitation. Thus, for the same types of sensitivity tests, e.g., on the prior for r, uncertainty in historic catches, and the specified value for the process error SD, BSP results have shown similar patterns in sensitivity for the different Sebastes stocks. For example, the stock status and projection results were relatively insensitive to the application of low and high process error SDs in both the 2009 Boccaccio assessment and this assessment (Stanley et al. 2009). The finding of common patterns in sensitivity of results to different input specifications between BSP assessments of Sebastes is thus not surprising. However, this finding does not negate the appropriateness of carrying out evaluations of the sensitivity of results in each new stock assessment, even if such common patterns has been found in previous assessments.

There remain numerous untested assumptions key to the validity of the results. For instance the results are heavily reliant on the survey data being proportional to the stock size, the applied catch values being accurate to within half or double of the applied values and the parameters of the SPM model remaining constant in time. The latter assumption may be particularly tenuous when extrapolating as far ahead as 60 years. For instance, there could be long-term shifts in carrying capacity (parameter K). Such long-term changes in the value of a model parameter would not be handled by the process error term, even with positive autocorrelation applied to the recent and future process error deviates as it was in this assessment (lag 1, with the autocorrelation term, ρ, set at 0.5).

CONCLUSIONS

The BSP stock assessment results provide consistent fairly precise estimates of high levels of depletion for *S. fasciatus* in Units 1 and 2. The posterior median value for B_{2011}/ B_{msy} for this stock was low at about 17% with a 90% probability intervals ranging between 8% and 50%. Quota policies of no more than 6 kt resulted in projected stock increases to the critical-cautious zone boundary but this was very slow with there being only about a 53% chance of the stock exceeding 40% of B_{msy} in three generations.

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Table 1. Swept Area Mature Biomass Estimates (in kt) and Coefficients of Variation (CVs) for S. fasciatus in Units 1 and 2.

Unit	Year	Index	Coefficient of Variation
1	1990	267.3	0.107
1	1991	188.6	0.158
1	1992	208.9	0.326
1	1993	108.9	0.630
1	1994	71	0.570
1	1995	11.3	0.234
1	1996	10.2	0.247
1	1997	26.3	0.389
1	1998	48	0.666
1	1999	13.3	0.354
1	2000	19	0.164
1	2001	21.6	0.373
1	2002	13.5	0.534
1	2003	71.9	0.606
1	2004	14.2	0.266
1	2005	24.4	0.234
1	2006	37.7	0.228
1	2007	24.1	0.153
1	2008	52.8	0.370
1	2009	18.7	0.208
1	2010	58.4	0.264
1	2011	27.8	0.185
2	2000	119.3	0.498
2	2001	177.1	0.700
2	2003	69.2	0.144
2	2005	168.2	0.277
2	2007	158.3	0.145
2	2009	127.7	0.694

Table 2. Catch in kt for S. fasciatus in Units 1 +2.. Catches for 2010 are filled in presuming the catch for 2009 where no catch values for 2010 are available.

Year	Catch	Year	Catch
1960	17.4	1991	41.53
1961	14.1	1992	41.76
1962	14.1	1993	35.37
1963	20.1	1994	20.46
1964	24.5	1995	6.34
1965	32.7	1996	4.87
1966	42.2	1997	5.13
1967	51.1	1998	5.64
1968	48.8	1999	9.69
1969	61.4	2000	5.77
1970	62.4	2001	4.84
1971	63.7	2002	3.87
1972	56.9	2003	4.31
1973	71.3	2004	3.55
1974	44.9	2005	3.89
1975	48.4	2006	3.84
1976	30.3	2007	2.11
1977	22.0	2008	2.27
1978	20.0	2009	3.18
1979	16.5	2010	3.77
1980	15.3	2011	1.25
1981	20.3		
1982	19.7		
1983	17.1		
1984	18.7		
1985	17.4		
1986	20.3		
1987	25.2		
1988	27.6		
1989	31.0		
1990	34.3		

Table 3. Life History Parameters for S. fasciatus..

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

		mean	CV	SD
S. fasciatus	ln(a)	-18.320	0.0050	0.0909
	b	3.080	0.0058	0.0178

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

	median	SD(log(M))	lower	upper
S. fasciatus	0.125	0.25	0.075	0.175

d. 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 4. *Median age at maturity for female Acadian redfish Unit 1 + 2. The standard deviation in the natural logarithm of age at maturity (SD in ln(age maturity)) is presumed to be 0.5 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. fasciatus	Gulf of St. Lawrence and Laurentian Channel	Unit 1	7.67 y
Canadian Atlantic		Unit 2	10.31 y
		Assumed for Units 1 and 2	8.99 y

Table 5. Prior probability distributions for the maximum rate of increase (r) for Acadian redfish in Unit 1+ 2.

Species	Management Unit	Mean r	Median r	SD	CV	SD(log(r))
S. fasciatus	U1, 2	0.145	0.129	0.069	0.471	0.517

Table 6. 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
$\{q_{j=1}, q_{j=2}\}$	Vector of catchability parameters for J abundance indices (where, J is Area-specific as described in Table 1 of main document)

Table 7. 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 8. 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(1.0),0.2^2)
r (*S. fasciatus*, Unit 1,2)	logNormal(log(0.145),0.517^2)
$\varepsilon_{process,y}$	Normal(0, 0.1^2)

Table 9. 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=U1 is for the Unit 1 survey index, j=U2 is for the Unit 2 survey index, j=U1.

	$\sigma_{obs,\ U1}$	$\sigma_{obs,\ U2}$
S. fasciatus, Unit 1, 2	0.41	0.79

Table 10. Summary of sensitivity runs in the Acadian redfish stock assessment, including their categorization.

Category code	Category Description	Table Code	Run Description
Ref	Reference run	Ref.S.1	Reference run
A	r prior mean	A.1	low r (mean = 0.67 reference run mean)
		A.2	high r (mean = 1.33 reference run mean)
B	Initial stock size assumptions	B.1	prior mean $B_{1960}/K = 0.75$
		B.2	prior mean $B_{1960}/K = 1.25$
C	Uncertainty over catch records	C.1	fixed catches are 50% of the reference case
		C.2	fixed catches are twice the reference case
D	Uncertainty over process error SD	D.1	Process error SD set at 0.05
		D.2	Process error SD set at 0.15

Table 11. Parameter estimates and stock status indicators for S. fasciatus in Unit 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 2011. The two quantiles represent the probability that biomass in 2011 is above the critical zone [$P(B_{2011} > 0.4B_{MSY})$] and the probability that biomass in 2011 is in the healthy zone [$P(B_{2011} > 0.8B_{MSY})$]. All biomass and yield values are in kilotons.

Estimated Variables

Variable	Mean	SD	CV	5th Percentile	Median	95th Percentile
r	0.128	0.051	0.40	0.055	0.122	0.220
K	824	338	0.41	480	741	1374
MSY	24	11	0.47	12	23	37
B_{msy}	412	169	0.41	240	371	687
B_{1960}	835	341	0.41	459	753	1380
B_{2011}	119	290	2.44	32	65	219
B_{2011}/B_{msy}	0.24	0.30	1.24	0.08	0.166	0.497
B_{2011}/B_{1960}	0.12	0.16	1.29	0.04	0.084	0.248
B_{2011}/K	0.12	0.15	1.24	0.040	0.083	0.248
F_{MSY}	0.06	0.03	0.40	0.027	0.061	0.110
F_{2011}	0.02	0.01	0.48	0.006	0.020	0.041
F_{2011}/F_{msy}	0.37	0.22	0.58	0.12	0.33	0.75
$REPY$	7.6	6.1	0.80	2.9	6.5	14.1
$Catch_{2011}/REPY$	0.21	0.11	0.53	0.08	0.19	0.40
Unit 1 trawl survey q	0.69	0.27	0.40	0.34	0.64	1.20
Unit 2 trawl survey q	2.78	1.27	0.46	1.24	2.53	5.18
Estimated quantiles						
$P(B_{2011} > 0.4B_{msy})$	0.071					
$P(B_{2011} > 0.8B_{msy})$	0.038					

Table 12. Decision table for S. fasciatus in Units 1 and 2 with median posterior estimates of biomass after five twenty and sixty years (up to three generations) (B_{2017}, B_{2031}, and B_{2071}) 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_{2011}).

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	0.26	0.26	0.05	0.04	0.89
	2	0.25	0.24	0.05	0.04	0.82
	4	0.22	0.20	0.05	0.04	0.70
	6	0.19	0.18	0.05	0.04	0.55
	7	0.17	0.17	0.05	0.04	0.49
20-year	0	0.93	0.84	0.58	0.46	0.96
	2	0.76	0.73	0.49	0.40	0.90
	4	0.54	0.61	0.39	0.31	0.75
	6	0.28	0.43	0.29	0.21	0.56
	7	0.13	0.36	0.23	0.17	0.46
60-year	0	1.74	0.98	0.91	0.86	0.98
	2	1.67	0.92	0.85	0.81	0.93
	4	1.41	0.75	0.69	0.65	0.76
	6	0.67	0.53	0.49	0.46	0.52
	7	0.00	0.43	0.39	0.36	0.42

Table 13. Stock assessment results for alternative settings to the Bayesian surplus production (BSP) stock assessment model for S. fasciatus in Unit 1 + 2. B_{2011} refers to the stock size in 2011, $RepY_{2011}$ refers to the replacement yield in 2011. F_{2011} refers to the fishing mortality rate in 2011. 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 10 for a description of each sensitivity run.

	r			B_{msy}			B_{2011}			$RepY_{2011}$			B_{2011}/B_{msy}			F_{2011}/F_{msy}			$Catch_{2011}/RepY_{2011}$		
	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	0.055	0.122	0.22	240	371	687	32	65	219	2.9	6.5	14.1	0.08	0.166	0.497	0.117	0.332	0.753	0.084	0.19	0.404
	r prior mean 33% lower and 33% higher																				
A.1	0.039	0.094	0.187	260	422	801	34	72	364	2.5	5.9	14.2	0.078	0.166	0.623	0.107	0.371	0.93	0.082	0.212	0.496
A.2	0.075	0.148	0.245	237	341	1354	30	63	2436	3.4	7.3	27.1	0.083	0.173	1.659	0.006	0.292	0.616	0.016	0.169	0.333
	Initial stock size, 0.6 K and 1.0 K																				
B.1	0.063	0.126	0.23	271	378	771	28	63	272	3.2	6.6	15.2	0.069	0.161	0.57	0.1	0.33	0.696	0.077	0.187	0.376
B.2	0.063	0.126	0.236	233	340	1047	32	67	1366	3.3	6.5	20.8	0.085	0.187	1.383	0.019	0.332	0.65	0.041	0.193	0.355
	Catches half or double																				
C.1	0.046	0.135	0.237	118	166	287	15	28	80	1.7	3	5.2	0.083	0.163	0.303	0.192	0.361	0.68	0.119	0.205	0.371
C.2	0.059	0.135	0.246	458	719	1407	59	117	323	6.3	13.3	26.6	0.069	0.166	0.42	0.139	0.324	0.729	0.093	0.187	0.394
	Process error SD set at 0.05 and then 0.15																				
D.1	0.077	0.150	0.246	242	319	462	34	62	119	3.8	7.5	13.3	0.101	0.187	0.339	0.15	0.285	0.592	0.094	0.166	0.325
D.2	0.047	0.112	0.227	243	466	1135	30	77	1293	2.6	7.2	46.1	0.061	0.176	1.537	0.015	0.295	0.795	0.023	0.17	0.421

Table 14. Probability that stock biomass exceeds 0.4 B_{msy} and 0.8 B_{msy} and relative credibility of alternative model runs for S. fasciatus in Units 1 and 2 as indicated by Bayes factors. Bayes factors 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 10 for a description of each sensitivity run.

Category Code	Category description	Run description	Code	$P(B_{2011}>0.4B_{msy})$	$P(B_{2011}>0.8B_{msy})$	Bayes factors
A	r prior mean	low	A.1	0.092	0.039	1.0
		reference	Ref.1	0.071	0.038	1.0
		high	A.3	0.107	0.085	0.7
B	Initial stock size uncertainty	low	B.1	0.062	0.044	1.1
		reference	Ref.1	0.071	0.038	1.0
		high	B.2	0.107	0.071	1.7
C	Catch history uncertainty	low	C.1	0.016	0.011	0.7
		reference	Ref.1	0.071	0.038	1.0
		high	C.2	0.054	0.030	0.6
D	Process error SD uncertainty	low	C.1	0.021	0.004	0.2
		reference	Ref.1	0.071	0.038	1.0
		high	C.2	0.224	0.141	4.8

Table 15. Decision table for alternative quota policies for S. fasciatus in Units 1 and 2 when alternative priors for r are applied (see Table 10 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2031 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	1.0	1.0	0.7
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.73	0.84	0.90
2	0.62	0.73	0.85
4	0.47	0.61	0.73
6	0.34	0.43	0.58
7	0.28	0.36	0.49

Table 16. Decision table for alternative quota policies for S. fasciatus in Units 1 and 2 when alternative priors for the ratio of initial stock size to K (0.75 or 1.25) are applied (see Table 10 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2031 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 ratio of initial stock size to K	0.75	reference	1.25
Bayes factor	1.1	1.0	1.7
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.83	0.84	0.88
2	0.72	0.73	0.82
4	0.59	0.61	0.67
6	0.47	0.43	0.52
7	0.40	0.36	0.46

Table 17. Decision table for alternative quota policies for S. fasciatus in Unit 1 + 2 when alternative historic catch scenarios (half or double the reference case catches) are applied (see Table 10 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2031 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	0.7	1.0	0.6
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.79	0.84	0.85
2	0.57	0.73	0.81
4	0.22	0.61	0.72
6	0.07	0.43	0.66
7	0.05	0.36	0.63

Table 18. Decision table for alternative quota policies for S. fasciatus in Unit 1 + 2 when alternative values for the process error SD (0.05 or 0.15) are applied (see Table 10 for a description of the alternative runs). Results are shown for the probability that stock biomass in 2031 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.

Process error SD	low	reference	high
Bayes factor	0.2	1.0	4.8
Quota option (kt)	$P(B_{2030} > 0.4\ B_{msy})$		
0	0.97	0.84	0.73
2	0.92	0.73	0.66
4	0.80	0.61	0.55
6	0.62	0.43	0.46
7	0.52	0.36	0.41

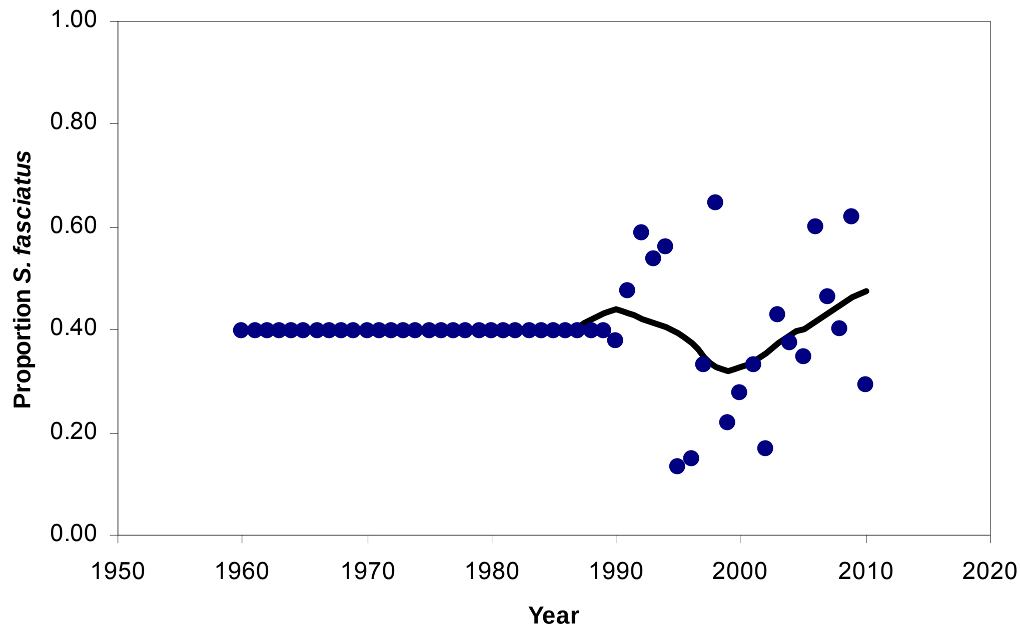

Figure 1: Proportion of mature S. fasciatus in the survey for Unit 1 (Gulf of St. Lawrence) summer survey. The survey data (points) were available from 1990 onward and a mean proportion applied in earlier years. A loess smooth (line) was run through the points and applied to aggregated Sebastes spp catch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

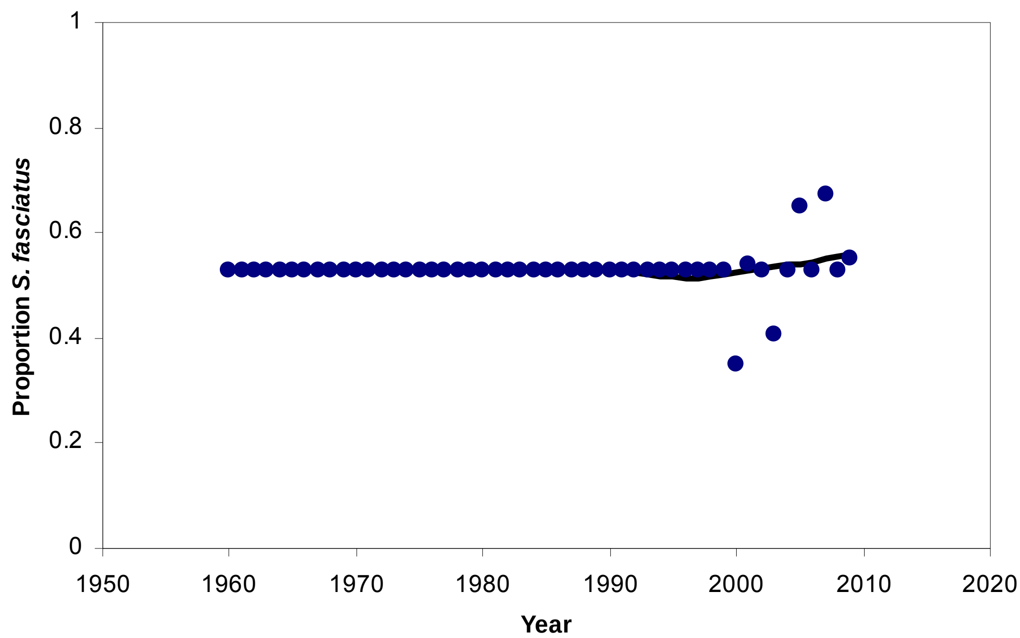

Figure 2: Proportion of mature S. fasciatus in the survey for Unit 2 summer survey. The survey data (points) were available every other year from 2000 onward and a mean proportion applied in other years. A loess smooth (line) was run through the points and applied to aggregated Sebastes spp. catch data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

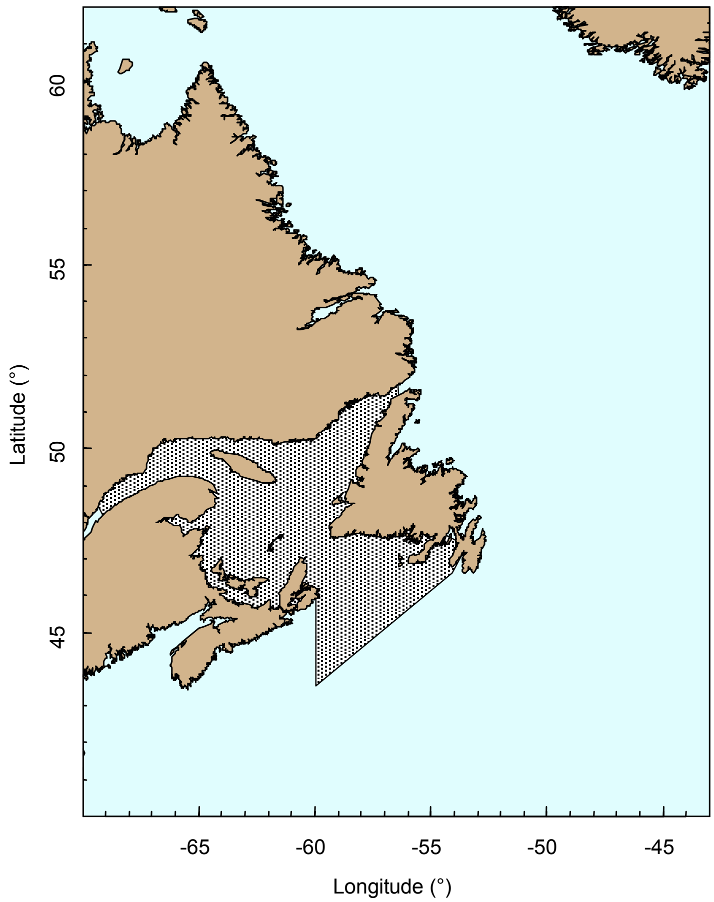

Figure 3: Map showing the rough geographic area corresponding to the Unit 1 + Unit 2 Sebastes fasciatus (dot filled area).

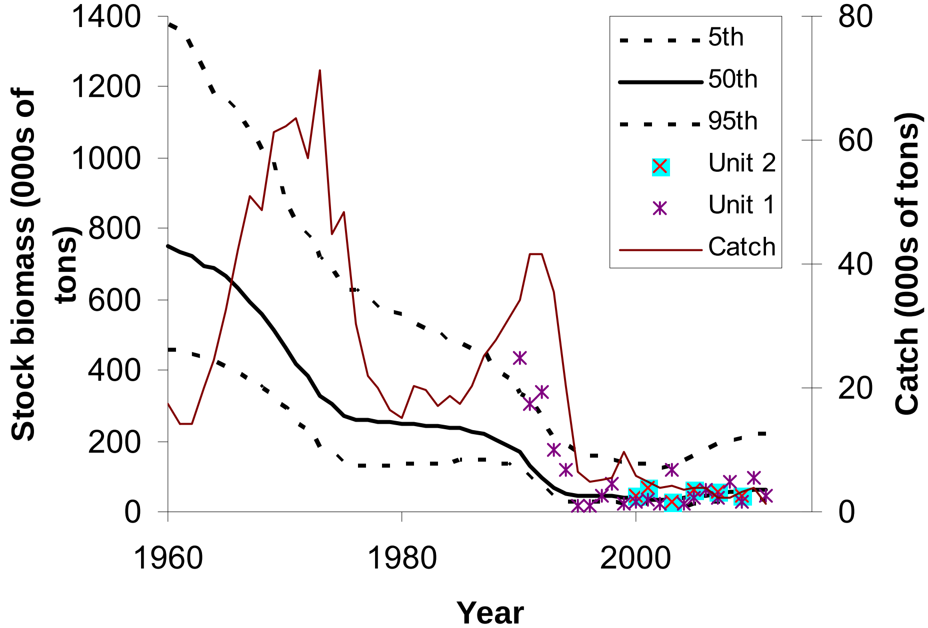

Figure 4. Plots of catch biomass (kt), and 5th, median and 95% percentiles for mature stock biomass of S. fasciatus in Units 1 and 2. The survey biomass indices divided by the median estimates of q are also shown.

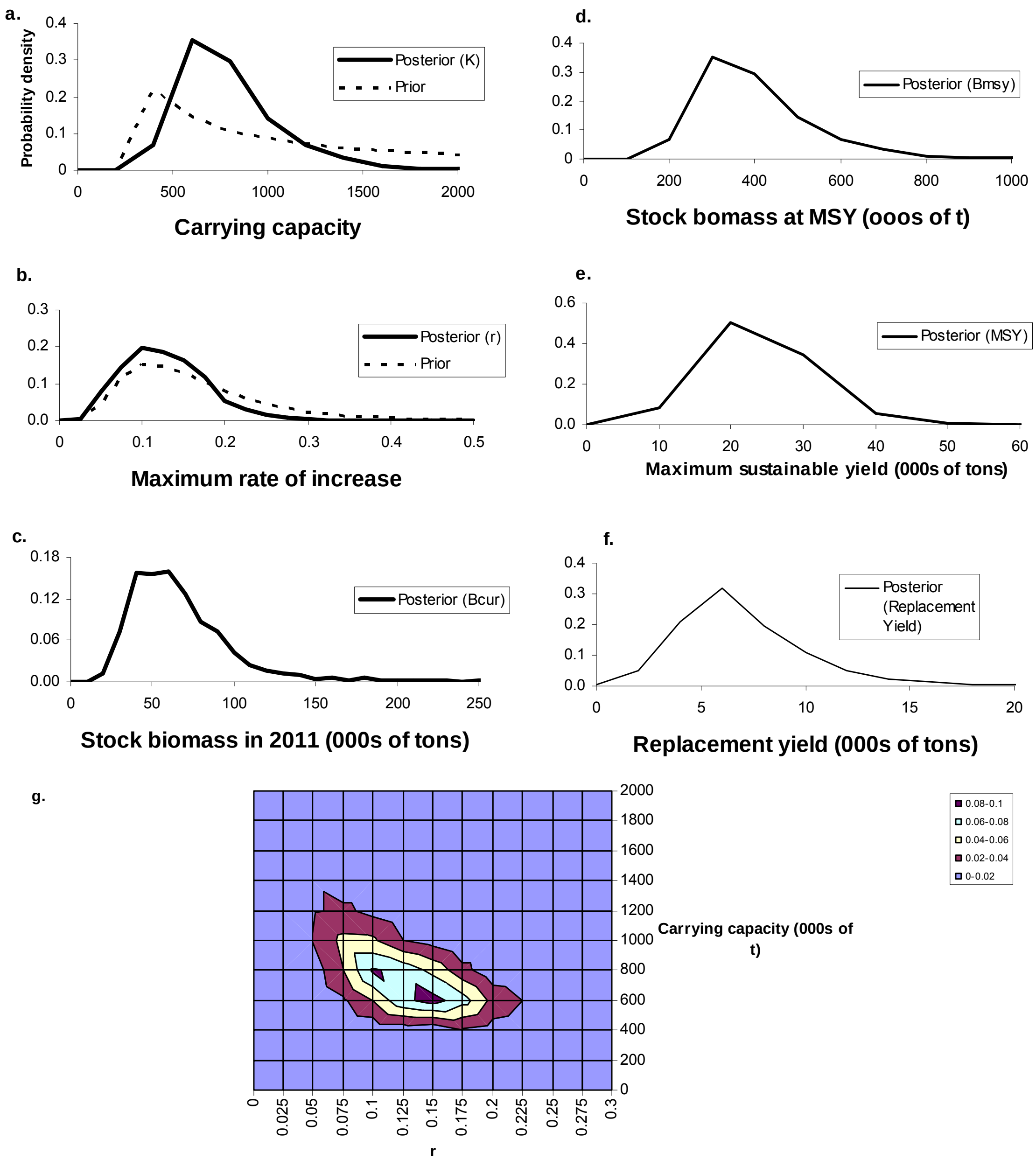

Figure 5. Parameter estimates and stock status outputs for S. fasciatus in Unit 1 + 2. Marginal posterior distributions for a) carrying capacity (K), b) maximum rate of increase (r), c) mature stock biomass in 2011, d) stock biomass that gives the maximum sustainable yield (Bmsy), e) MSY, f) the replacement 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.

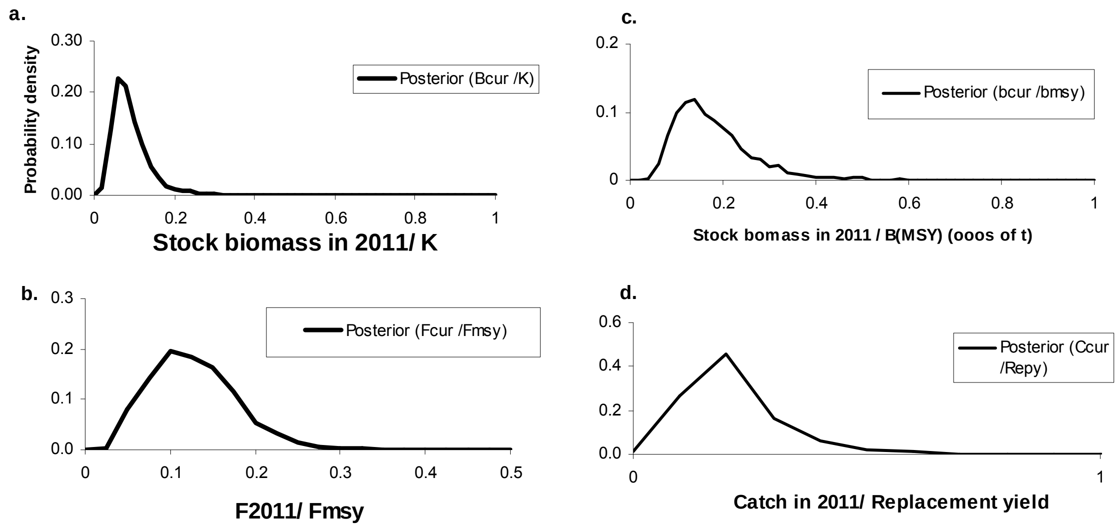

Figure 6. Stock status outputs for S. fasciatus in Unit 1 + 2. Marginal posterior distributions for the ratios of a) stock biomass in 2011 to carrying capacity (K), b) fishing mortality rate in 2011 to Fmsy, c) mature stock biomass in 2011 to stock biomass that gives MSY, and d) catch biomass in 2011 to the replacement yield.

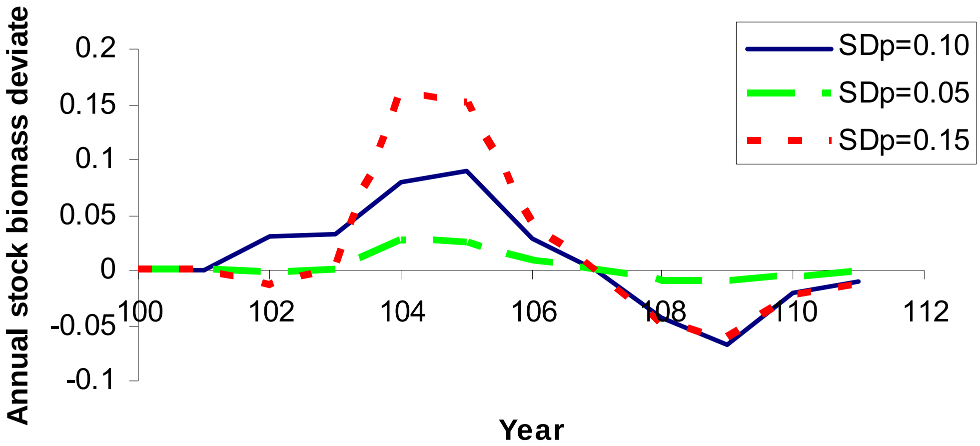

Figure 7. Posterior mode estimates of process error Unit 1 + 2 Acadian redfish for the reference case (SD_p=0.10), and sensitivity runs for this term.