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Research Document 2008/028

Document de recherche 2008/028

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Recovery Potential Assessment of 4VWX Cusk (*Brosme brosme*): Population models

Évaluation du potentiel de rétablissement du brosme de 4VWX (*Brosme brosme*) : modèles de la population

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ISSN 1499-3848 (Printed / Imprimé)

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ABSTRACT

In May 2003, cusk (*Brosme brosme*) was designated as Threatened by the Committee on the Status of Endangered Wildlife in Canada. In this report, we use Bayesian state-space implementations of the Schaefer surplus production and stochastic exponential growth models to estimate population parameters of cusk in the 4X and combined 4VWX NAFO divisions. Models were fit using either single or multiple datasets simultaneously of the following: the groundfish longline fishery CPUE index spanning 1986 to 2007 in 4Xnopqu; the standardized research vessel summer trawl survey conducted by DFO from 1970 to 2007; two industry/science surveys, the 4VsW sentinel survey spanning 1995 to 2003 and yearly sampled stations in the 3NOPs4VWX halibut survey from 1998 to 2007; and the Northeast Fisheries Science Center autumn bottom trawl survey in the Gulf of Maine from 1963 to 2007.

All models identified significant reductions in cusk exploitable biomass, although uncertainty in historical exploitable biomass estimates was large. The 4Xnopqu longline CPUE index, which is thought to most closely meet the assumption of proportionality to overall biomass estimated a 62% decline since 1986, however, parameter estimates had large credible limits. The model using the summer RV survey index estimated a decline of 94% since 1970; however, there is concern that some hyper-depletion may be occurring in this index giving over-estimates of total decline. The GoM autumn trawl survey estimated a similar decline, 86% since 1964, but may have similar proportionality issues as the RV survey index. The sentinel and halibut surveys were of insufficient duration and contrast to estimate declines in a useful historical context.

Stochastic simulation using median parameter values derived from the model using the 4Xnopqu longline data estimated the required reductions in landings needed to give a 75% chance of meeting three different management outcomes: no further decline in biomass, at least a 50% increase in biomass, or, at least a 100% increase in biomass after 15 years in the 4X NAFO division. Assuming that unquantified fishing mortality remains constant, landings in 4X would need to be reduced to 625 t or 200 t to provide a 75% chance of the population either remaining stable or increasing 50% after 15 year, respectively.

RÉSUMÉ

En mai 2003, le brosme (*Brosme brosme*) a été désigné en tant qu'espèce menacée par le Comité sur la situation des espèces en péril au Canada. Dans le présent rapport, nous utilisons des applications bayésiennes état-espace des modèles de la production excédentaire et de la croissance exponentielle stochastiques de Schaefer pour estimer les paramètres de la population de brosme de 4X et des divisions combinées 4VWX de l'OPANO. Les modèles ont été adaptés à l'aide d'ensembles de données simples ou multiples – employés simultanément – provenant de l'indice des PUE des pêches à la palangre au poisson de fond menées de 1986 à 2007 dans 4Xnopqu; du relevé normalisé d'été au chalut par navire scientifique effectué par le MPO de 1970 à 2007; de deux relevés de l'industrie/de scientifiques, à savoir le relevé des pêches sentinelles de 4VsW réalisé de 1995 à 2003 et le relevé sur le flétan mené à des stations échantillonnées sur une base annuelle de 3NOPs4VWX de 1998 à 2007; finalement, le relevé d'automne au chalut de fond effectué par le Northeast Fisheries Science Center dans le golfe du Maine de 1963 à 2007.

Tous les modèles ont révélé des réductions importantes de la biomasse exploitable de brosme, bien que l'incertitude relative aux estimations de la biomasse exploitable historique soit grande. L'indice des PUE des pêches à la palangre menées dans 4Xnopqu, qui est censé se rapprocher le plus de l'hypothèse de la proportionnalité par rapport à la biomasse totale, donne un déclin de 62 % depuis 1986; cependant, les estimations des paramètres affichent de grandes limites de crédibilité. Le modèle utilisant l'indice du relevé d'été par navire scientifique indique quant à lui un déclin de 94 % depuis 1970; cependant, on se demande si un certain degré d'hyper-épuisement peut être reflété dans cet indice, ce qui se traduit par une surestimation du déclin total. Le relevé d'automne au chalut effectué dans le golfe du Maine indique un déclin semblable, soit 86 % depuis 1964, mais peut présenter des problèmes de proportionnalité semblables à ceux touchant l'indice des relevés par navire scientifique. Les relevés des pêches sentinelles et du flétan sont d'une durée et d'un contraste insuffisants pour que l'on puisse estimer les déclins dans une perspective historique utile.

Grâce à la simulation stochastique effectuée à l'aide de valeurs paramétriques médianes dérivées du modèle utilisant les données des pêches à la palangre de 4Xnopqu, on a estimé les réductions des débarquements nécessaires pour obtenir une probabilité de 75 % d'atteinte de trois résultats de gestion différents, à savoir aucun autre déclin de la biomasse, une augmentation d'au moins 50 % de la biomasse ou, encore, une augmentation d'au moins 100 % de biomasse au bout de 15 ans dans la division 4X de l'OPANO. Ainsi, si l'on présume que la mortalité par la pêche non quantifiée demeure constante, les débarquements de 4X devrait être réduit à 625 t ou à 200 t pour obtenir respectivement une probabilité de 75 % que la population demeure stable ou qu'elle s'accroisse de 50 % au bout de 15 ans.

INTRODUCTION

In May 2003, cusk was designated as Threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2003) and is under consideration for listing under Schedule 1 of Canada's *Species at Risk Act* (SARA). If listed under SARA, activities that would harm the species may be limited and a recovery plan would be required.

Cusk (*Brosme brosme*, Family Gadidae) is a monotypic genus of the North Atlantic. Little is known about the life history and population dynamics of this species. Preferred habitat is on hard, rocky substrate or gravel (Oldham 1966, Scott and Scott 1988). Depth preference, as indicated by the highest catch rates from the Halibut Industry longline survey, is between 400 and 600 m, but cusk have been caught on the deepest sets (1185 m) on this survey. Fishing is the only identified major source of mortality for cusk. Cusk smaller than 35 cm are rarely captured in either the longline or trawl surveys or as bycatch in the groundfish longline fishery. Fishing was unregulated until 1999, after which a landing limit of 1000 t was imposed in the 4VWX North American Fisheries Organization (NAFO) divisions. Due to increased conservation concerns, this limit was further reduced to 750 t in 2003 and extended to 4VWX5Zc (DFO 2004). There is no directed fishery, but cusk are frequently caught as bycatch in the lobster and groundfish fisheries, with discard mortality estimated to be over 50% in the lobster fishery (L. Harris *personal communication*). This estimate may be conservative and requires further research.

There is general agreement that the cusk population in Canada has declined; however, the extent of decline is controversial. The decision by COSEWIC to categorize cusk as Threatened was based largely on an analysis of the Department of Fisheries and Oceans (DFO) research vessel (RV) bottom trawl summer survey index which indicated that the cusk population in NAFO Div. 4X had declined by more than 90% since 1970 (COSEWIC 2003). The magnitude of decline has been disputed by DFO because the RV trawl survey samples only fringe cusk habitat, which may invalidate the assumption of constant proportionality of the survey index to overall stock biomass. Non-proportionality of the RV survey, however, has not been quantitatively demonstrated, but is thought to arise from lower biomass production rates in marginal or trawlable habitats resulting in the survey index declining faster than overall stock biomass (hyperdepletion). At the Recovery Potential Assessment (RPA) meeting in November 2007, it was argued that other datasets that sample preferred cusk habitat might more closely meet the assumption of constant proportionality. The predominant opinion at the RPA meeting was that the 4Xnopqu commercial groundfish longline catch rate (CPUE) index better sampled preferred cusk habitat and was more likely to meet the assumption of proportionality to stock biomass than the RV trawl survey.

We modeled the population dynamics of cusk using Bayesian state-space implementations of the Schaefer surplus production (SP) and stochastic exponential growth (SEG) models for 4VWX. There were insufficient data to model the population dynamics in div. 5Z. As per the consensus of the RPA meeting, analyses were focused on the 4Xnopqu longline CPUE index spanning 1986 to 2007 but, for comparison, we also fit models to: (1) the standardized DFO summer RV trawl survey, spanning 1970 to 2007; (2) two industry/DFO longline surveys, the 4VsW Sentinel survey, spanning 1995 to 2003, and yearly sampled stations in the 3NOPs4VWX Halibut survey, spanning 1998 to 2007; and (3) the Northeast Fisheries Science Center (NEFSC) autumn bottom trawl survey in the Gulf of Maine (GoM), spanning 1964 to 2005. In all cases, commercial landings data from either 4VWX or the GoM, as appropriate, were treated as removals in the models.

The main focus of this modelling work was to estimate current and historical biomass levels, to derive population parameters for cusk in 4X, and to explore the potential for population recovery under different commercial catch levels.

DATA SOURCES AND METHODS

Fishery Dependent Data

The longline CPUE index is derived from the 4Xnopqu commercial groundfish longline fleet from 1986 to 2007. The index was restricted to the groundfish longline fishery, because this sector has the highest cusk landings (greater than 95% of all landings since 1990) and approximately 76% of all landings from 4VWX5Z were captured by longline in the 4X NAFO division in these years. Areas of marginal cusk habitat and low cusk catches, such as the Bay of Fundy and shallow inshore regions, were not included.

There are anecdotal reports that landings at the beginning of the time series may be inflated due to intentional misreported cusk landings. Prior to 1999, there was no catch limit on cusk and it has been suggested that other species, such as cod, were landed as cusk when quotas were exceeded, thus potentially adding bias to the catch rate index. Unfortunately, the level of misreporting is not quantified, and therefore, no correction could be made to the catch rate index. Two methods, however, were employed to reduce bias. First, the time series was restricted to the months from July to September to avoid introducing bias from the imposed catch limits that were implemented in 1999 and 2003. Second, the index was restricted to vessels of tonnage classes 2 and 3 (25 to 149.9 gross registered tons), since no effort information was available for longliners of gross registered tonnage less than 24.9 t in earlier years (L. Harris *personal communication*).

Research Vessel Data

The DFO RV and GoM surveys began in 1970 and 1963, respectively, and continue today, thus potentially providing 38, and 45 years of information on cusk exploitable biomass. There are insufficient data to determine if there are distinct cusk populations in the northwest Atlantic, and therefore, the NMFS GoM autumn research vessel trawl survey was also modeled. The GoM trawl data were limited to 1964 through 2005 due to the availability of landings data from that region.

Few cusk are caught in trawl surveys. The low catchability is attributed to cusk preferring complex rocky habitat which is difficult to trawl and/or avoided due to the possibly for gear damage. Mean weight per tow was highly variable from year to year in both surveys due to sporadic relatively large catches. Yearly index values were calculated by taking the arithmetic mean within strata and the weighted mean based on geographic coverage over all strata.

Concerns regarding the assumption of proportionality of the trawl surveys to stock biomass were raised at the RPA meeting in November 2007. Some attendees felt that the large declines observed in the trawl RV survey may be partially due to the survey areas being outside the preferred depth and habitat range for cusk; and therefore, the trawl surveys may have a hyperdepletion relationship with stock biomass. If this is the case, then the estimate of overall stock decline derived from the trawl surveys may be exaggerated. Cusk are still relatively common as bycatch in groundfish and lobster fisheries; however, no data was identified to compare current catch rates in the lobster fishery to historical norms. It is important to note that non-proportionality of the trawl surveys has not been quantitatively tested or explicitly demonstrated. However, due to the significant concerns about these indices, the population parameters derived using the RV data were not used in the population projections. Further research is needed to test whether the DFO RV survey suffers from proportionality issues for certain species, and if they exist, determine calibration methods to correct for these biases.

Industry/Science Survey Data

Two industry/science longline surveys, the 4VsW sentinel survey from 1995 to 2007 and yearly sampled stations in the 3NOPs4VWX halibut survey from 1998 to 2007 were available.

The sentinel longline survey is of stratified random design and was designed primarily to develop abundance indicators for Atlantic cod (*Gadus morhua;* McDonald 2005). When the survey began in 1995, the program sampled a total of 253 stations per year; however, sampling effort was reduced to 53 stations in 2004. The 53 remaining stations in the survey since 2004 were selected based on higher catch rates of economically valuable groundfish species. How this affected cusk catch rates is unknown; therefore, to avoid potentially introducing bias in the latter parts of the time series, years after 2003 were omitted from analysis (see McDonald 2005; for history and description of survey protocols). Yearly index values were calculated by taking the arithmetic mean within strata and then the weighted mean based on geographic coverage over all strata.

The 3NOPs4VWX halibut survey began in 1998 and has a fixed station design based on Atlantic halibut (*Hippoglossus hippoglossus*) catch rates. Sampling of stations has been sporadic; and therefore, only 50 stations that were consistently sampled every year were included in analysis (see Zwanenburg and Wilson 1999, 2000, 2003; for detailed description of survey protocols). Since the relationship between halibut and cusk catch rates is unknown, yearly index values were calculated by taking the arithmetic mean catch at each station and then the arithmetic mean of all stations sampled.

Population Models

We used Bayesian state-space models, implemented in WinBUGS 1.4.3 (Lunn et al. 2000), to investigate trends in exploitable biomass and derive population dynamics parameters. State-space models differ from traditional deterministic population models in that they consist of two coupled components, a state process model and an observation model. The state process model represents the unobservable stochastic processes governing the population dynamics. In contrast, the observation model describes the error structure inherent in the observations of species abundance or biomass. By coupling these two components in a state-space framework, the errors inherent in the observation process can be separated from “noise” in the population processes to allow for optimal estimation of population parameters. Indeed, if measurement error is significant and simply combined with process error, the uncertainty of population projections can be overestimated and potentially biased (Dennis et al. 2006).

Unlike a winter skate RPA (Swain et al. 2006), we were unable to fit a stage-structured state-space model due to insufficient age-disaggregated and life history data, and low susceptibility of juvenile cusk to both trawl and longline gear. We were therefore limited to relatively simple population models and employed both a Schaefer surplus production model and stochastic exponential growth model in state-space form to investigate the decline in, and estimate population parameters for, cusk biomass in 4X and combined 4VWX NAFO divisions.

Surplus Production Model

In a SP model, the parameters for recruitment, growth, and natural mortality are combined in the single parameter r, the intrinsic rate of population growth. Other simplifying assumptions of the model are that the intrinsic rate of population growth and carrying capacity are both held constant (ie. changes in the biotic and abiotic environment are not included) and are the same for all individuals in the population, productivity instantly changes in relation to population size, there is no size or age structure to the population, and the population is at equilibrium (Hilborn and Walters 1992).

The Schaefer (Schaefer 1954) form of a surplus production model is:

$$B_t = \left[B_{t-1} + rB_{t-1}\left(1 - \frac{B_{t-1}}{K}\right) - C_{t-1} \right] \times \eta_t \qquad (1)$$

Where B_{t-1} and C_{t-1} denote exploitable biomass and catch (catch is assumed to be synonymous with landings), respectively, for year $t-1$. Carrying capacity, K, is the level of stock biomass at equilibrium prior to commencement of the fishery, r is the intrinsic rate of population growth, and η_t is a log-Normal random variable, $\eta_t \sim \mathrm{LN}(0, \sigma^2)$, describing stochasticity in the population dynamics.

The observation equation relates the unobserved biomass, B_t, to the observations, I_t. Here we are able to combine information from multiple surveys into a single model by using multiple observation equations, each with their own catchability parameter q_i and observation error $\varepsilon_{i,t}$:

$$I_{i,t} = q_i B_t \varepsilon_{i,t} \qquad (2)$$

where the random variable $\varepsilon_{i,t}$ is log-Normal, $\varepsilon_{i,t} \sim \mathrm{LN}(0, \tau_t^2)$. A more thorough description of a state-space surplus production model is described in Meyer and Millar (1999).

Population parameters and levels of exploitable biomass can be reliably estimated using a SP model when a time series spans a period of heavy exploitation, followed by rebuilding, and then another exploitation phase (Hilborn and Walters 1992). Unfortunately, all available cusk time series show a continuous trend from high to low biomass which is referred to as a “one-way trip” in the fisheries literature (Hilborn and Walters 1992). The relatively low contrast of the data causes confounding between the model parameters r, K, and q, and can result in significant uncertainty in parameter estimates, particularly K. Confounding can be further exacerbated when the starting biomass of the time series, B_0, is estimated rather than defined. To limit confounding, B_0 was set equal to K for all SP models.

Due to the confounding among the model parameters r, K, and q, we also fit a simpler stochastic exponential growth model to the 4Xnopqu CPUE index to evaluate the robustness of our estimates of population trends and overall decline using this time series.

Stochastic Exponential Growth Model

The SEG model has the same assumptions as the SP model with two major differences: 1) the SEG model lacks any density-dependence (introduced by (1 – B_{t-1}/K)) so there is no carrying capacity parameter to estimate; and 2) the SEG model is in a continuous rather than discrete form. Consequently, the rate of population increase (μ) of the SEG model is not directly comparable to the intrinsic rate of population growth (r) calculated in the SP model. Regardless, SEG models of the general form presented here can be effective in estimating declines in species at risk when data are limited (Dennis et al. 2006; Lindley 2003).

The SEG model has a process equation of the form:

$$B_t = \left(B_{t-1}e^{\mu} - C_{t-1}\right) \times\ e^{\omega_t} \tag{3}$$

where μ is the mean rate of population growth, and ω_t is a random variable for the process error, ie. $\omega_t \sim N(0, \sigma^2)$. Alternatively, the equation can be rearranged so catches occur before growth; however, this had minimal impact on results so is not described further.

The observation equation linked to Equation 4 is:

$$I_t = qB_t\xi_t \tag{4}$$

As in the SP model (Equation 2), the observation equation relates the unobserved biomass B_t to the observations, I_t. In this case, the parameter q is the catchability coefficient for the 4X CPUE index and ξ_t is a log-Normally distributed random variable for the observation error of the survey index, ie. $\xi_t \sim LN(0, \tau^2)$.

Modelling Approach

In this document, our focus is the analysis of the 4Xnopqu CPUE longline index using state-space implementations of the SP model (SP.cpue) and two SEG models, one that does not include catches and another that does (SEG.cpue1 and SEG.cpue2 respectively). We use the SP model to calculate changes in biomass through time and derive parameter estimates for the population dynamics and use these to predict the outcome of three different catch limit scenarios 15 years into the future. We also employ the simpler SEG model to ensure that our estimates of biomass change are robust.

Despite evidence that commercial CPUE indices frequently fail to meet the assumption of constant proportionality to stock biomass (Harley et al. 2001), discussions at the RPA meeting concluded that the 4Xnopqu CPUE index more closely met this assumption than did the DFO RV trawl survey. The most common criticism of using CPUE indices is that they frequently suffer from “hyperstability”, which can lead to overestimation of biomass and an underestimation of the total level of biomass decline (Hilborn and Walters 1992). Hyperstability, however, may not be a factor due to cusk being a bycatch species, rather than the target species in the cod longline fishery. Unfortunately, no method was identified to test whether the index suffered from hyperstability; therefore, for this assessment, the CPUE is assumed to be proportional to stock biomass. Data are summarized in Table 1.

We also examine the DFO RV (SP.rv) and GoM (SP.GoM) trawl datasets using a SP model. Both datasets have been criticized for potentially suffering from hyperdepletion; however, this has not been quantitatively demonstrated and therefore both are modeled. We also combine the Sentinel and Halibut surveys in a single SP model (SP.h.s). Both surveys have relatively high cusk catch rates but unfortunately only started after the large declines occurred in the CPUE index and trawl surveys. These datasets were modeled to determine how much information regarding population parameters and trends in biomass could be obtained from these indices. This model is further extended to also include the RV trawl survey (SP.h.s.rv). A summary of model names, data used, and key model assumptions are contained in Table 2.

Population Projections

Projections were based on stochastic simulation (n=10 000) using fixed median parameter estimates derived from the SP.cpue model to project population biomass forward 15 years using Equation 1 under 3 management scenarios. A projection period of 15 years was chosen as this is the estimated generation time, defined as the age when 95% of cusk are mature, based on new aging data (S. Campana *unpublished data*). This is longer than the estimate for generation time of 9 years used in the COSEWIC assessment (COSEWIC 2003).

The first scenario estimated the reduction in mortality due to fishing needed to ensure a 75% chance of no further decline in cusk biomass after 15 years. The second and third scenarios estimated the reduction in fishing mortality to give a 75% chance of observing a biomass increase of at least 50% or doubling, respectively, after 15 years. Increases in biomass were relative to the 2007 median biomass estimate from the SP model.

No observation error or ability to detect changes in exploitable biomass was considered in the simulations (ie. observation error variance (τ^2), was not used).

Prior Distributions

Little is known about the life history, population dynamics or the catchability of cusk to the various survey methods or to the cod longline fishery. Consequently, we are unable to formulate informative priors for the intrinsic rate of population growth, r, in the SP model, or the common parameters for both models: catchability (q), or the observation and process error parameters. In the SP model, information from the landings data is incorporated in the model as a slightly informative prior on carrying capacity, K. Typically, K is set to the stock biomass in the year prior to the onset of fishing (B_0; Meyer and Millar 1999). We specified a uniform distribution for K with the lower boundary set to the maximum landings throughout the time series (5219 t) and an upper boundary of 500 000 t. The upper boundary is greater than reasonable predictions for K; however, it was used to ensure that some probability density would be present in unlikely, although possible estimates of K. Although this prior contained little information regarding the value of K, its purpose was to restrict the parameter search away from mathematically possible, but biologically implausible parameter combinations (eg. a high estimate for r coupled with an extremely low estimate for K that was less than the maximum recorded landings). Obviously, landings could not exceed the carrying capacity of the population; therefore, restricting the parameter space of K disallowed this ecologically impossible parameter combination.

We assumed that cusk biomass at the start of all time series was close to virgin biomass. This assumption may be realistic for the trawl surveys; however, we also used this assumption for the SP.cpue and SP.h.s models even though these datasets begin after declines had been observed in both trawl surveys. Although this assumption is unlikely, estimating, rather than specifying B_0, further increases confounding in the parameters (Hilborn and Walters 1992) which is already problematic due to the “one-way trip” trajectory and low contrast of the data. Therefore, estimates of absolute decline need to be viewed in the context of this assumption.

Marginal posterior distributions of model parameters and unobserved states were based on 250 000 iterations of two chains after discarding the first 200 000 iterations (burn-in). These 50 000 iterations were reduced to 2 000 by sampling every 25th value to avoid sample autocorrelation.

The priors used for the SP and SEG models are summarized in Tables 3 and 4, respectively.

RESULTS

Surplus Production Models

July to September 4Xnopqu Longline CPUE Index

The SP.cpue model showed a relatively steady decline over time with median fitted CPUE state estimates starting at a maximum of 1.65 t per trip in 1986 to 0.63 in 2007, a decline of 62% in 21 years (Figure 1). The poor contrast of the data yielded parameter estimates with large credible limits (Table 5). The model was able to separate process and observation error, with the latter being slightly larger although credible limits for both were relatively large. Upper credible limits of biomass estimates were higher than what is biologically reasonable (Figure 2) when compared to historical exploitable biomass estimates of other fish species such as cod in the 4X division (Clark and Hinze 2003). The comparison of posterior and prior distributions for the main parameters indicated that the data contained some information about each of these parameters (Figure 3). The estimate for r had a 95% credible interval of 0.007 – 0.730 and a median value of 0.173. The estimate for K had wide 95% credible interval of 9409 t to 125 201 t and a median value of 26 820 t. There was little sensitivity in estimates of decline to the assumption $B_0 = K$, although estimates of K and B_t were sensitive.

DFO RV Bottom Trawl Survey

Cusk catches in the DFO RV survey were low and variable throughout the time series. The maximum mean weight per tow was 2.8 kg in 1975, after which a steady, yet variable decline in the index was observed until 1992 where it stabilized at the low mean level of approximately 0.18 kg per tow. The index state estimates of the SP.rv model declined from a maximum of 2.5 kg in 1975 to 0.15 in 2007, a decline of 94% over 38 years (Figure 4). The estimated decline in the RV survey over the same time period of the 4Xnopqu CPUE index (1986 – 2007) was 55%. Similar to the biomass estimates of the SP.cpue models, the high level of uncertainty in K resulted in biomass state estimates with exceptionally large upper credible limits (Figure 5). The estimate for r has a 95% credible range of 0.009 – 0.562 and a median value of 0.158. The estimate for K also has wide 95% credible limits of 30 830 t – 359 708 t and a median value of 77 610 t (Table 6; Figure 6).

Combined Halibut and Sentinel Surveys

Both the Sentinel and Halibut surveys capture substantially more cusk than the trawl surveys. Indeed, the maximum mean catch per set for the Sentinel and Halibut surveys was 6.3 kg per 1500 hooks in 1997, and 19.2 kg per 1000 hooks in 2007, respectively, in comparison to the

DFO RV trawl survey during the same time period that had a maximum mean weight per tow of 0.24 kg.

Both time series began after the large declines observed in the RV trawl survey had occurred and displayed little variability over the span of their relatively short time series. The short time series and exceptionally poor contrast in the data provided insufficient information to estimate *r* and *K* reliably (Table 7). Consequently, the upper credible limits of the biomass estimates for the SP.h.s. model are large (Figures 7 and 8).

There was very little information about the *r* parameter in the data and the posterior exhibited a slight bimodal distribution (Figure 9). The SP.h.s. model predictions of the individual catchability coefficients, *q*, were, as expected, higher for the Halibut than the Sentinel survey.

Combined Halibut, Sentinel, and RV Surveys

The SP.h.s.rv model that combined the Halibut, Sentinel, and RV surveys was able to fit the data well (Figure 10); but similar to the other models, the upper credible limits of the biomass estimates were large (Table 8; Figure 11). The estimate *of r* was lower in comparison to the SP.h.s model but higher than the SP.rv model. Estimated catchability was largest for the Halibut and Sentinel surveys, and the RV survey catchability was the smallest.

The 95% credible interval for *r* was 0.047 – 0.799 with a median of 0.304 (Figure 12). The posterior for *K* has a 95% credible range of 22 709 t – 137 308 and a median value of 45 140 t.

Gulf of Maine Autumn Bottom Trawl Survey

Similar to the DFO RV survey, catches of cusk in the NEFSC GoM bottom trawl survey were low and variable throughout the time series. The maximum mean weight per tow was 3.1 kg in 1964, after which a relatively steady, yet variable decline in the index was observed until 1991, where it stabilized at the low mean level of approximately 0.31 kg per tow. The state estimates of the SP.GoM model declined 86% over 44 years from the maximum 1.4 kg in 1964 to 0.2 in 2005 (Figure 13). Similar to the SP.rv model, the high level of uncertainty in *K* resulted in the upper credible limits of the biomass state estimates to be exceptionally large (Figure 14).

The estimate for *r* has a 95% credible range of 0.004 – 0.521 and a median value of 0.100 (Table 9; Figure 15). The estimate for *K* also has wide 95% credible limits of 20 650 t – 399 300 t and a median value of 64 655 t.

Precision of the parameter estimates of all models, particularly estimates of carrying capacity, *K*, and the intrinsic rate of population growth, *r*, was limited due to the low contrast of all datasets that is a result of the “one-way trip” trajectory of the datasets.

Stochastic Exponential Growth Models

July – September 4Xnopqu Longline CPUE Index

The SEG.cpue1 model that used the 4Xnopqu CPUE data but did not include landings showed a decline similar in magnitude to the SP.cpue model over the span of the time series (Figure 16). The median estimate for μ was -0.055 with a 95% credible limit range of -0.124 – 0.022 (Table 10; Figure 17). The median CPUE state estimates showed a decline of 62% over 21 years from a starting CPUE of 1.64 t per trip in 1986, to 0.63 in 2007.

The SEG.cpue2 model that included landings also fit the data well (Figure 18). The median biomass state estimates were similar to the SEG.cpue1 model with a starting CPUE estimate of 1.52 t per trip in 1986, to 0.53 in 2007 predicting a total reduction in CPUE of 65% over the span of the time series. Including landings in the model had little effect on the process (σ) and observation (τ) error and the catchability parameter estimates; however, the rate of population increase parameter, μ, was positive and had a median estimate 0.042 and a 95% credible range from -0.033 – 0.149 (Table 11; Figure 19). The majority of the probability density of μ was greater than zero, suggesting that the stock would not have declined in the absence of fishing.

Biomass Projections

Stochastic simulation using median parameter estimates from the SP.cpue model was used to estimate the effect of different total annual catch limits on the probability of observing three different management outcomes after 15 years (1 generation) in 4X: (1) no further decline in exploitable biomass; (2) at least a 50% increase in exploitable biomass; and (3) at least a 100% increase in exploitable biomass. In all cases, projections assume that mortality not accounted for in the model (eg. bycatch in the lobster fishery) remains constant.

The projections suggest that total landings in 4X need to be reduced to 625 t in order to achieve a 75% chance of observing outcome 1, no further decline in exploitable biomass (Figure 20). Landings in 4X would have to be reduced to 200 t in order to achieve a 75% chance of observing outcome 2, at least a 50% increase in exploitable biomass. Outcome 3, at least a 100% increase in exploitable biomass, can only be obtained with 60% certainty if landings in 4X are reduced to 0 t.

DISCUSSION

Four important conclusions arise from the population models fit to the various indices of cusk biomass. First, a significant decline in cusk biomass is seen in the commercial CPUE index and the DFO and GoM trawl indices. Although the decline in the RV survey is 94% since its peak biomass in 1975, estimated declines in the RV and the CPUE index since 1986 (55 and 62% respectively) are comparable. Second, despite the potential biases in the trawl survey indices, all of the surplus production models fit to the different indices, with the exception of the model combining RV, halibut, and sentinel, yielded similar estimates of *r*. Third, the confounding between the *K*, *r* and *q* parameters in the surplus production models, which arises from the poor contrast in all indices due to the “one-way trip” trajectory of this stock (Hilborn and Walters 1992), results in large uncertainties associated with these estimates. This, in turn, makes it particularly difficult to provide precise population projections under different management scenarios. Lastly, the SEG model fit to the CPUE index suggests that fishing mortality is largely responsible for declines in the 4X cusk stock.

A central assumption to these analyses is that the indices are proportional to stock biomass. We use this assumption for the commercial longline CPUE index even though the index is focused on core distribution areas and therefore some hyperstability may be occurring, where biomass has declined more than the index suggests. Indeed, fish may be moving from suboptimal habitats (eg. trawlable areas) to preferred rocky habitat as the stock declines resulting in a slower decline in the CPUE index relative to the decline in total stock biomass. Strong hyperstability would explain why cusk are still regularly captured in the lobster fishery in spite of the stock decline. However, cusk are a bycatch species; therefore, there is the potential that hyperstability of the CPUE index may be slight or non-existent since hyperstability is also caused by fishers moving effort to areas of higher fish concentrations. Thus, hyperstability may not be an issue if cusk densities are not tightly associated with the distribution of cod. Unfortunately, there are insufficient data to test these hypotheses.

The large declines observed in the trawl surveys is cause for concern; however, the habitat preferences of cusk, and the prevalence of cusk in other fisheries suggests that the large decline observed in the trawl survey index may partially be due to hyperdepletion, where a subset of the stock is still in core distribution areas, and consequently the true decline may be less than estimated using these data. If this is the case, then the RV survey index would not meet the assumption of constant proportionality to biomass and a model using this assumption would give an exaggerated estimate of cusk decline. However, the hypothesis and scale of hyperdepletion cannot be tested at this time and therefore may not be occurring. Indeed, unregulated landings of cusk prior to 1999 closely follow the trend observed in the RV survey (Figure 21). This is somewhat surprising given the anecdotal information that prior to the imposed catch limits in 1999, landings of cod and other species were misreported as cusk thus biasing cusk landings upwards. These matching time series suggest that misreporting may have been minimal or fluctuated in proportion to cusk biomass.

The relatively short duration and low contrast of both the Halibut and Sentinel surveys provided little useful information to identify historically relevant trends since both time series begin well after the decline in the RV survey and 4Xnopqu commercial index had occurred. Furthermore, the exceptionally low contrast of the Halibut and Sentinel survey data yielded exceptionally poor parameter estimates from the SP.h.s model and had such large credible limits that they were not useful for population projections or deriving population parameters. Combining multiple surveys in a single model improved parameter estimates from what would have otherwise been achieved if the surveys were modeled by themselves. In retrospect, combining these surveys may not have been appropriate due to possible differences in cusk productivity between the two survey regions. Although no stock differentiation has been identified, approximately 76% of cusk landings have historically been from the 4X region where the majority of the Halibut surveys stations are located, in contrast to the Sentinel survey that samples exclusively the 4VsW division which accounts for slightly less than 10% of all landings. The differences between the two regions; however, may be due to differences in fishing effort rather than different cusk production rates.

Combing the RV survey with the Sentinel and Halibut surveys in a single model (SP.h.s.rv) decreased the uncertainty of parameter estimates; however, the RV survey was heavily weighted in the model due to the paucity of information on population parameters in both the Halibut and Sentinel surveys. Furthermore, the possibility of hyperdepletion in the RV survey and the potential productivity differences in the Halibut and Sentinel survey areas limits the value of this analysis.

The SEG.cpue models estimated biomass declines of similar magnitude to the SP.cpue model. The majority of the posterior density for the rate of population increase parameter, μ, for the model that included landing is an indication that the population has had positive growth rate over the period of decline which strongly suggests that the declines observed in the exploitable biomass of cusk are due to fishing activities.

Biomass Projections

The biomass projections indicate only relatively modest increases in biomass in the short term. Indeed, projections using the median parameter estimates from SP.cpue model predicted 75% chances of no further decline or a 50% increase or more in 4X if landing are reduced to 625 t or 200 t, respectively. From 2003 to 2006, cusk landings in 4X accounted for an average of 70% (60-79%) of the total reported cusk landings. If we assume that mortality and growth are similar across the entire management area, then cusk landings in 4VWX and 5Zc would be in the order of 1.43 times the landing limits estimated from the projection model. In this case, landing limits for the entire 4VSWZ5Zc area would need to be 894 and 286 t, respectively, to achieve either no further decline in biomass, or an increase of 50% or more, with 75% certainty. It is likely, however, that mortality and growth differ across the management area but we have insufficient data on cusk life history to test for spatial variation.

There is a high degree of uncertainty in our projections due to the limited amount of information regarding the population dynamics of cusk in the 4X longline fishery time series. The simplifying assumptions of the Schaeffer model (ie. constant r and K) do not explicitly account for the effects of age structure or lags in the biomass dynamics of the population. Furthermore, the projections do not include all of the uncertainty inherent in the parameter estimates since we used median parameter values rather than incorporating all of the uncertainty contained in the parameter posteriors. Confounding of the r and K parameters, however, results in small values of r associated with large values for K, and therefore, projections based on the extremes of both parameters (which we did not do) would give biased biomass projections. We also did not include observation error in our projections. Although observation error does not propagate through time and does not directly affect the biomass dynamics of the population, substantial observation error does limit our ability to track further population declines or signals of recovery (Maxwell and Jennings, 2005). The higher catch rates of the Sentinel and Halibut surveys may allow for more precise tracking of future population dynamics; however, these surveys may suffer from hyperstability by focusing on core distribution areas. Further research is required to delineate the relationship between cusk biomass and these survey indices.

The r parameter in the SP models combines recruitment, growth, and natural mortality into a single parameter. However, if all mortality from fishing is not accounted for in the landing statistics, the r parameter will also include unaccounted fishing mortality. For example, we are aware that there is unaccounted mortality from the lobster fishery (L. Harris *personal communication*) and discards at sea that are unreported. There are currently no estimates of cusk mortality caused by the lobster fishery or fishery discards levels throughout the entire range of cusk. Further biomass declines are possible if either of these sources of mortality substantially increase.

Future Work

The fishery dependent longline index should be further examined to ensure that bias has not been introduced from historical misreporting and/or imposed management measures, and determine whether it suffers from hyperstability. In addition, the level of hyperdepletion of the RV survey needs to be quantified if it is going to be discarded due to presumed proportionality issues. If the RV survey is not proportional to stock biomass, but the relationship between the survey and biomass can be quantified, the RV and the longline CPUE index could be combined in a single model potentially allowing more precise parameter estimates. Further work is required to identify and estimate significant sources of mortality (eg. lobster fishery and unreported discards) in order to obtain better estimates of population parameters. Furthermore, parameter estimates may be improved by adding informative priors derived through demographic methods (McAllister et al. 2001); however, the value of this approach is currently limited due to the lack of substantial information on the life history and natural mortality rate for cusk. Consequently, we recommend that concerted effort be made to gather more data on length at age, growth and maturity for cusk.

CONCLUSIONS

Regardless of the model used or the data employed, large declines (55 – 95%) were consistently estimated from the fishery dependent and fishery independent data. Declines in cusk biomass were estimated using the 4Xnopqu longline, the DFO RV, and the NEFSC GoM bottom trawl indices with a SP model. The results of the SP model, fit to the commercial longline data, were also corroborated by a SEG model. The Halibut and Sentinel surveys were of insufficient length and contrast to identify trends in exploitable biomass in a useful historical context. The apparent "one-way trip" trajectory of cusk biomass and relatively low contrast of the datasets resulted in parameter estimates with significant levels of uncertainty, particularly for the *K* parameter of the SP model. Consequently, our estimates of biomass have high levels of uncertainty with large credible limits. The lack of precise estimates of past and current levels of biomass limits our ability to obtain robust estimates of overall stock decline. However, the consistent finding from examining all the useful datasets is that cusk have undergone significant decline over at least the past 20 years.

Collection of age-disaggregated data would allow more realistic stage-structured models to be fit that could better account for various time delays and changes in population structure associated with growth and recruitment. This would also allow more refined management strategies to be evaluated that could include gear or area restrictions that could aid in population recovery. However, the extremely low catchability of young cusk to both trawl and longline gear will limit the application of stage structured models. If age disaggregate data are collected, it is of critical importance to conduct an age-validation study to determine whether the generation time and maximum age of cusk is 15 and greater than 40 years, respectively as suggested by recent radiocarbon bomb dating (S. Campana *personal communication*) or 9 and 20 years as reported in the literature (COSEWIC 2003).

The biomass projections suggest that the current landings cap of 750 t for 4VWX5Zc may be sufficient to stop the decline in cusk biomass but is unlikely to result in stock rebuilding. In order for the landings cap to be an effective strategy, reducing landings must result in decreased fishing mortality. This may not be occurring as limits on landings may simply be increasing unreported discards, and thus have very little impact on reducing the fishing mortality of cusk. If this is the case, reducing landings further will have little or no impact on improving stock biomass. Better quantification of fishery-induced mortality could be achieved with more effective observer coverage to account for unreported discarding. Better estimates of fishing mortality would help increase the certainty of biomass and parameter estimates and allow for the development of management strategies with more certain outcomes.

ACKNOWLEDGMENTS

We thank Lei Harris, Peter Comeau, and Jim Simon for information on cusk biology and help with data extraction. Coilìn Minto, Stephen Smith, and Kurtis Trzcinski provided helpful suggestions on the modelling.

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APPENDICES

Appendix 1: Script for WinBUGS version of Surplus Production (SP) Model

```
model;
{
# Prior for intrinsic rate of increase; r
r ~ dunif(0, 4)

# Prior for carrying capacity K
logK ~ dunif(8.56, 13.12)
K <- exp(logK)

# Priors for catchabilities; q
q ~ dunif(0, 1)

# Prior for process noise; sigma
sigma ~ dunif(0, 10)
isigma2 <- pow(sigma, -2)

# Prior for observation errors; tau
tau ~ dunif(0, 10)
itau2 <- pow(tau, -2)

# Prior for initial population size as proportion of K; P[1]
Pmed[1] <- log(1)

P[1] ~ dlnorm(Pmed[1], isigma2)I(0.001, 10)

# State equation
for(t in 2:T) {
        Pmed[t] <- log(max(P[t-1] + r * P[t-1] * (1 - P[t-1]) - C[t-1] / K, 0.0001))
        P[t] ~ dlnorm(Pmed[t], isigma2)I(0.01, 10)
        }

# Observation equation
for (t in 1:T) {
        Imed[t] <- log(q * K * P[t])
        I[t] ~ dlnorm(Imed[t], itau2)
        }

# Output
for(t in 1:T) {
        B[t] <- P[t] * K
        }
}       ## END

### INITIALIZATION VALUES
# list(list(q = 0.00001, r =0.1, sigma = runif(1,0,1), tau =runif(1, 0, 1), P = rep(1, data$T), logK =
log(80000)), list(q = 0.000005, r = 0.08, sigma = runif(1,0,1), tau = runif(1, 0,1), P = rep(1, data$T), logK
=log(100000)))
```

Appendix 2: Script for WinBUGS version of Stochastic Exponential Growth (SEG) Model

```
model;
{
# K is a scaling constant for more efficient sampling
K <- exp(11)

# Prior for drift term; mu
mu ~ dnorm(0, 0.000001)

# Priors for catchability; q
q ~ dunif(0, 1)

# Prior for process noise; sigma
sigma ~ dunif(0, 10)
isigma2 <- pow(sigma, -2)

# Prior for observation error; tau
tau ~ dunif(0, 10)
itau2 <- pow(tau, -2)

# Prior for initial population size; n[1]
P[1] ~ dlnorm(0, isigma2)I(0.0001, 10)

# State equation
for (t in 2:T) {
        Pmed[t] <- log(max(P[t-1] * exp(mu), 0.0001))
        P[t] ~ dlnorm(Pmed[t], isigma2)I(0.0001, 10)
        }

# Observation equation
for (t in 1:T) {
        Imed[t] <- log(q * K * P[t])
        I[t] ~ dlnorm(Imed[t], itau2)
        }

# Output
for(t in 1:T){
        B[t] <- P[t] * K
        }
}       ## END

### INITIALIZATION VALUES
# inits <- list(list(q = 0.00001, mu = 0, sigma = runif(1,0,1), tau = runif(1, 0, 1), P = rep(1, data$T)),list(q =
0.0001, mu = 0, sigma = runif(1,0,1), tau = runif(1, 0, 1), P = rep(1, data$T)))
```

Table 1. Catch of cusk per unit effort (tons/trip) caught by the longline fishery in 4Xnopqu by vessels in tonnage classes 2 and 3 restricted to July – September each quota year.

Quota year	CPUE (t / trip)	Catch (t)
1986	1.576	1639
1987	1.873	3154
1988	1.266	2279
1989	1.117	2304
1990	1.143	2448
1991	1.978	3125
1992	1.676	3678
1993	0.895	2039
1994	0.580	1207
1995	1.135	1530
1996	0.765	1044
1997	1.124	1476
1998	1.012	1304
1999	0.612	880
2000	0.696	732
2001	0.986	1043
2002	0.650	872
2003	0.443	688
2004	0.687	492
2005	0.572	632
2006	0.413	601
2007	0.683	

Table 2. Summary of names, data used and key identifying assumptions of models summarized in this document.

Model	Data	Identifying model assumptions
SP.cpue	• 4Xnopqu longline index (1986 – 2007) • 4X landings data (1986 – 2007)	B_0 = LN(K,σ^2)
SP.rv	• DFO RV trawl survey (1970 – 2007) • 4X landings data (1970 – 2007)	Single survey only
SP.h.s	• 4VWX Halibut survey (1998 – 2007) • 4VsW Sentinel survey (1995 – 2003) • 4VWX landings data (1995 – 2007)	Halibut and Sentinel surveys combined
SP.h.s.rv	• DFO RV trawl survey (1970 – 2007) • 4VsW Sentinel survey (1995 – 2003) • 4VWX Halibut survey (1998 – 2007) • 4VWX landings data (1970 – 2007)	Halibut, Sentinel, and RV surveys combined
SP.GoM	• Gulf of Maine trawl survey (1964 – 2005) • Gulf of Maine landings data (1964 – 2005)	Gulf of Maine survey only
SEG.cpue1	• 4Xnopqu longline index (1986 – 2007)	Catches not included
SEG.cpue2	• 4Xnopqu longline index (1986 – 2007) • 4X landings data (1986 – 2007)	Catches included

Table 3. Prior probability density functions for parameters for surplus production model(s). Separate priors were specified for observation error (τ) and catchability (q) parameters where multiple biomass indexes were used in a model.

Parameter (model)	Prior
K	U(5219,500 000)
r	U(0,4)
σ	U(0, 10)
$\tau_{1:n}$	U(0, 10)
$q_{1:n}$	U(0,1)
B_0 (SP.cpue)	LN(K, σ^2)

Table 4. Prior probability density functions for parameters for stochastic exponential growth model(s).

Parameter	Prior
μ	N(0,1000)
σ	U(0, 10)
τ	U(0, 10)
q	U(0,1)
B_0	LN(K, σ^2)

Table 5. Median and 95% credible limits for the surplus production model using the July-September 4Xnopqu longline CPUE index and landings from the 4X NAFO area (SP.cpue). The DIC for this model is -47.8.

Parameter	0.025	median	0.975
K	9409	26820	125201
r	0.007	0.173	0.730
σ	0.012	0.209	0.481
τ	0.022	0.233	0.389
q	1.0×10^{-5}	6.2×10^{-5}	2.1×10^{-4}

Table 6. Median and 95% credible limits for the surplus production model (SP.rv) using DFO bottom trawl RV survey (1970 – 2007).

Parameter	0.025	median	0.975
K	30830	77610	359708
r	0.009	0.158	0.562
σ	0.147	0.345	0.615
τ	0.110	0.337	0.511
q	4.8×10^{-9}	2.4×10^{-8}	6.9×10^{-8}

Table 7. Median and 95% credible limits for the surplus production model (SP.h.s) that combined the Sentinel survey (1995 – 2003), Halibut survey (1998 – 2006), and landings data (1970 – 2006).

Parameter	0.025	median	0.975
K	5628	15045	74084
r	0.150	1.29	2.83
σ	0.006	0.121	0.514
τ_2: Sentinel	0.188	0.390	0.824
τ_3: Halibut	0.108	0.295	0.614
q_2: Sentinel	1.0×10^{-7}	4.7×10^{-7}	1.1×10^{-6}
q_3: Halibut	4.1×10^{-7}	1.8×10^{-6}	4.6×10^{-6}

Table 8. Median and 95% credible limits for the surplus production model (SP.h.s.rv) that combined the DFO summer RV bottom trawl (1970 – 2007), Sentinel (1995 – 2003) and Halibut surveys (1998 – 2006), and landings data (1970 – 2006).

Parameter	0.025	median	0.975
K	22709	45140	137308
r	0.047	0.304	0.799
σ	0.154	0.283	0.464
τ_1: RV	0.269	0.373	0.519
τ_2: Sentinel	0.194	0.357	0.714
τ_3: Halibut	0.160	0.314	0.607
q_1: RV	2.0×10^{-8}	5.0×10^{-8}	1.1×10^{-7}
q_2: Sentinel	3.5×10^{-7}	1.0×10^{-6}	2.3×10^{-6}
q_3: Halibut	1.6×10^{-6}	4.4×10^{-6}	1.0×10^{-5}

Table 9. Median and 95% credible limits for the surplus production model (SP.GoM) using the Gulf of Maine autumn trawl survey index (1964 – 2005).

Parameter	0.025	median	0.975
K	20650	64655	399300
r	0.004	0.100	0.521
σ	0.025	0.217	0.588
τ	0.410	0.595	0.782
q	4.0×10^{-9}	2.4×10^{-8}	8.3×10^{-8}

Table 10. Median and 95% credible limits for the stochastic exponential growth model (SEG.cpue1) using the July – September 4X longline CPUE index (1986 – 2007). Landings were not included in this model.

Parameter	0.025	Median	0.975
μ	-0.124	-0.055	0.022
σ	0.006	0.076	0.407
τ	0.103	0.277	0.410
q	1.9×10^{-5}	2.8×10^{-5}	4.5×10^{-5}

Table 11. Median and 95% credible limits for the stochastic exponential growth model (SEG.cpue2) that included the July – September 4X longline CPUE index (1986 – 2007) and landings (1986 – 2006).

Parameter	0.025	Median	0.975
μ	-0.033	0.042	0.149
σ	0.004	0.086	0.425
τ	0.110	0.286	0.426
q	1.6×10^{-5}	2.5×10^{-5}	3.7×10^{-5}

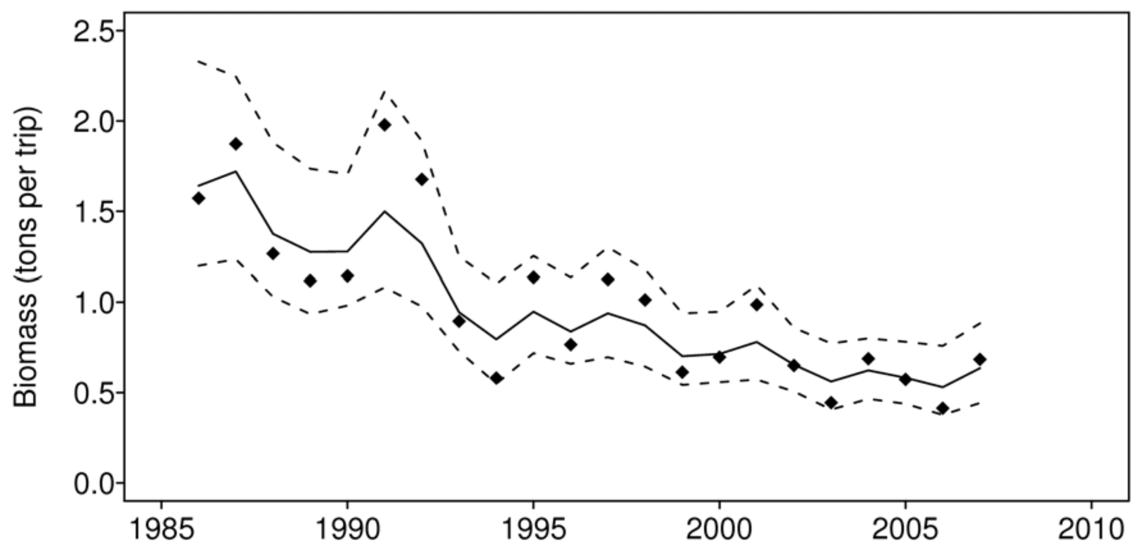

Figure 1. Surplus production model fits to CPUE data (◆) from 4Xnopqu longline fishery restricted to July – September. Solid lines represent median, and dashed lines are 95% credible limits of state estimates.

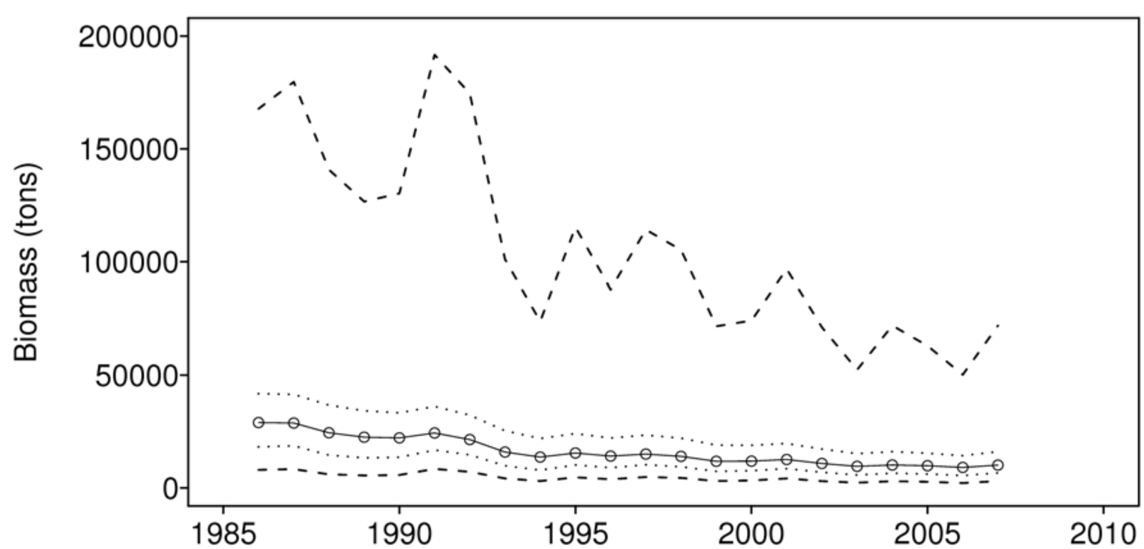

Figure 2. Biomass state estimates from the surplus production model using CPUE data from 4Xnopqu longline fishery restricted to July – September. Black solid line with open circles, and dotted and dashed lines are median, 50 and 95% credible limits, respectively.

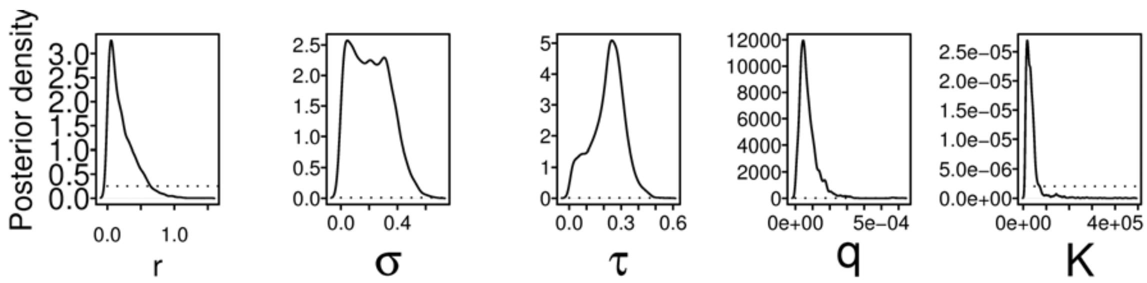

Figure 3. Prior (dotted line) and posterior (black line) density plots for select model parameters for surplus production model using CPUE data from 4Xnopqu longline fishery restricted to July – September.

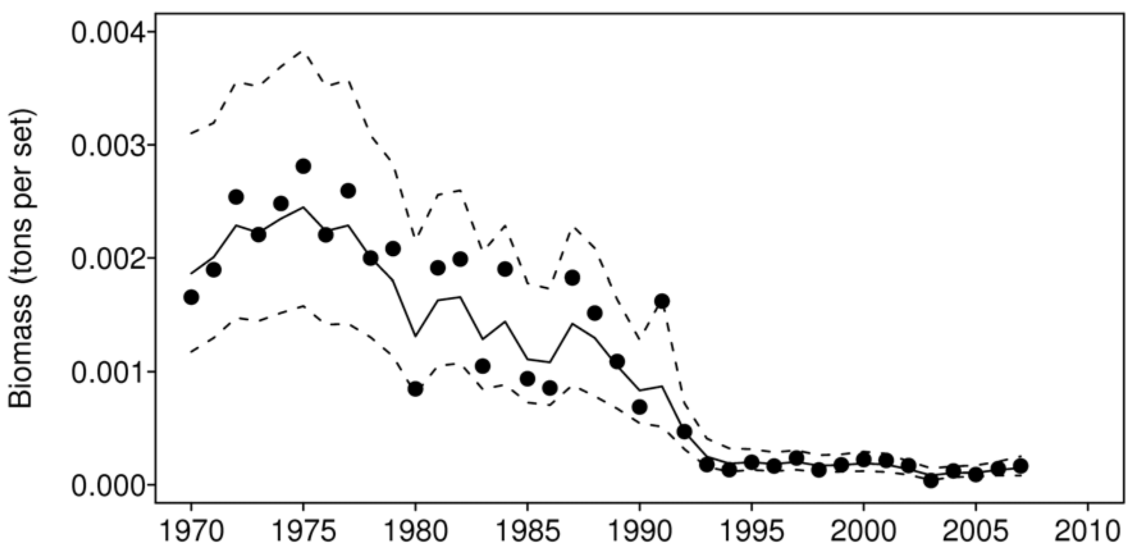

Figure 4. Surplus production model fits to the DFO RV summer trawl survey (●). Solid line and dashed lines are median and 95% credible limits, respectively.

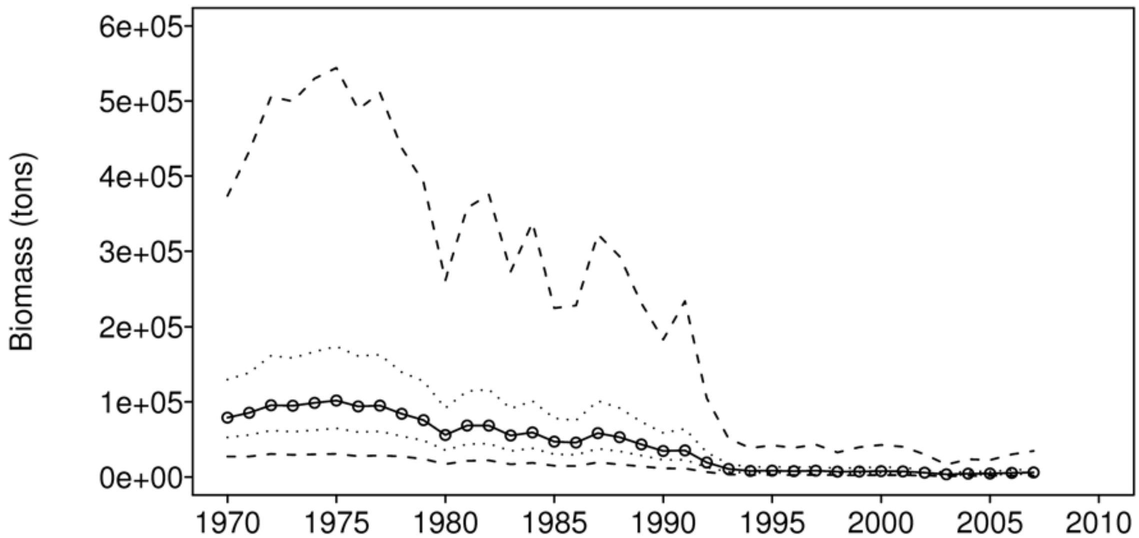

Figure 5. Biomass state estimates of the surplus production model using the DFO RV summer trawl survey data. Black solid line with open circles, and dotted and dashed lines are median, 50 and 95% credible limits, respectively.

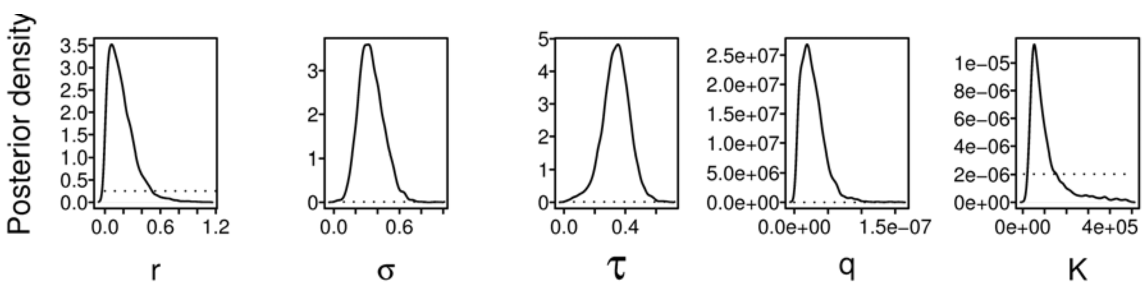

Figure 6. Prior (dotted line) and posterior (black line) density plots for select model parameters for surplus production model using RV trawl data.

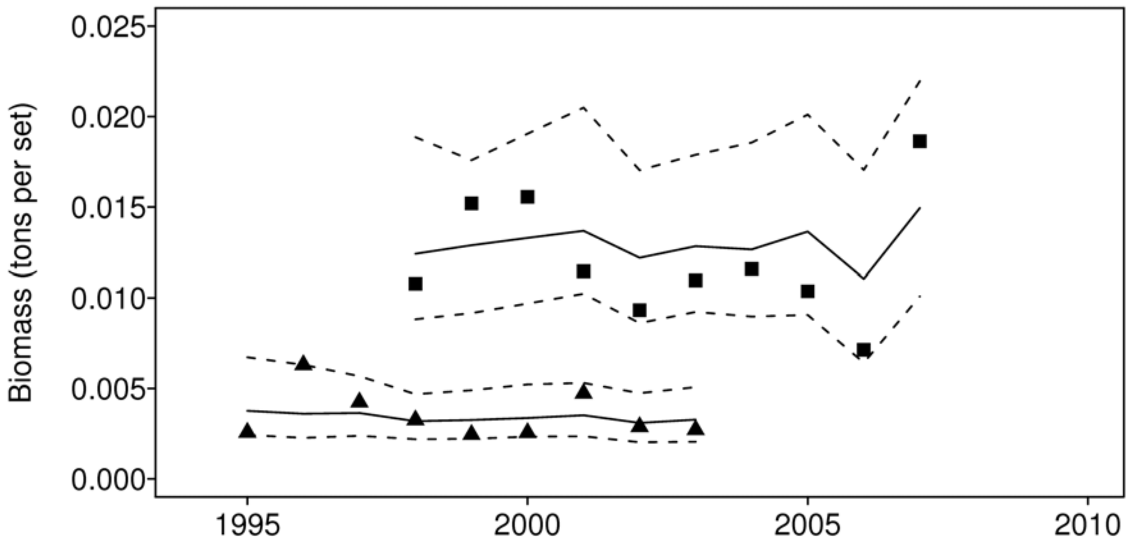

Figure 7. Surplus production models fits to Sentinel (▲) and Halibut (■) longline surveys. Solid lines represent median, and dashed lines are 95% credible limits of state estimates.

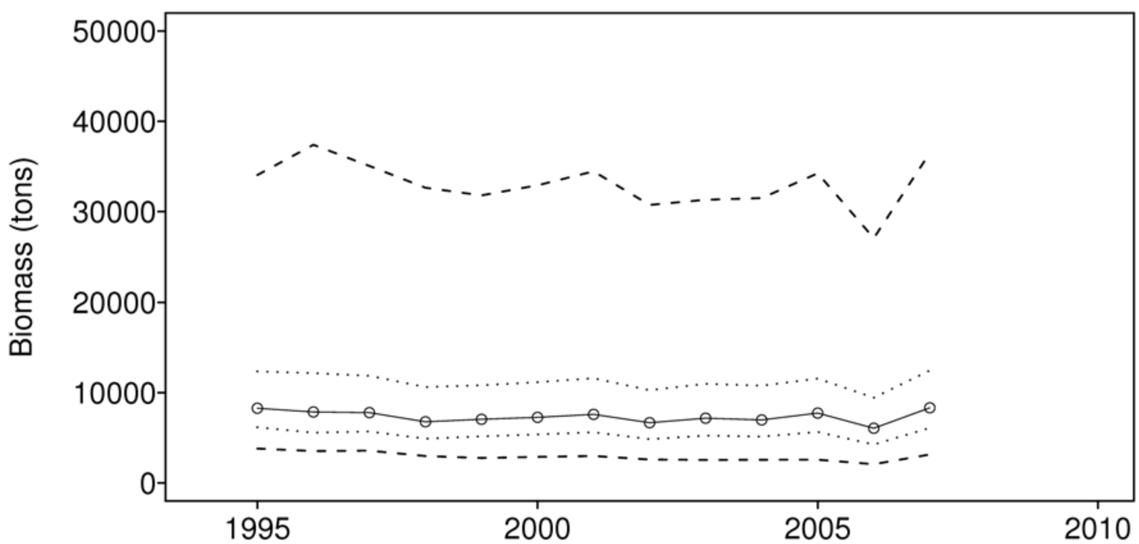

Figure 8. Biomass estimates from the surplus production model incorporating and Sentinel and Halibut longline surveys. Black solid line with open circles, and dotted and dashed lines are median, 50 and 95% credible limits, respectively.

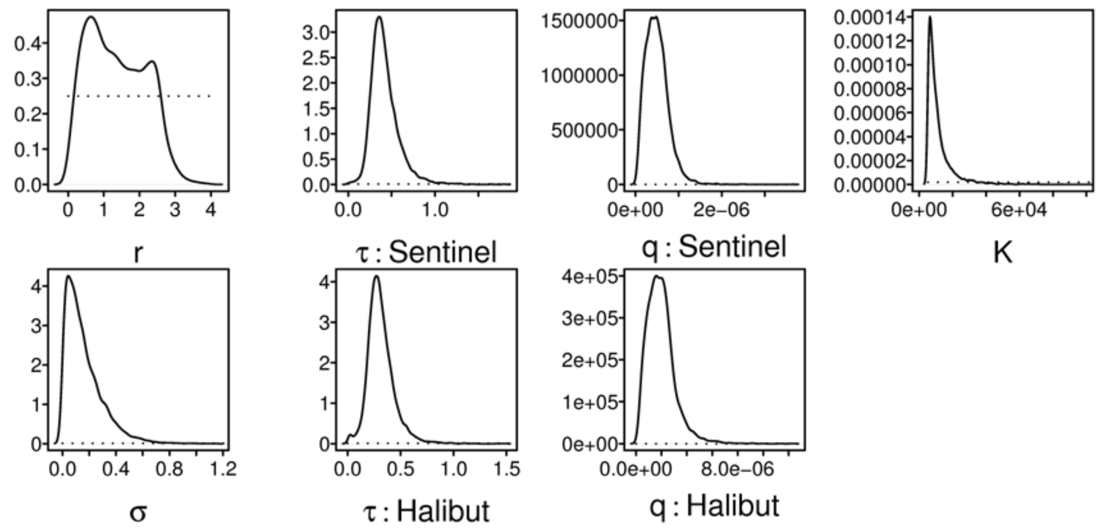

Figure 9. Prior (dotted line) and posterior (black line) density plots for select model parameters for surplus production model using sentinel and halibut survey only.

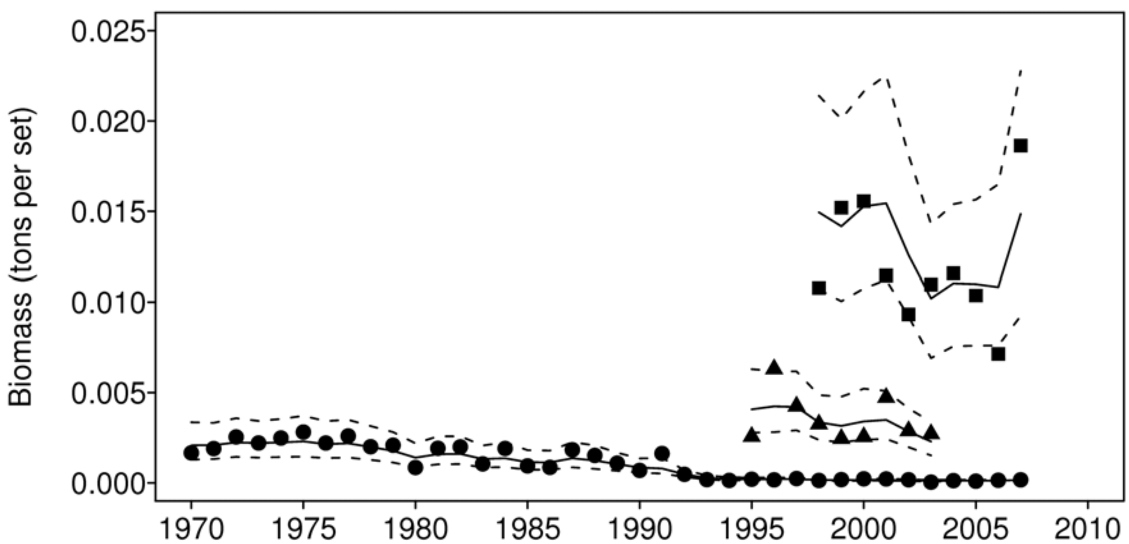

Figure 10. Surplus production model fits to the DFO RV trawl (●) and Sentinel (▲) and Halibut (■) longline surveys. Solid lines represent median, and dashed lines are 95% credible limits of state estimates.

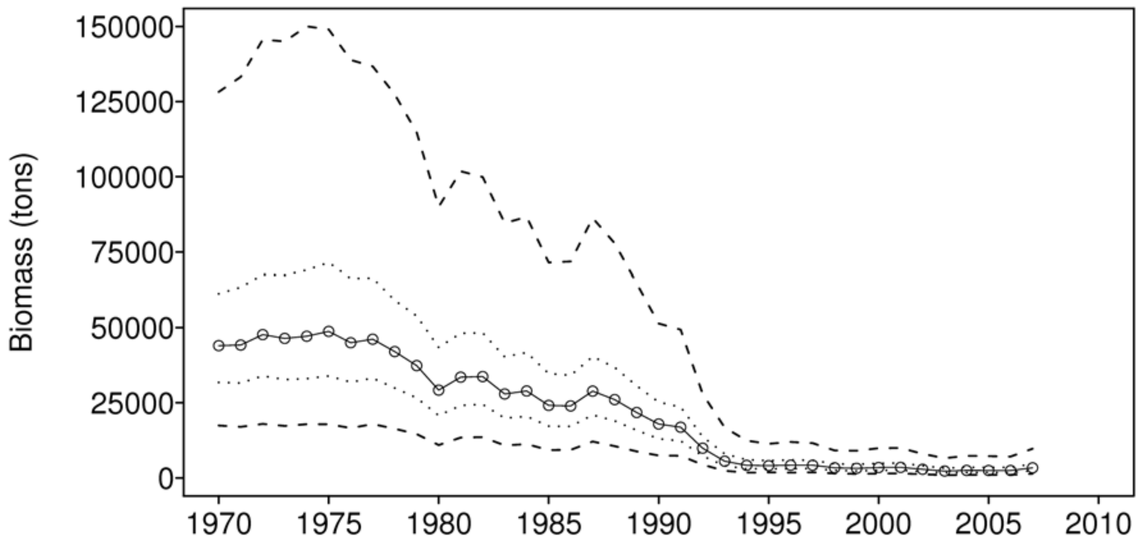

Figure 11. Biomass estimates from the surplus production model incorporating RV trawl, and sentinel and halibut longline surveys. Black solid line with open circles, and dotted and dashed lines are median, 50 and 95% credible limits, respectively.

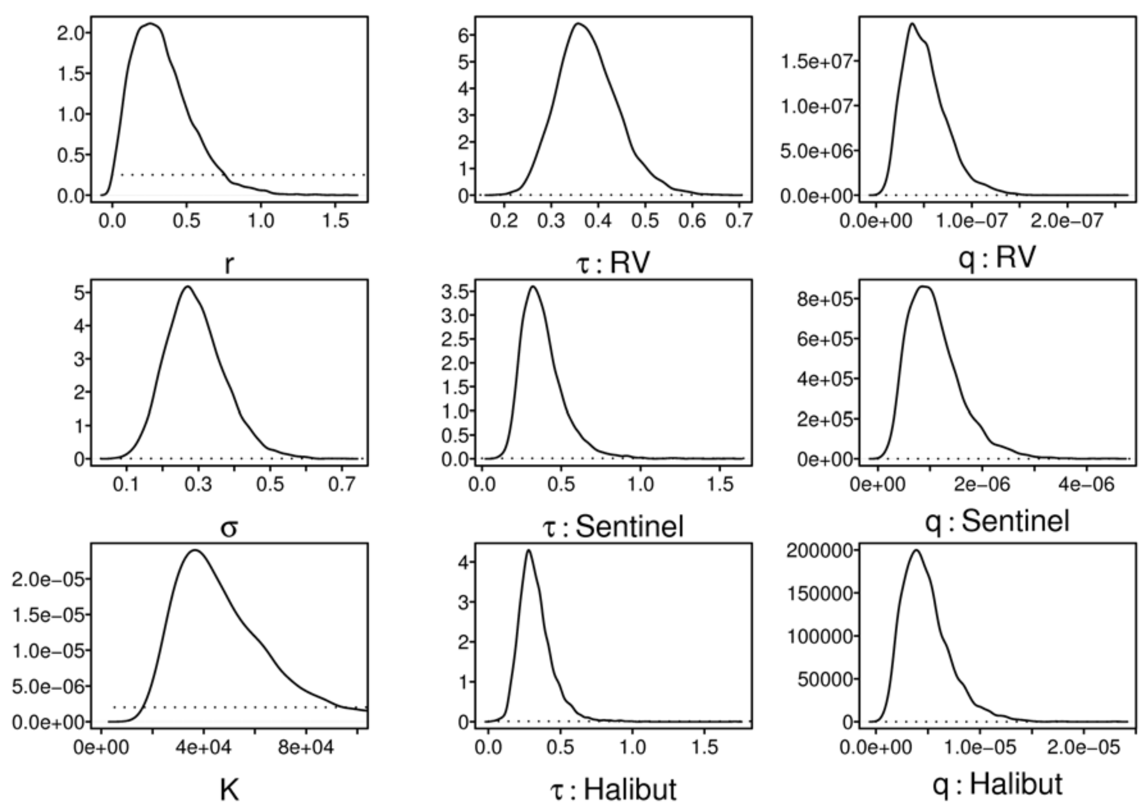

Figure 12. Prior (dotted line) and posterior (black line) density plots for select model parameters for surplus production model incorporating DFO RV trawl, and Sentinel and Halibut longline surveys.

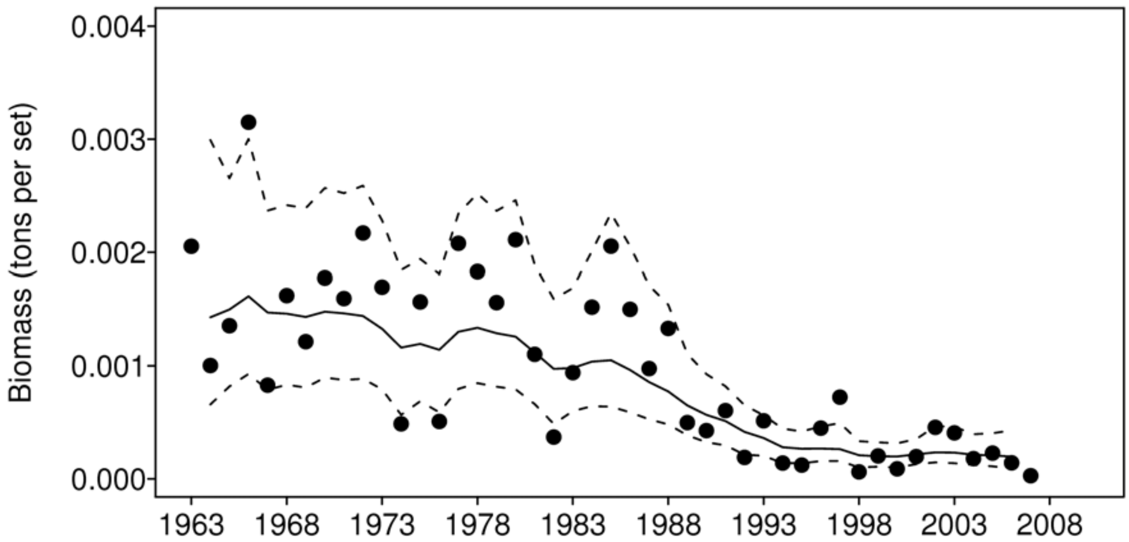

Figure 13. Surplus production model fits to the GoM trawl survey (●). Solid line and dashed lines are median and 95% credible limits, respectively.

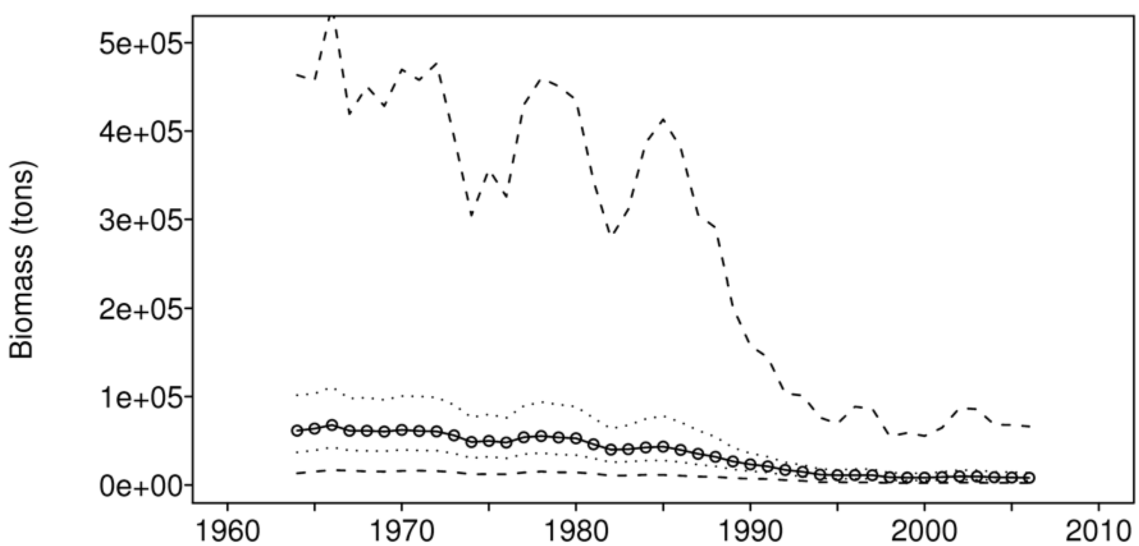

Figure 14. Biomass estimates from the surplus production model using the GoM trawl data. Black solid line with open circles, and dotted and dashed lines are median, 50 and 95% credible limits, respectively.

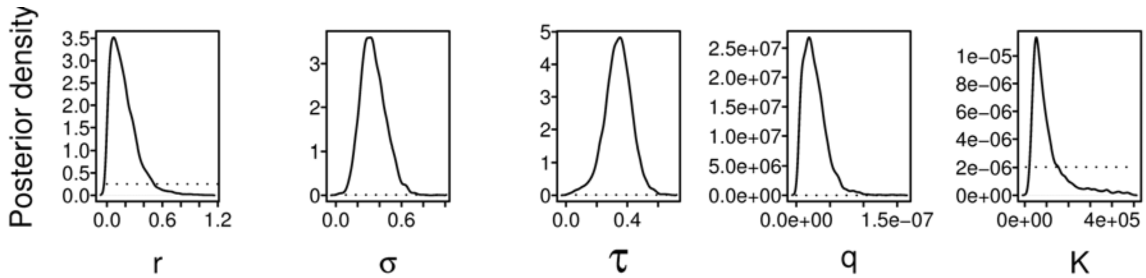

Figure 15. Prior (dotted line) and posterior (black line) density plots for select model parameters for surplus production model using GoM trawl data.

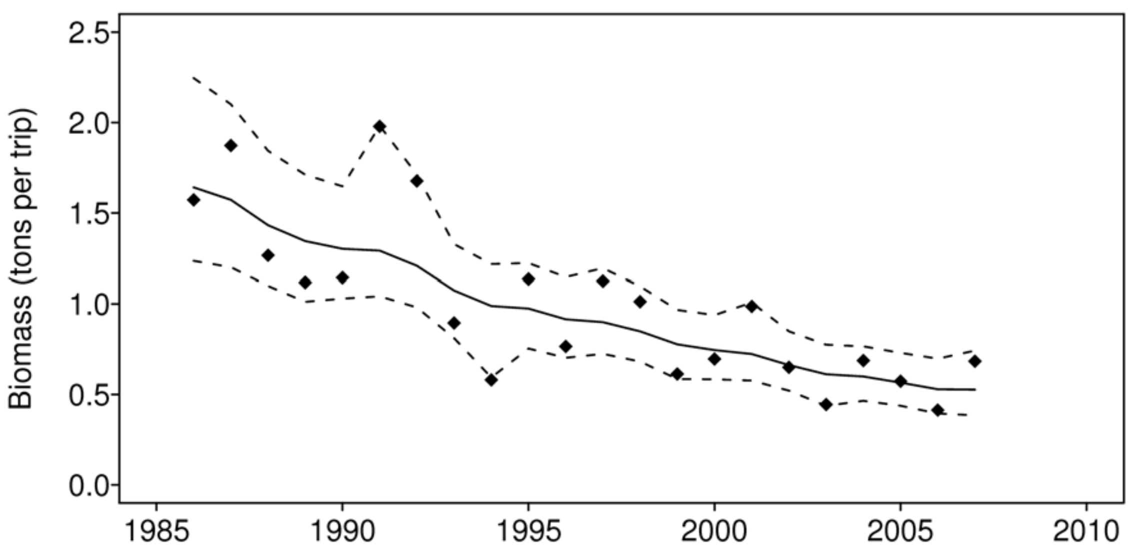

Figure 16. Model fits of stochastic exponential growth model to CPUE data (◆) from 4Xnopqu longline fishery restricted to July – September but not incorporating landings data. Solid lines represent median, and dashed lines are 95% credible limits of state estimates.

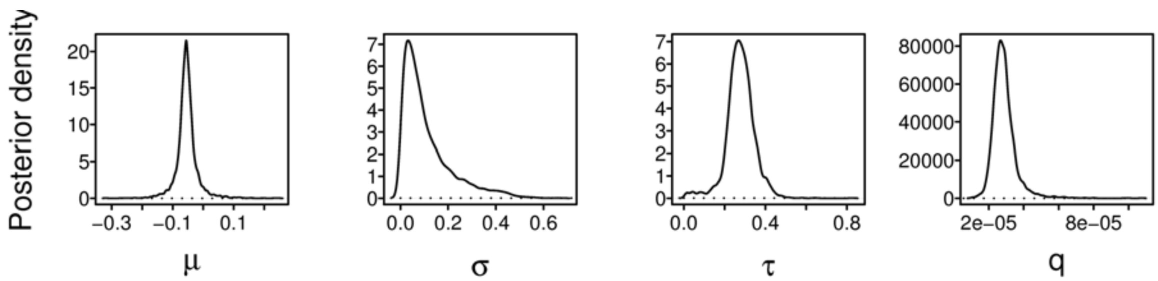

Figure 17. Prior (dotted line) and posterior (black line) density plots for select model parameters for stochastic exponential growth model using CPUE data from 4Xnopqu longline fishery restricted to July – September without incorporating landings data.

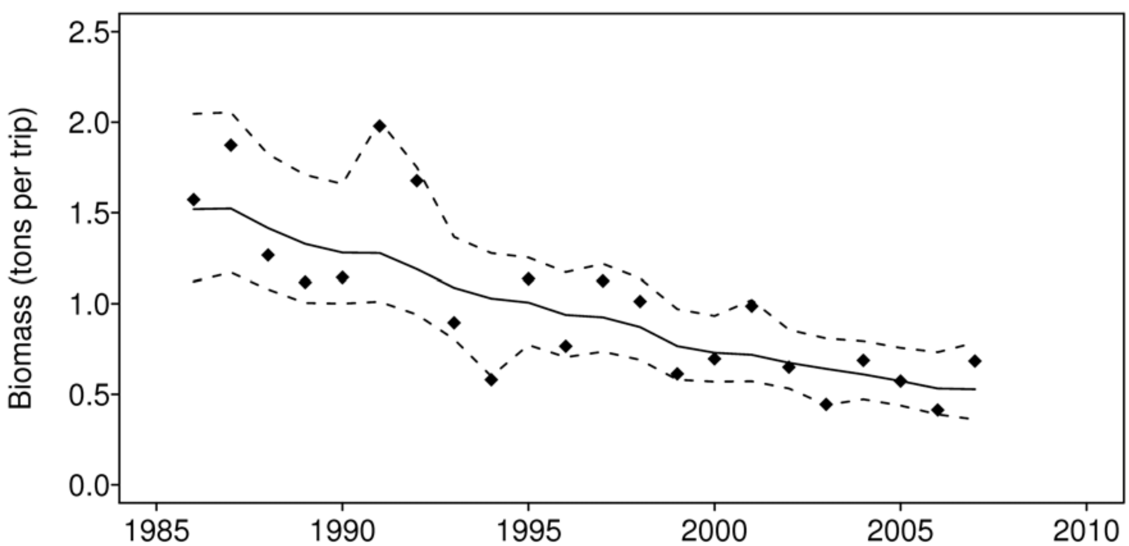

Figure 18. Model fits of stochastic exponential growth model to CPUE data (◆) from 4Xnopqu longline fishery restricted to July – September including landings data. Solid lines represent median, and dashed lines are 95% credible limits of state estimates.

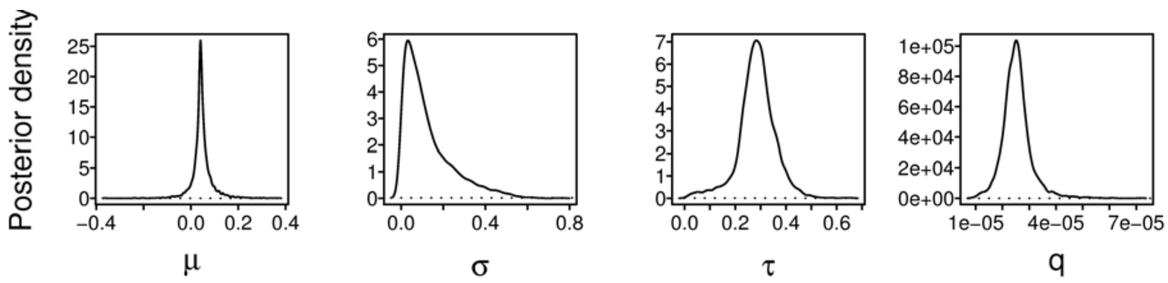

Figure 19. Prior (dotted line) and posterior (black line) density plots for select model parameters for stochastic exponential growth model using CPUE data from 4Xnopqu longline fishery restricted to July – September including landings data.

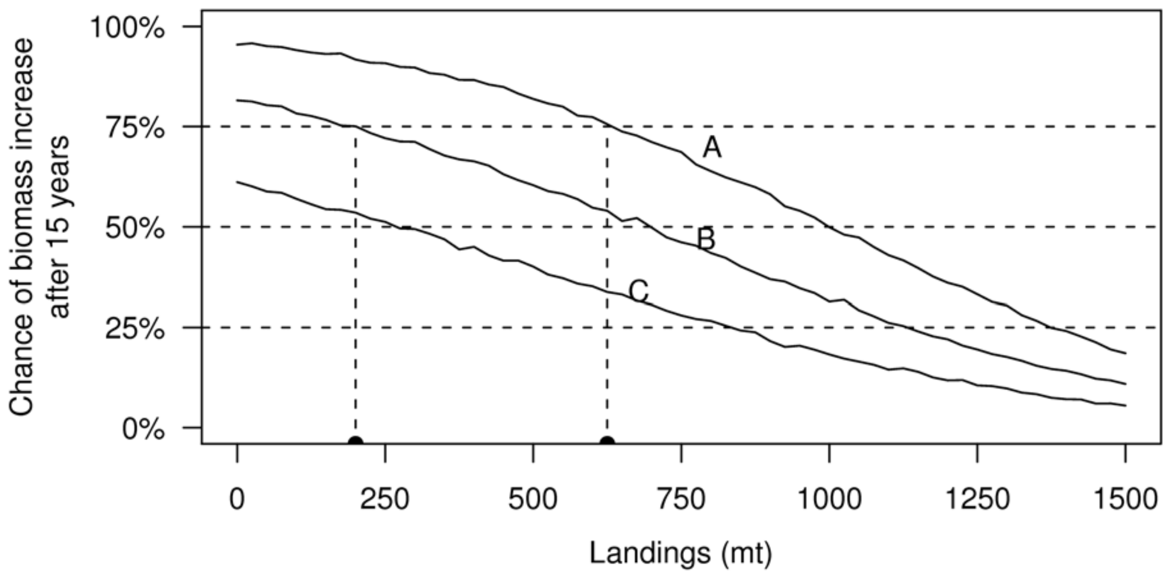

Figure 20. Forecasts of cusk recovery scenarios after 15 years (1 generation). Forecast results are presented as the probability of (A) no further decline in biomass, (B) at least a 50% increase in biomass and (C) at least a 100% increase in biomass. For example, in order to obtain a 75% chance of obtaining at least a 50% increase in biomass, landings would have to be reduced to 200 t. These forecasts assume that unreported bycatch and discards remain constant over the 15 year period. Forecasts based on median parameter values from 4Xnopqu SP model (Table 3).

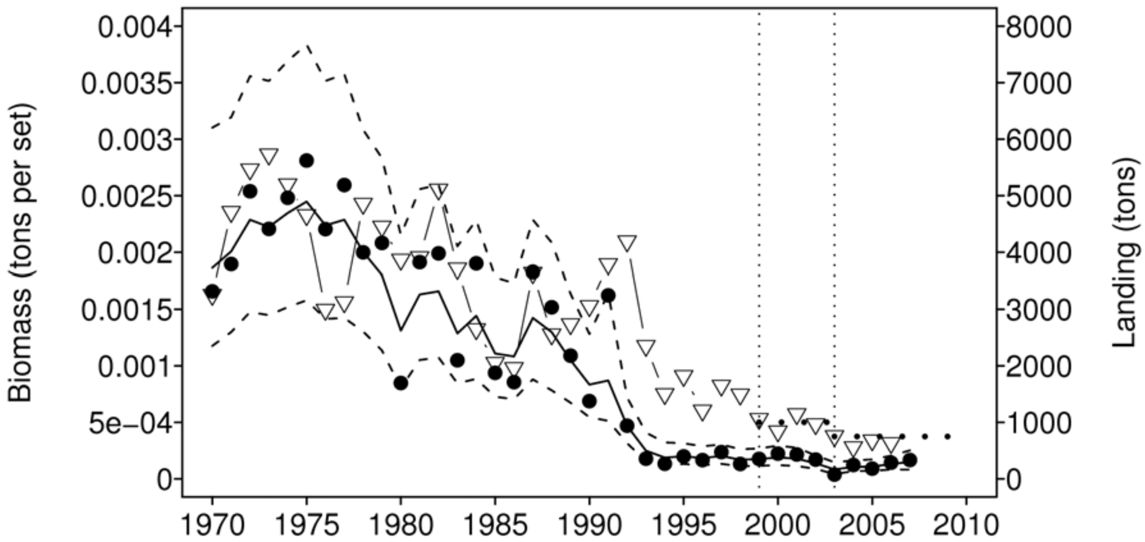

Figure 21. Plot of landings (▽) and RV survey data (●) and surplus production model fit to the RV trawl survey data. Solid line is the median and dashed lines are 95% credible limits of model fit, respectively. Dotted lines identify landing caps of 1000 t, and 750 t imposed 1999 and 2003 respectively.