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Bayesian State Space Biomass Dynamic Modelling and Assessment of 4VWX Silver Hake 1993-2012

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Foreword

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ABSTRACT

The population dynamics of Northwest Atlantic Fisheries Organization division 4VWX silver hake (*Merluccius bilinearis*) was examined using a logistic biomass dynamic model with parameters estimated through a Bayesian state space framework. Due to changes in both the population dynamics and fishery distribution the time series was truncated to 1992-2012. The modelled biomass was projected one and two years ahead under a range of landings scenarios including (0, 9.89 12,15,18, 45.1 t = F_{MSY}). To provide further context on the status of the population, several additional indicators, including age structure, recruitment levels, fish condition and habitat use were provided. Furthermore, simple correlation analyses were performed to relate recruitment, fish condition and bottom temperatures.

Overall, 4VWX silver hake are currently at the highest biomasses estimated throughout the 1993:2012 time block. Biomass has increased over the past ten years and has been high and relatively stable for the last four years. Fishing mortality has decreased over the past five years and is currently at the lowest level in the last twenty years. Biomasses are projected to be lower in 2013 than in 2012 under all total allowable catch scenarios examined. In 2013 and 2014, the probability that biomass will fall below 80% of B_{MSY} was 0.1 and 0.15, respectively. There is evidence of a strong 2009 year class which has shown up in both the 2010 and 2011 summer research vessel surveys, and has likely made a significant contribution to the fishery landings in each of 2011 and 2012. There were some interesting correlations between environmental variables, habitat preferences and biological characteristics, which may prove useful in describing some population characteristics and should be examined more closely in future silver hake assessments. Furthermore, the model used here was an aggregated biomass model which does not fully capture the dynamics of a species, such as silver hake, which has sporadic recruitment events. It is suggested that age or stage disaggregated models continue to be explored for future assessments.

Évaluation et modélisation de la dynamique de la biomasse du modèle bayésien de type état-espace pour le merlu argenté de 4VWX de 1993 à 2012

RÉSUMÉ

La dynamique des populations du merlu argenté (*Merluccius bilinearis*) de la division 4VWX de l'Organisation des pêches de l'Atlantique Nord-Ouest a été examinée à l'aide du modèle logistique dynamique de la biomasse et des paramètres estimés dans un cadre d'évaluation bayésienne de type état-espace. En raison des changements de la dynamique des populations et de la distribution des pêches, la série chronologique a été limitée à 1992-2012. La biomasse modélisée a été projetée sur une ou deux années conformément à un éventail de scénarios de débarquements, y compris (0; 9,89; 12;15; 18; 45,1 t = F_{RMS}). Pour approfondir le contexte de l'état de la population, plusieurs indicateurs supplémentaires, y compris la structure d'âge, les niveaux de recrutement, la condition des poissons et l'utilisation de l'habitat, ont été fournis. De plus, des analyses de corrélation simples ont été menées pour faire état du recrutement, de la condition des poissons et des températures au fond.

En général, la biomasse du merlu argenté de la division 4VWX est actuellement au niveau estimé le plus élevé dans la tranche de temps 1993-2012. La biomasse a augmenté au cours des dix dernières années et s'est avérée élevée et relativement stable pour les quatre dernières années. La mortalité par pêche a diminué au cours des cinq dernières années et elle est actuellement à son niveau le plus faible depuis 20 ans. On s'attend à ce que la biomasse soit moins élevée en 2013 qu'en 2012, en fonction des scénarios de total autorisé des captures examinés. En 2013 et en 2014, la probabilité d'une chute de la biomasse en dessous de 80 % du B_{RMS} était de 0,1 et de 0,15, respectivement. Des preuves portent à croire que la classe d'âge de 2009 était solide, selon les relevés estivaux des navires scientifiques de 2010 et de 2011, et elle a probablement contribué grandement aux débarquements de pêche en 2011 et en 2012. Il existait des corrélations intéressantes entre les variables environnementales, les préférences en matière d'habitat et les caractéristiques biologiques, qui peuvent aider à la description de certaines caractéristiques des populations et qui devraient faire l'objet d'un examen plus approfondi au cours des futures évaluations du merlu argenté. En outre, le modèle utilisé correspondait au modèle agrégé de biomasse, qui ne saisit pas pleinement les dynamiques d'une espèce comme le merlu argenté, dont les périodes de recrutement sont irrégulières. On suggère que les modèles sans regroupement par âge ou par stade continuent de faire l'objet d'un examen pour des évaluations futures.

INTRODUCTION

The population dynamics of the Northwest Atlantic Fisheries Organization (NAFO) division 4VWX silver hake (*Merluccius bilinearis*) stock has been modelled using an age structured sequential population analysis (SPA) since the early 1980's; however, there has not been an accepted model for more than the past decade, owing to large retrospective patterns and a general lack of confidence in the model's output. It is in this context, a less explicit model of population dynamics was examined.

One of the simplest, and most robust, families of models that can be used to explore population dynamics are the biomass dynamic models, which describe the variations in biomass in year t, B_t, as a function of the previous year's biomass, B_{t-1} and other population specific parameters (θ). Here, a logistic biomass dynamic model incorporating annual landings (C_t; eq. 1) was used. In this formulation, θ was represented by r, the intrinsic population growth parameter and K, the population carrying capacity.

$$B_t = B_{t-1} + rB_{t-1}\left(1 - \frac{B_{t-1}}{K}\right) - C_{t-1} \qquad \text{Eq.1}$$

In this model, r is an integrative parameter accounting for population recruitment, mortality and growth. The data requirements for this type of model are a time series of landings data and one or several indices of biomass. A Bayesian state-space modelling (SSM) approach was used to estimate the states of B_t, r and K. This approach was proposed by Millar and Meyer (2000) because it allowed for the estimation of random errors for both the population dynamics (process errors) and the observed data (observation errors) and because it incorporates non-linearity in the dynamics. The 'process errors' refer to the errors propagated through the transitional states B_{t-1} and B_t, whereas the 'observation errors' refer to the uncertainties associated with measurement and observation. This SSM approach is useful for fishery time series analysis because the data collected are typically indices of the true stock biomass or abundance which cannot be observed directly. Moreover, SSM has been suggested to provide more realistic parameter estimates and more credible forecasts.

The logistic biomass dynamic model also provides parameter estimates which allow for the estimation of maximum sustainable yield (MSY) reference points where MSY=0.25rK, B_{MSY}=0.5K and F_{MSY}=0.5r. In a SSM framework, the estimates of process error can be incorporated to provide stochastic MSY reference points (Bousquet et al. 2008). Applying deterministic MSY rules to stochastic environments may lead to increased probability of decreasing stock sizes and productivity (Bousquet et al. 2008). The inclusion of process error has previously been shown to decrease the MSY reference points, making them more precautionary, and dependent on the level of process error or non-stationarity in the system, these decreases may be significant (Bousquet et al. 2008; Cadigan 2012).

DATA INPUTS

For a full account of the available data sources for 4VWX silver hake population please refer to Stone et al. 2013.

LANDINGS DATA

Landings data for 4VWX silver hake was available from 1960–2011 (Figure 1) and were dominated by the foreign fishery for most of the time series. Since the mid 1990's, the domestic

Canadian fishery has been responsible for most of the landings, which are approximately 7% of historic levels. For the modelling described here, landings from both foreign and domestic fleets were combined into a single time series which was truncated to 1993–2012 as this largely coincides with the initiation of the Canadian fishery, standardization of fishing gear and a relative stable spatial distribution of fishing effort (Stone et al. 2013).

BIOMASS INDICES

There were several multi-species fishery independent surveys which can provide information on the status of the 4VWX silver hake stock (Stone et al. 2013). However, the only survey that covers the entire stock area was the Canadian Department of Fisheries and Ocean's summer research vessel ecosystem survey (herein summer RV survey). This stratified random survey has been conducted annually during July and August since 1970 using bottom trawl gear and has used the same survey design throughout (Figure 2). There were vessel changes in 1981 and again in 1982 from the RVs *A.T. Cameron* to the *Lady Hammond* and then to the Canadian Coast Guard Ship (CCGS) *Alfred Needler* which has performed the survey every year since, with exceptions in 1991 when a portion of the survey was conducted by the *Lady Hammond*, in 2004 and 2007 when the CCGS *Teleost* performed the survey and in 2008 when the survey was conducted by the CCGS *Wilfred Templeman*. As with the landings data, this survey series was truncated to the 1993-2012 time period and as such no vessel corrections were required (Fowler and Showell 2009).

The relative influence of individual sets on the annual biomass index were estimated by calculating the proportion of the annual index accounted for by each set following the methods outlined by Smith (1996). Briefly, under a stratified random sampling survey design each observation (y_{hi}) will represent $\left(\frac{W_h y_{hi}}{n_h}\right) \Big/ y_{st}$ proportion of the stratified mean (y_{st}). In this equation W_h is the relative weight of stratum h, and n_h is the number of sets with stratum h. Using a process termed winsorizing, sets with catches that constituted greater than 40% of the annual stratified mean were replaced by the next highest catch within the survey year and stratified estimates were recalculated. Throughout the 43 year duration of the summer survey, only five sets were above this threshold, and one since 1993 which occurred in 2004. Resultant stratified total biomass estimates from this survey along with confidence intervals estimated by bootstrapping with replacement were shown in Figure 3. The summer survey biomass index was treated as a pre-fishery biomass estimate with annual landings being the sum from July to the following June.

MODEL DETAILS

As per the suggestion of Meyer and Millar (1999), the B_t's and C_t's in equation 1 were rescaled by K as:

$P_t = B_t / K$ and $c_t = C_t/K$ to improve the convergence of the Gibbs sampler. The resulting model was:

$$P_t = P_{t-1} + rP_{t-1}\left(1 - P_{t-1}\right) - c_{t-1} \qquad \text{Eq. 2}$$

The biomass of silver hake, similar to most other species, was assumed to follow a lognormal distribution, and a multiplicative observation model with variance, τ^2, estimated as:

$$I_t \sim LN(\log(q^*K^*P_t), \tau^2) \quad \text{Eq. 4}$$

where I_t was the biomass index at time t, q was the catchability or proportionality constant which scales the biomass index to the estimate of 'true' biomass. Similar to the observation errors, the process errors, were assumed to also follow a (multiplicative) lognormal distribution with variance σ^2,

$$P_t \sim LN(\log(P_{t-1} + rP_{t-1}(1-P_{t-1}) - c_{t-1}), \sigma^2) \quad \text{Eq. 3}$$

PRIORS FOR SSM PARAMETERS

r

The Euler-Lotka demographic method of McAllister et al. (2001) was used to develop an informative prior on the parameter r. Briefly the Euler equation,

$$1 = \sum_{a=1}^{a_t} l_a m_a e^{-a \cdot r} \quad \text{Eq. 4}$$

was used to numerically solve for r given values or distributions of survivorship at age (l_a), the number of age 1 recruits produced by adult females at age a (m_a). Here, l_a was computed as:

$$l_a = l_i \cdot e^{\left(-\sum_{a=1}^{a} M_a\right)} \quad \text{Eq. 5}$$

where l_1 was set to 1 and the natural mortality rate (M) was sampled from a U(0.4,0.5) distribution based on the estimates of M from Terre and Mari (1977), Rikhter (1991) and Defeo and Caddy (2001). m_a was estimated from the product of the number of age 1 recruits produced per ton of spawners as spawner abundance approaches 0 (R_s), observed weights at age (W_a) and the proportion of individuals mature at age (f_a),

$$m_a = R_s \cdot W_a \cdot f_a \quad \text{Eq. 6}$$

Normal probability distributions for W_a were estimated using maximum likelihood methods from the observed weight at age data across all years of the summer RV survey (Figure 4). f_a were determined from the maturity at age ogive (Figure 5) modelled using a binomial generalized linear model from the maturity data collected during the summer RV surveys between 1970 and 2011 and were assumed stationary. Assuming a Beverton-Holt stock-recruitment relationship, R_s can be expressed as a function of the spawning biomass produced per age 1 recruit (S) and the steepness parameter (h; Michielsens and McAllister 2004)

$$R_s = \frac{4h}{S(1-h)} \quad \text{Eq. 7}$$

Here the probability distribution of h was assumed to follow a N(0.79,0.079) distribution, which was obtained from the Gadidae estimate of h published in Myers et al. (1999) and a series of model runs using a statistical catch at age software (iSCAM) and providing a standard deviation of 10% of the mean. The parameter S was defined as:

$$S = \sum_{i=1}^{a} W_a \cdot f_a \cdot e^{-a \cdot M} \qquad \text{Eq. 8}$$

where variables were the same as those defined above. A distribution of *r* estimates were obtained after 10,000 iterations through the calculations incorporating random selection from respective probability distributions. A maximum likelihood estimation procedure was used to determine the best fit probability distribution and associated moments. Comparisons of the negative log-likelihood estimates for fits from each of normal, lognormal, weibull and gamma distributions suggested that a normal distribution was the best fit with N(0.84,0.13) (Figure 6). This distribution was similar to the posterior distribution for *r* reported by Brodziak et al. (2001) for silver hake in the Northeastern United States stock with first, second and third quartiles at 0.53, 0.69, 0.98, respectively.

K

The prior for the parameter *K* followed a lognormal distribution the mean and standard deviation were estimated from by setting the 90% quantile range to the maximum observed biomass from the summer RV survey and six times that biomass yielding a distribution of LN(5.48,0.293).

q

A uniform prior on *q* was used for all survey series following the probability distribution of U(0.05,1.1).

Process Errors σ, Observation Errors τ

Uninformative prior distributions for both process and observation error were U(0.01,7).

MODEL DETAILS AND DIAGNOSTICS

winBUGS software (version 1.4.2; Lunn et al. 2000) was used to perform Markov Chain Monte Carlo (MCMC) integration required to implement the Bayesian state-space filter. Three chains of length 500,000 with a burn in phase of 20,000 and thinning of 125 were determined to be sufficient to allow for adequate mixing, removal of the initialization phase and decrease in autocorrelation, respectively. Convergence of chains was tested with a Gelman-Rubin diagnostic (Gelman and Rubin 1992).

A retrospective analysis was conducted on the final model to assess the coherence in model parameters. In this analysis, beginning in 2012, a single year was systematically peeled off the end of the biomass indices and landings data and the model was refit. This analysis was performed removing data annually back to 2005. For each year of the peel, the time series of estimated biomasses were compared.

A further analysis was conducted to assess the model's ability to project future biomasses. Biomass estimates in year *t* from the model were compared to projections in year *t* after removing two years of biomass index and projecting forward a two years using the observed landings.

The relationship between annual surplus production ($ASP=B_t-B_{t-1}+C_{t-1}$) and biomass was examined.

LANDINGS SCENARIOS

Several landings scenarios were used to project the 2013 prefishery and 2014 March biomass estimate. These scenarios included 0 t, 9890 t, 12750 t, 15000 t (total allowable catch; TAC), 17250 t, 18000 t and catch at F_{MSY} (F_{MSY}=0.32) or 45100 t. For all scenarios, the mean landings over the past three years (9890 t) was used as the estimate of total landings for the 2012-2013 fishing year knowing that 3221 t had been removed during April, May and June 2012. The projections were based on the sum of the remaining landings for 2012-2013 fishing year (9890-3221=6669 t) and the percent of the total landings for each catch scenario assumed to be landed prior to July 2013. The value 28.8% (observed range 25.6–33.3%) was the mean percentage of fishing year landings that were captured between April and June since 2005. The second year of projections were estimated using the remainder of the catch for each landings scenario.

For each scenario, the posterior probability distributions of the projected biomass for 2013 and 2014 were used to determine the probability of biomass falling below 40 and 80% of stochastic B_{MSY}.

ADDITIONAL CONSIDERATIONS

Several additional habitat, environmental and biological characteristics were examined to explore some of the habits of silver hake, their responses to environmental conditions and perhaps suggest some factors that may prove important in describing their biology and population dynamics.

HABITAT ASSOCIATIONS

The relationship between silver hake distribution and the habitat variables salinity, temperature and depth for trawl data was described using the methods outlined by Perry and Smith (1994) for two size classes of fish, either above or below 20 cm. Briefly, cumulative distribution functions (cdf) described species associations with temperature and depth from as the cdf for each habitat variable (*x*) for each set (*i*) in a stratum (*h*) incorporating the survey design was:

$$f(t) = \sum_h \sum_i \frac{W_h}{n_h} I(x_{hi}) \qquad I(x_{hi}) = \begin{cases} 1, & if \ x_{hi} \le t; \\ 0, & otherwise. \end{cases} \qquad \text{Eq. 2.9}$$

where W_h is the proportion of the survey area in stratum h, n_h is the number of sets performed within the stratum and t is an index ranging between the minimum and maximum levels of the observed habitat variable. Similarly, the cdf for catch of a particular species within a set (y_{hi}) with specific habitat conditions is:

$$g(t) = \sum_h \sum_i \frac{W_h}{n_h} \frac{y_{hi}}{\bar{y}_{st}} I(x_{hi}) \qquad I(x_{hi}) = \begin{cases} 1, & if \ x_{hi} \le t; \\ 0, & otherwise. \end{cases} \qquad \text{Eq. 2.10}$$

By scaling the catch to the stratified mean ($\bar{y}_{st}$), the sum of *g(t)* equals 1 across all values of *t*. Large values of $y_{hi}/\bar{y}_{st}$, which are consistently associated with a particular habitat condition, suggest strong associations. Randomization tests were used to test the significance of habitat associations. The test statistic, *L*, was the maximum absolute difference between the *f(t)* and *g(t)* curves. Statistical significance of *L* was determined by its comparison with to the distribution of values from 2999 random perturbations of the data (3000 repetitions, including *L*; Perry and Smith 1994). For an example plot of the cumulative distribution functions refer to the Appendix.

Fultons K

The time series of size and sex specific estimates of Fulton's K (weight/length^3) anomalies were calculated from the 1993:2012 period of summer RV survey data. Similar to the habitat association, size classes were defined for those above or below 20 cm, representing mature or maturing and immature fish, respectively.

Proportions at Age and Recruitment Index

Proportions of numbers or biomass at age were obtained from the catch at age and weight at age information collected during the summer RV survey. The time series of recruitment index anomalies were calculated from the number of age 1 fish in the proportions at age matrix.

Water Temperature

Water temperature anomalies were calculated as stratified mean estimates collected during the summer RV survey in strata 440-483.

Analyses of Additional Information

Several of the silver hake biological characteristics, habitat preferences, biomass indices and their coefficient of variation and environmental variables were compared through correlation analysis.

RESULTS AND DISCUSSION

The plots of prior and posterior distributions of parameters indicated that there was sufficient information to update the prior information as can be seen by the change in shape or center of posteriors (Figure 7). Median estimates for r, K, q, σ, and τ were 0.70, 121,000 t, 0.35, 0.32 and 0.35, respectively.

Model fits to the summer RV survey biomass index captured the overall trends as there was general coherence in the time series of data and model fits (Figure 8). The current estimates of biomass are the highest that they have been in the 1993-2012 time series (Table 2). Estimates of fishing mortality (F) are currently among the lowest in the series (Figure 9). The model is currently under predicting the q-corrected survey indices in each of the past four years as there was a dramatic increase in the survey index which could not be captured by the dynamics of this model formulation (Figure 10). Due to this dynamic increase, the model has been under-projecting the biomasses when compared to the biomass estimated in the following year. Moreover, this type of aggregated biomass model does not incorporate annual changes in recruitment, growth and mortality as all are combined into a single parameter, *r*. This generally led to underestimation of biomass in the year following a strong recruitment event. That said, the 2012 model projections are more in line with the biomass estimates (Figure 11). The retrospective analysis for biomass model fits suggest that the model is relatively coherent and does not have any systematic biases across the past several years as the biomass trajectories are very similar (Figure 12). That said, the full model (red line in Figure 12) median biomass estimates are above the previous three retrospective peels as the high survey biomass index during the past several years is maintained and the model is trying to compensate for this apparent increase.

A plot relating surplus production to biomass was used as a diagnostic of the behavior of stock production. The relationship shown here follows a clockwise hook-cycle, in which surplus production declines with increasing biomass and remains low at low biomass (Figure 13). This pattern was the most common form of surplus production-biomass relationships across a range of species which were shown in a recent meta-analysis (Walters et al. 2008). This pattern can largely be explained by recruitment anomalies, coupled with fishing pressure, such that periods of low recruitment precede stock declines. This explanation appears to hold for 4VWX silver hake as the low levels of recruitment throughout most of the 1990's led to biomass and surplus production declines (figures 14-16), sporadic recruitment and higher fishing mortality through the early to mid 2000's led to the hook cycles in the production and biomass plot. The several recent years of good recruitment and decreasing fishing mortality has likely allowed both the stock size and production to increase (Figure 13). The 2009 year class (2010 anomaly) is the highest observed in the 1993:2012 time series.

Biomass reference points were calculated from the biomass dynamic model outputs incorporating the process uncertainty estimated from the state space model. The current median estimates of stochastic F_{MSY}, MSY and B_{MSY} are 0.32, 16,000 t and 59,000 t, respectively (Figure 17). Using these estimates B_{MSY} and $F_{MSY,}$ the relationship between stock size and fishing mortality can be tracked through time (Figure 18). For most of the years since 1993, estimated biomass has been above B_{MSY}; although for several years during the early 2000's stock sizes did fall below B_{MSY}. F has remained below F_{MSY} throughout the time series of observed landings and estimated biomasses (Figure 18).

Several landings scenarios were explored to assess their impact on the projected 2013 and 2014 biomass estimates (tables 3, 4). Biomass is expected to be lower for 2013 than in 2012 regardless of landings scenario. Similarly for 2014, projected median biomass estimates were lower than the 2013 projections for landings above 0. The probability distributions of projected biomass estimates from each scenario were compared against 80 and 40% of B_{MSY} to determine the probability of projected biomasses falling below these reference levels. Across all TAC scenarios examined, the probability of biomass falling below 80% B_{MSY} in 2013 was less than 0.1 and in 2014 was less than 0.15 (tables 3, 4). With landings at $F_{MSY,}$ the probability of falling below 80%B_{MSY} increases to 0.13 in 2013 and 0.32 in 2014. As expected with increased landings, projected biomass decreased and probability of falling below reference biomass levels increases.

Projections using biomass dynamic models such as those presented here assume median recruitment and productivity through the projected years. The uncertainty of these estimates is high given our lack of understanding of stock recruitment patterns in silver hake, as well as the fishery targeting recruiting fish.

OTHER CONSIDERATIONS

Silver hake distribution varied across environmental variables in some years, which may have an impact on availability or catchability to survey gear. The most stable habitat association for small silver hake (<20 cm) was that with depth as fish are captured at a much higher rate at depths between 150 and 200 m across all years (Figure 19). For large silver hake, the distribution of catch is more annually variable as fish may occur at a higher frequency in shallow depths in some years. The changes in depth distribution of the fish are inversely related to the catch rate, such that catch rates are highest when the species were predominantly found in shallow waters (Figure 20, left). This did not appear to be due to an increased distribution with increasing stock size as there was no significant relationship between catch rate and area occupied (data not shown). Silver hake regardless of size were found at higher water temperatures than many of the other species sampled on the summer RV survey at an overall mean of 8.3°C, which is likely tied to the depth preference of the fish during the summer months.

Body condition (Fulton's K) anomalies of silver hake vary temporally and are highly correlated with bottom temperatures (Figure 21), such that cool years result in high body condition. This result was consistent for both <20 cm and >20 cm females, as well as >20 cm males regardless of state of maturity of the fish. There was also evidence to suggest that in some years when females are in good condition during summer, recruitment of age 1 fish is higher at a two year time lag (i.e. high female condition in 1995 lead to high recruitment in 1997; Figure 20 right).

CONCLUSIONS

Overall, 4VWX silver hake are at the highest biomasses estimated throughout the 1993:2012 time block. Biomass has increased over the past ten years and has been high and relatively stable for the last four years. Fishing mortality has decreased over the past five years and is currently at the lowest level in the last twenty years. Biomasses are projected to be lower in 2013 than in 2012; however, under all TAC scenarios examined, in 2013 and 2014, the probability that biomass will fall below 80% of B_{MSY} was 0.1 and 0.15, respectively. There is evidence of a strong 2009 year class, which has shown up in both the 2010 and 2011 summer RV surveys. There were some interesting correlations between environmental variables, habitat preferences and biological characteristics, which should be examined more closely in future silver hake assessments. The model used here was an age aggregated model, which does not fully capture the dynamics of a species with sporadic recruitment events. It is suggested that age or stage disaggregated models continue to be explored for future assessments.

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TABLES

Table 1: Prior distributions of parameters used in Bayesian state space logistic model of silver hake in 4VWX.

Parameter	Distribution
r	N(0.84,0.13)
K	LN(5.48,0.239)
q	U(0.05,1)
σ	U(0.02,400)
τ	U(0.02,400)

Table 2: Estimated median (with first and third quartiles) of biomass for 4VWX silver hake from a logistic biomass dynamic model.

Year	Median Biomass	Q1	Q3
1993	92.0	62.5	142.4
1994	80.6	56.6	119.7
1995	104.7	72.9	155.5
1996	103.5	69.6	156.6
1997	82.0	55.9	124.8
1998	65.1	44.7	98.5
1999	59.8	40.9	90.6
2000	68.4	47.3	102.4
2001	72.4	49.2	109.6
2002	46.4	31.1	71.5
2003	54.9	37.6	83.8
2004	70.1	46.7	107.1
2005	49.0	32.7	74.9
2006	57.8	39.2	88.0
2007	54.6	36.9	82.4
2008	62.7	42.9	94.3
2009	94.1	65.1	139.2
2010	102.6	71.8	152.5
2011	123.2	86.1	182.8
2012	120.0	84.3	177.9

Table 3: Results of different landings scenarios on the projected biomass (x10 ^{3} T) estimates for July 2013. Accompanying the median and credible intervals for 2013 biomass are the probabilities of biomass falling below a range of percentages of B_{MSY}.

	Scenario ('000 t)	Landings used for projections (July-June)	Fishing Mortality	Median Biomass 2013	50%CI Biomass 2013	Probability of 2013 Biomass falling below X% of B_{MSY} 80%	40%
TAC	0	6.7	0.05	108	74-164	0.062	0.006
	9.89	9.5	0.08	105	71-160	0.074	0.007
	12	10.1	0.08	105	71-159	0.077	0.007
	15	11	0.09	104	70-158	0.081	0.007
	18	11.9	0.09	103	69-157	0.085	0.008
F_{MSY}	45.2	19.7	0.15	95	62-148	0.127	0.014

Table 4: Results of different landings scenarios on the projected biomass (x10 ^{3} T) estimates for March 2014. Accompanying the median and credible intervals for 2014 biomass are the probabilities of biomass falling below a range of percentages of B_{MSY}.

	Scenario	Landings used for projections (July-March)	Fishing Mortality	Median Biomass 2013	50%CI Biomass 2013	Probability of 2014 Biomass falling below X% of B_{MSY} Levels 80%	40%
TAC	0	0	0	108	75-162	0.085	0.023
	9.89*	7.1	0.07	100	67-153	0.114	0.025
	12	8.6	0.08	98	66-151	0.12	0.025
	15	10.7	0.10	96	64-148	0.137	0.029
	18	12.8	0.12	93	61-145	0.144	0.03
F_{MSY}	45.1	32.2	0.29	70	40-119	0.327	0.125

FIGURES

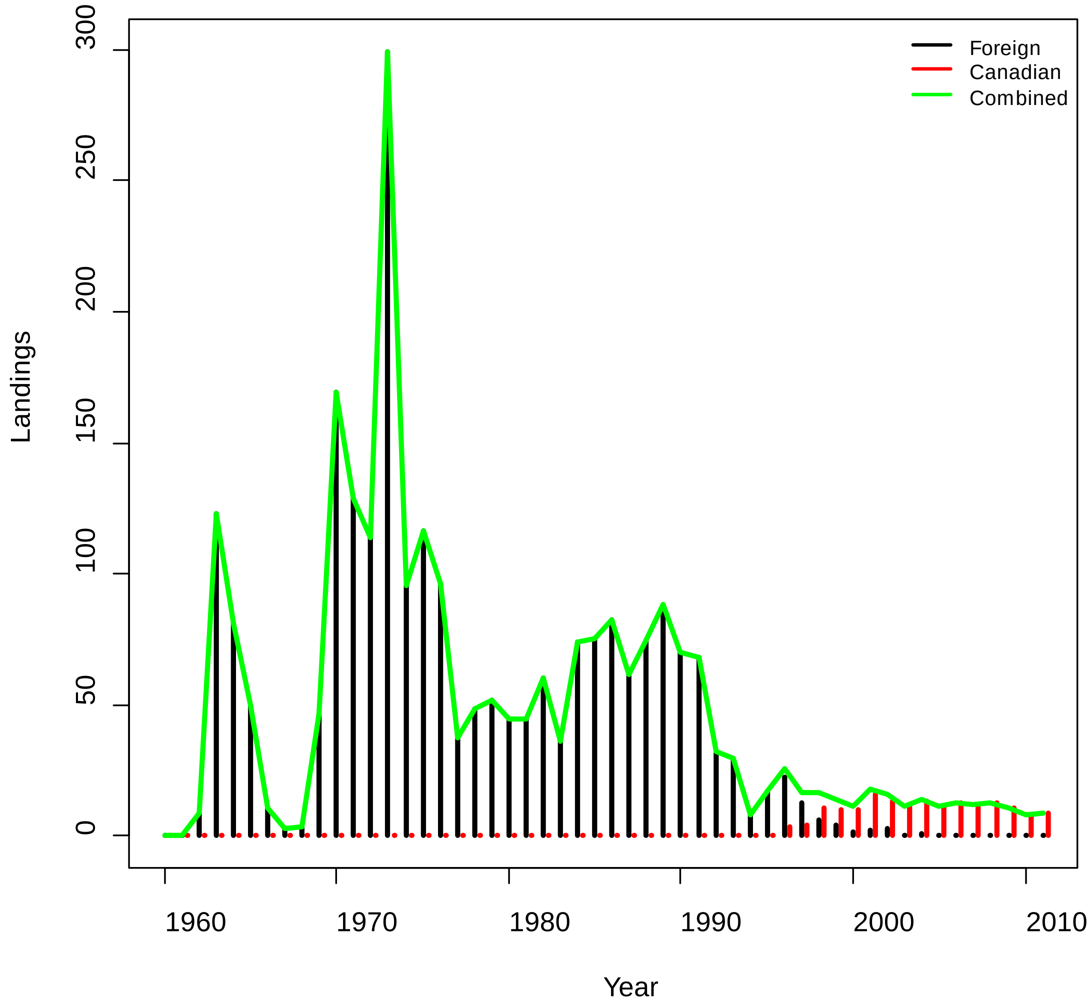

Figure 1: 4VWX silver hake landings data (x10^3 t) separated by fleet calculated on a calendar year basis.

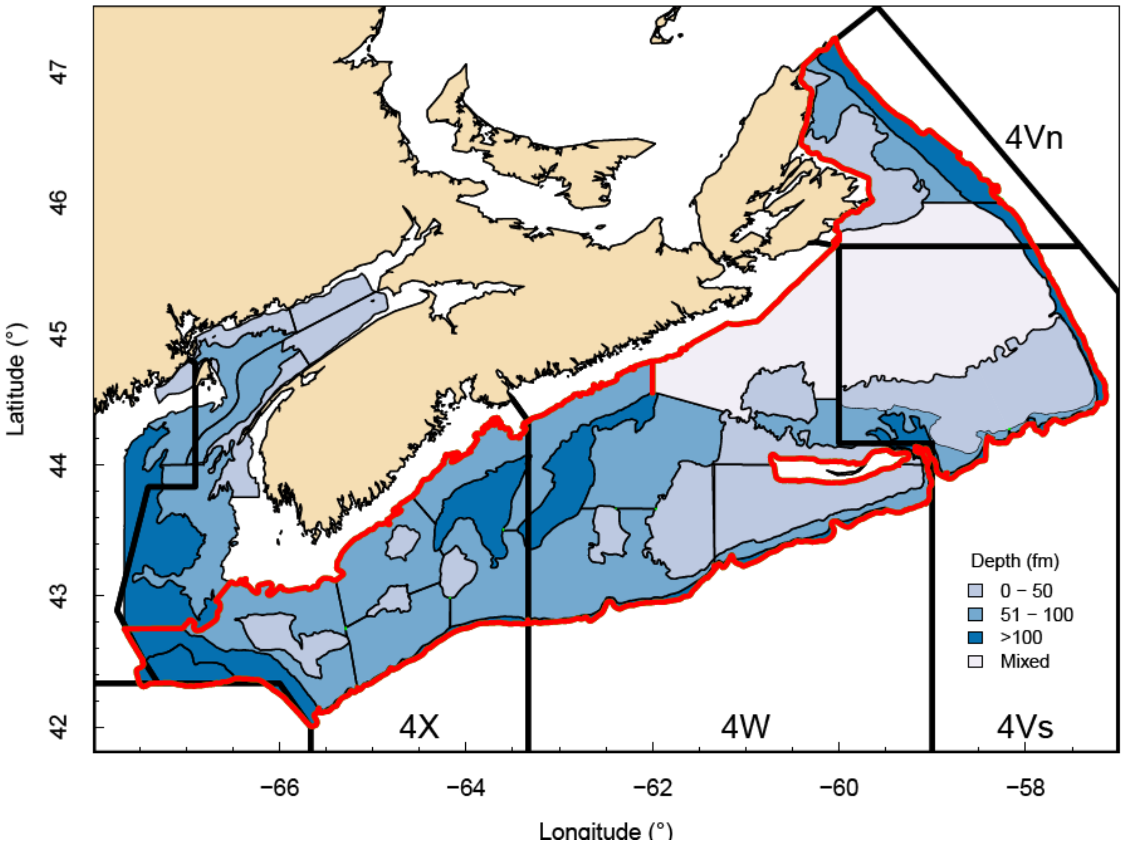

Figure 2: Map of the Scotian Shelf with the summer RV survey strata lines outlined in black and colour coding for the depth ranges within a strata. Red outline represents the strata used to define the 4VWX stock of silver hake.

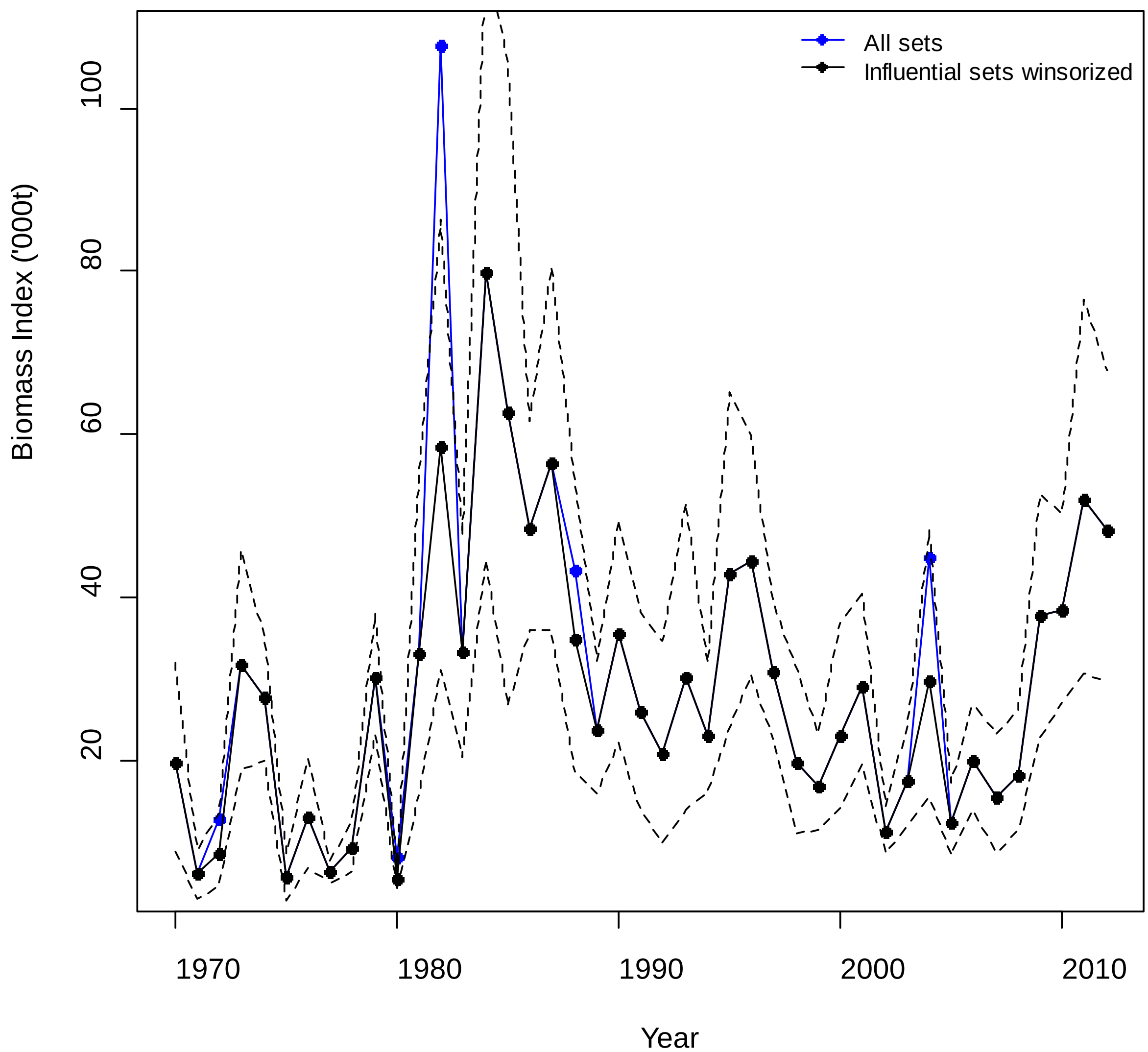

Figure 3: Silver hake biomass index (x10^3 t) from the summer RV survey for strata 440 to 483. Black lines and symbols represent the biomass index with influential sets winsorized (reduced to the catch of the next highest non-influential set). Dashed black lines represent the 90% confidence bounds. Blue lines represent the stratified mean biomass estimates without winsorizing.

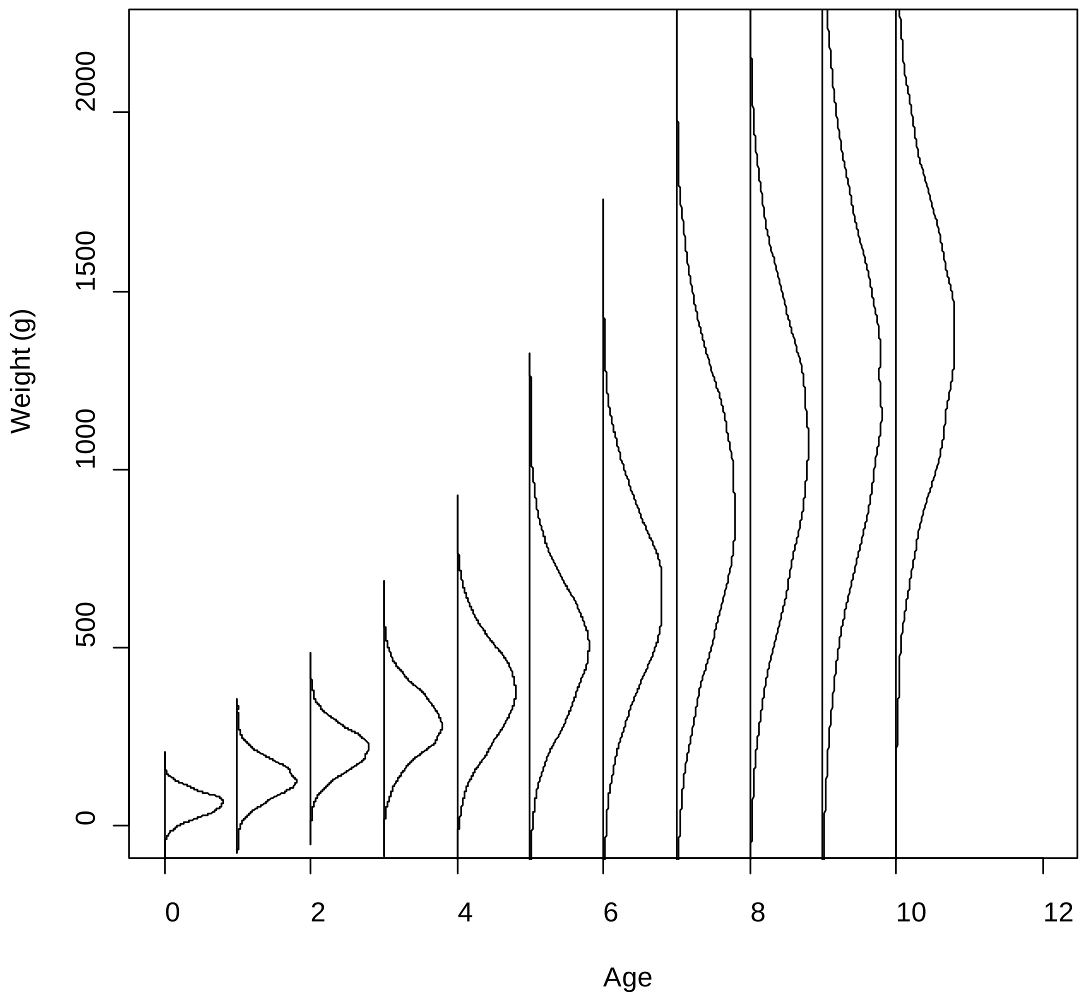

Figure 4: Maximum likelihood estimated normal probability distributions of weight at age using the observed data from the summer RV survey between 1970 and 2011 in strata 440-483.

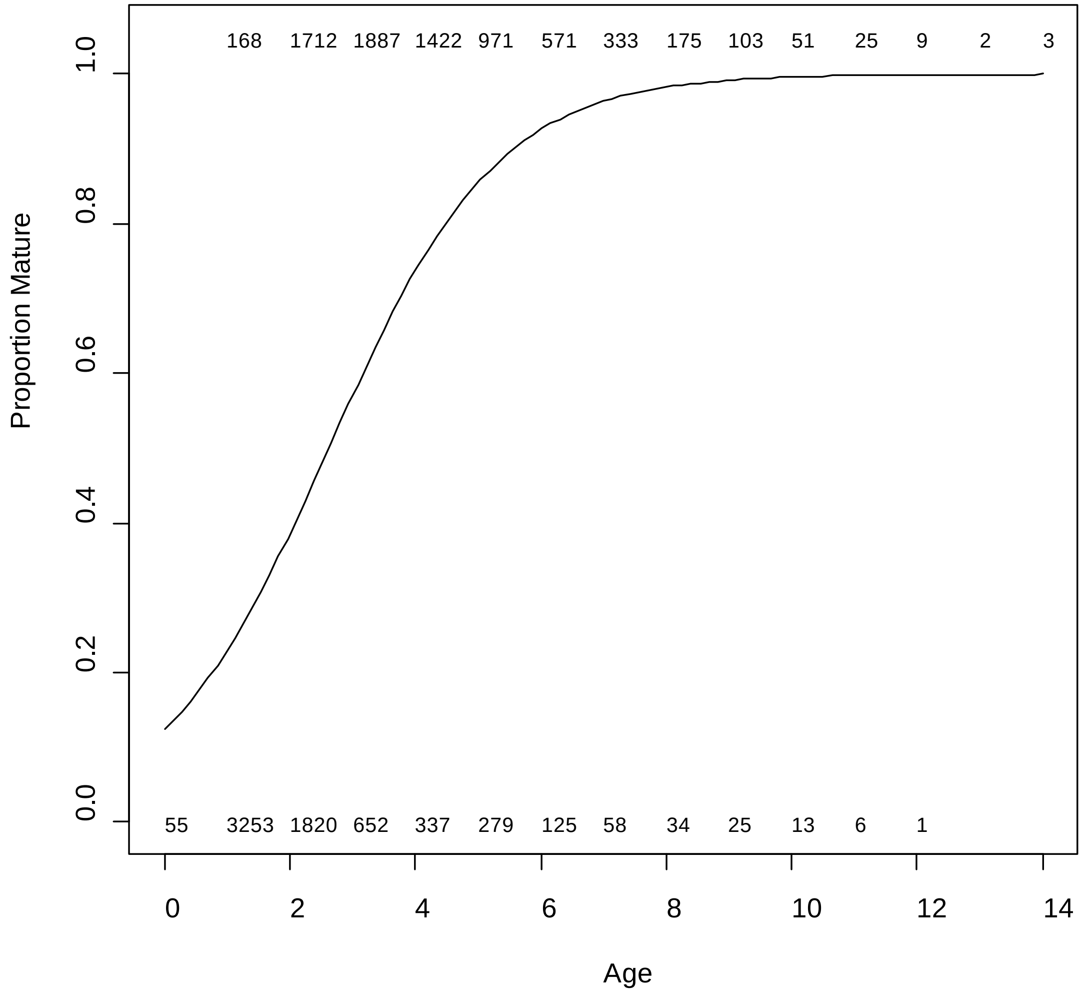

Figure 5: Maturity status at age of female silver hake from the complete time series of data from the summer RV surveys in strata 440-483. Solid line represents the best fit model from a generalized linear regression model assuming a binomial distribution in response. Numbers represent the number of females assessed as mature (1) or immature (0) at each age.

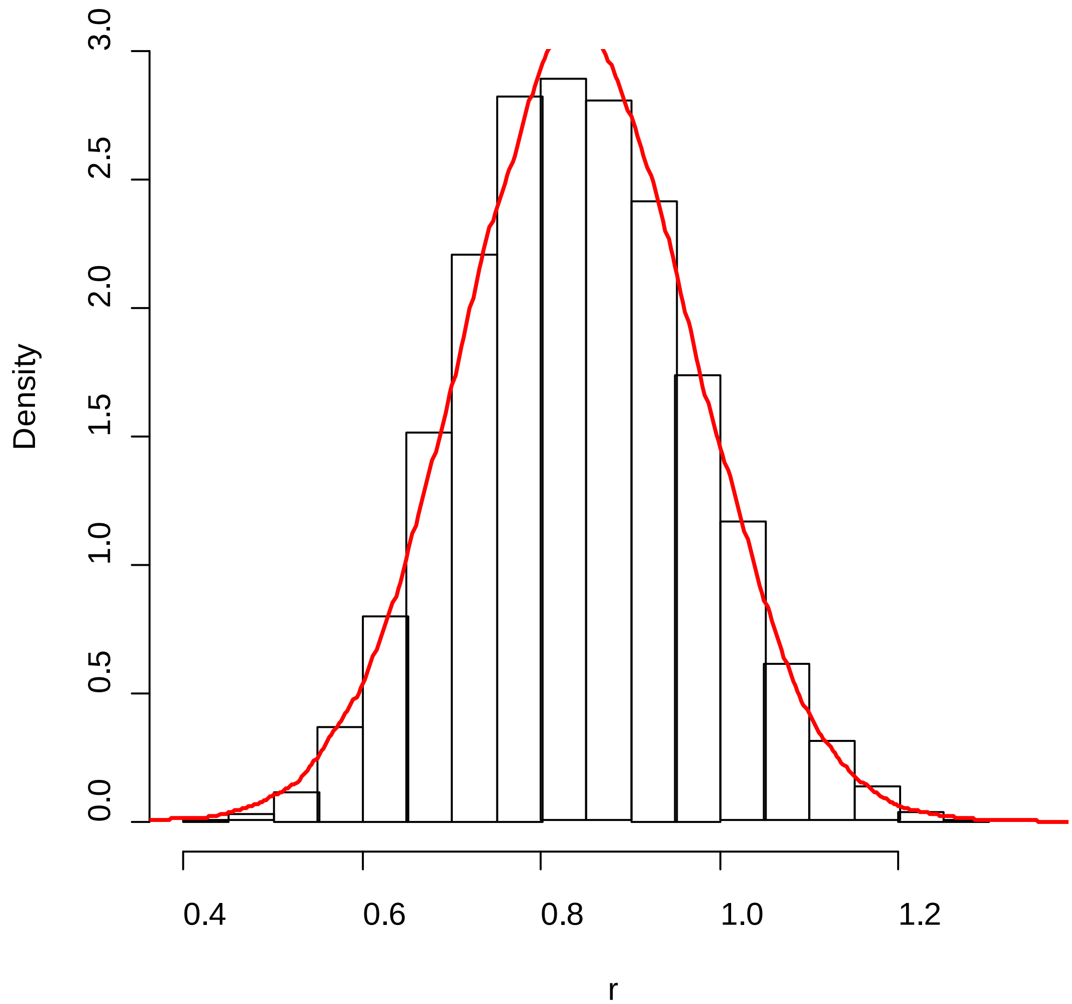

Figure 6: Histogram of the estimates of r, using the demographic method of McAllister et al. (2001). In red (curved line) was the best fit normal probability distribution used as an informative prior in the state space biomass dynamic modelling of 4VWX silver hake.

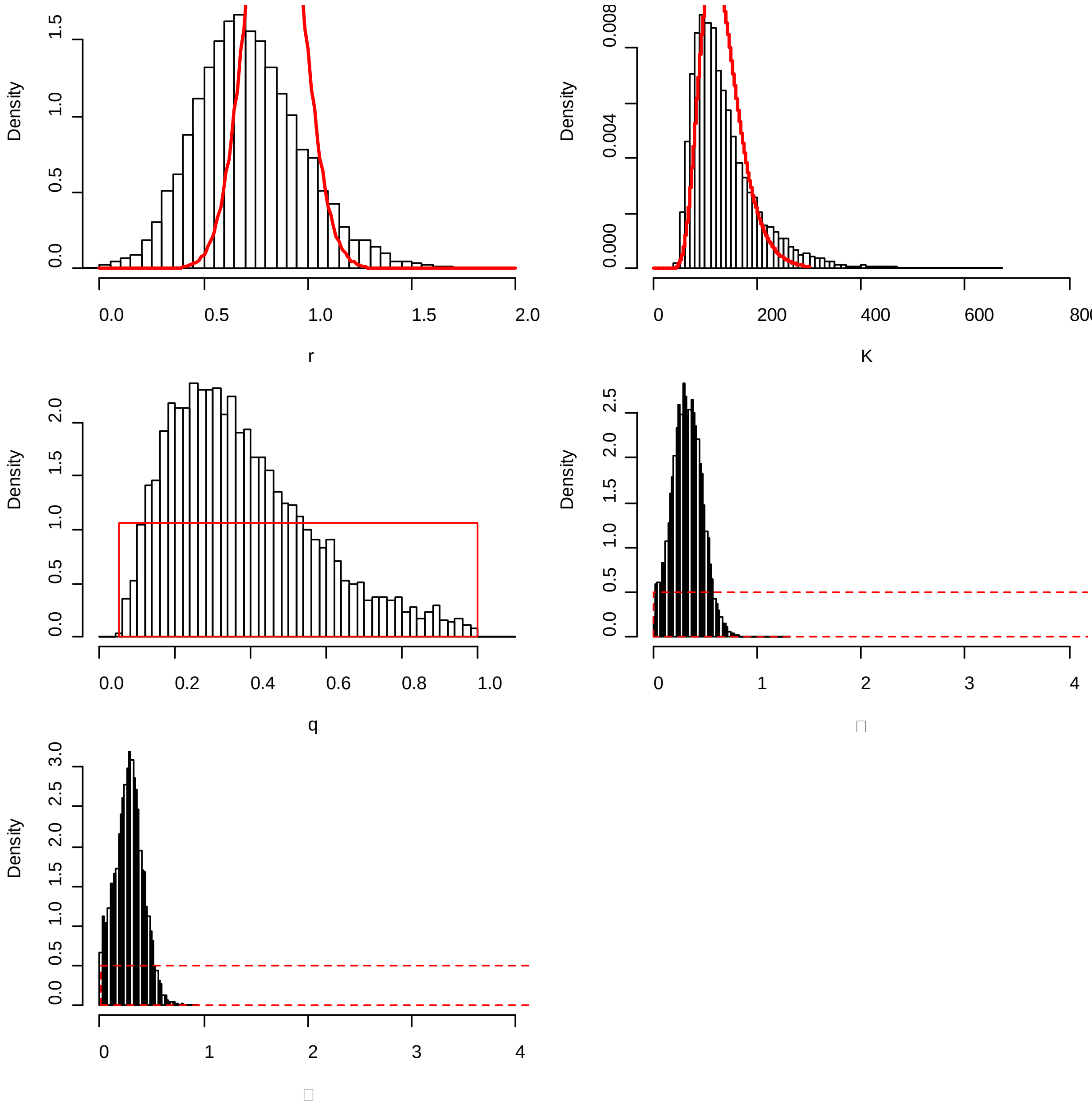

Figure 7: Prior (red) and posterior distributions (bars) of r, K ($x10^3$ t), q, σ (process error) and τ (observation error) from the state space biomass dynamic modelling of 4VWX silver hake.

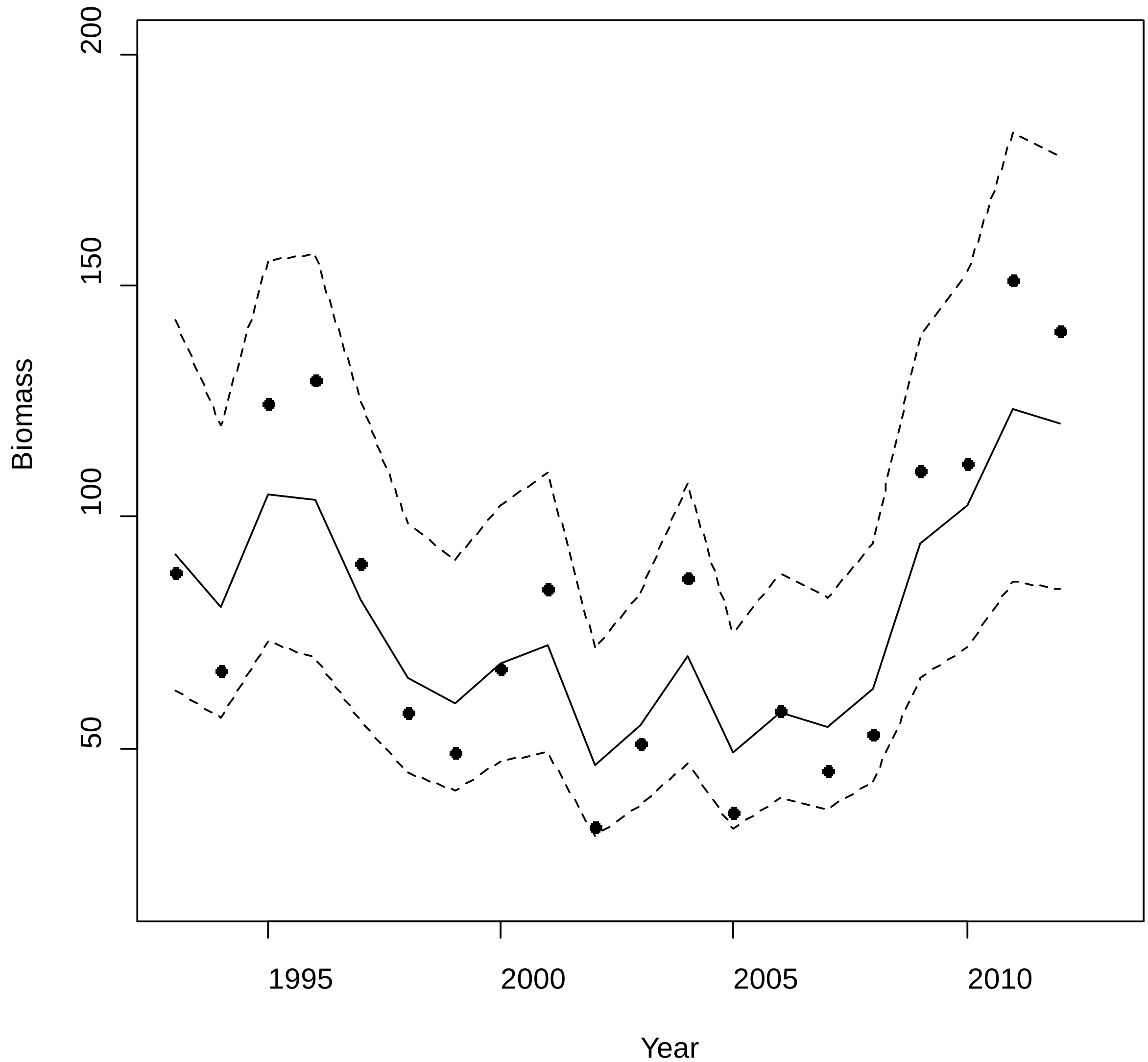

Figure 8: Model fits (solid line) to the q-corrected summer RV survey biomass index (points, x10^3 mT) from strata 440-483. Dashed lines represent 50% credible intervals for biomass estimates.

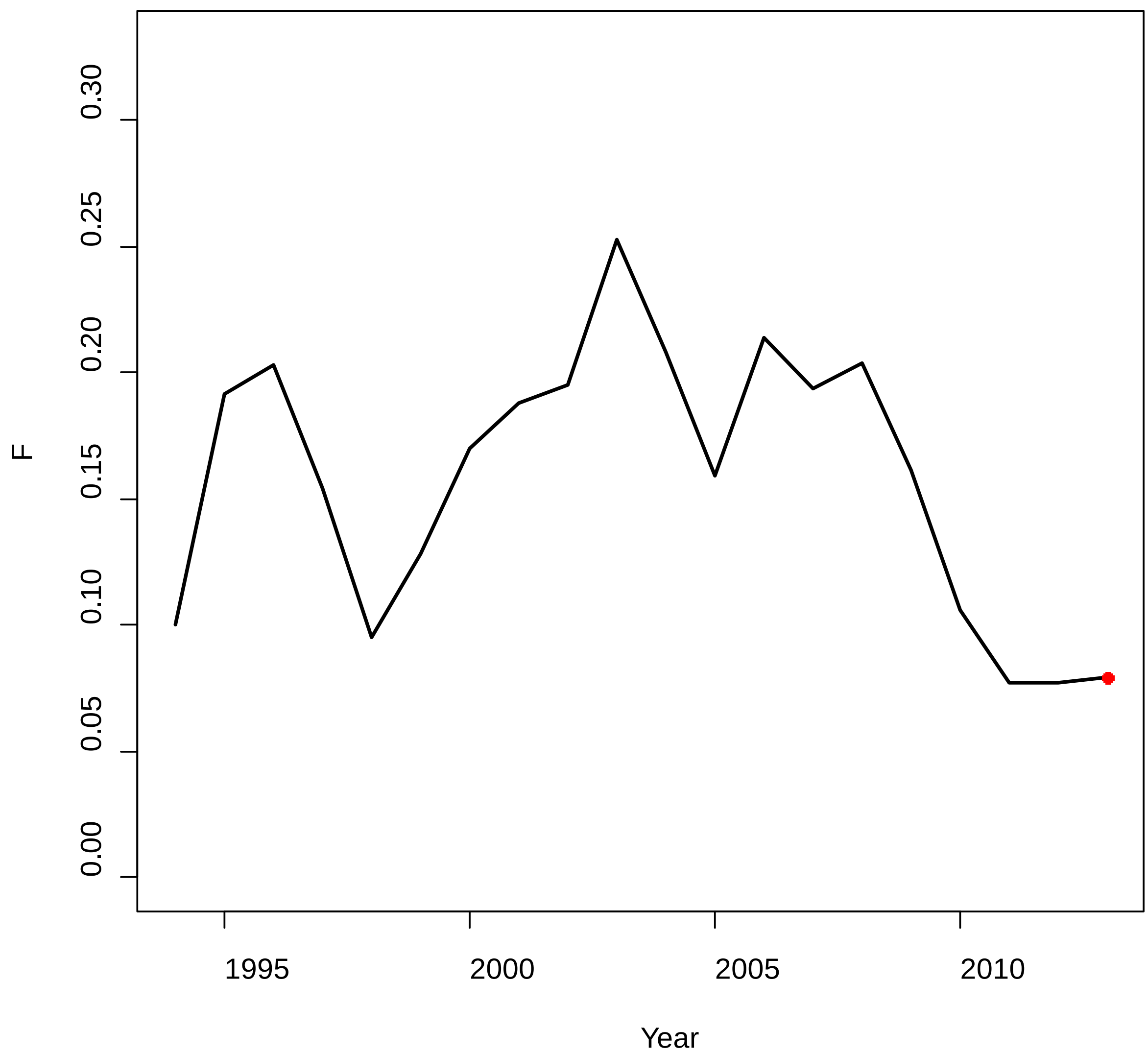

Figure 9: Time series of estimated fishing mortality (F) for 4VWX silver hake. Red point represents the projected estimate of F under catch scenario 2, lands equal to the mean of the past three years.

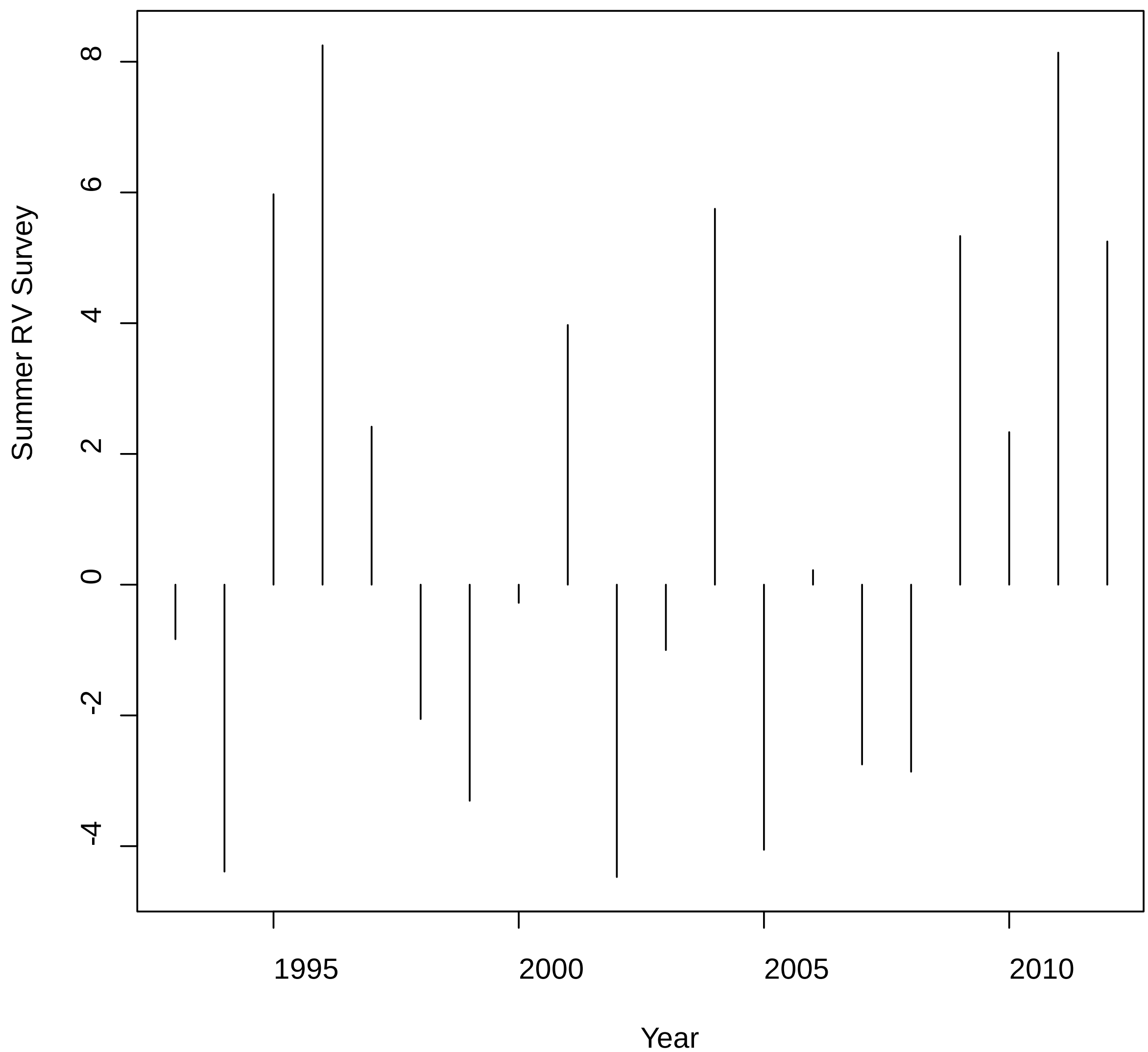

Figure 10: Time series of residual differences between model fits and observed biomass indices for from 4VWX silver hake Bayesian state space logistic modelling.

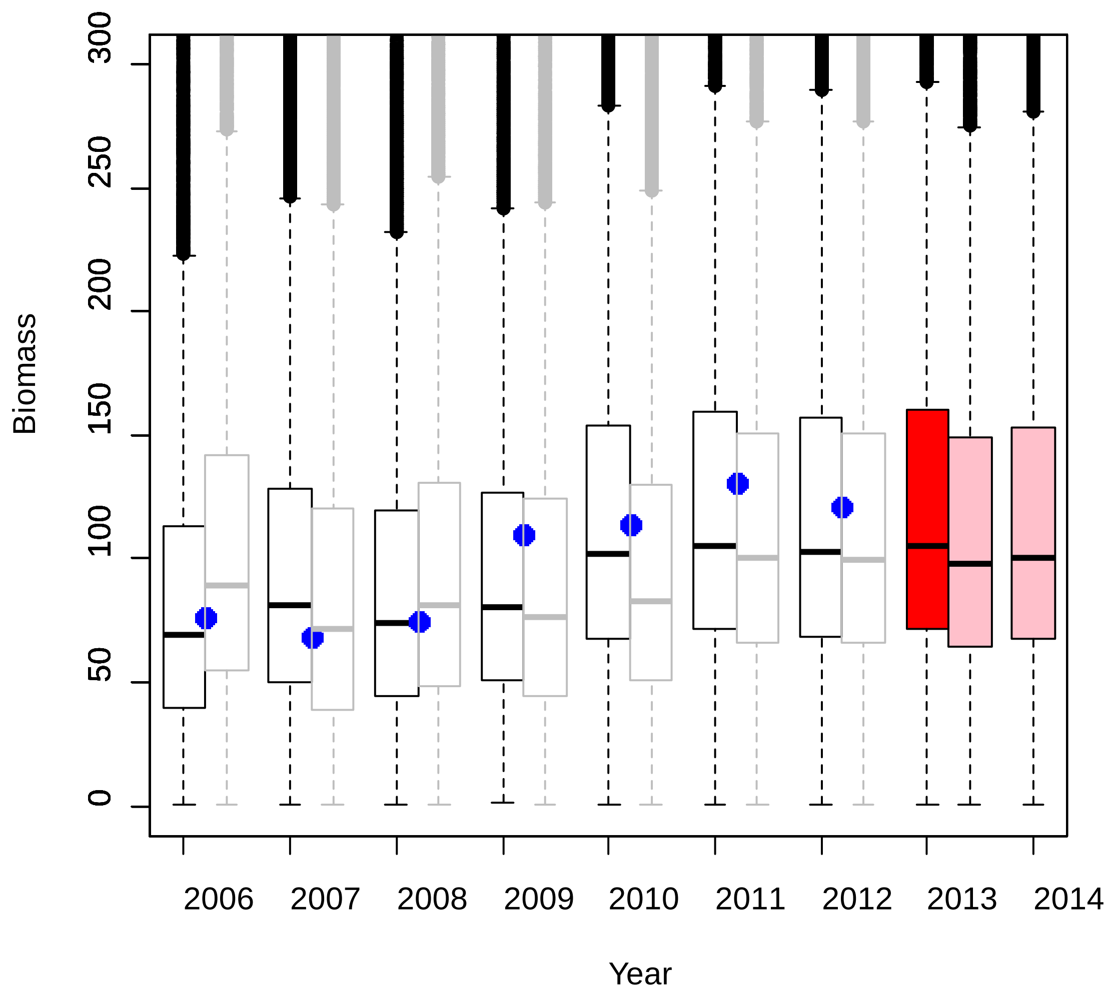

Figure 11: Projected (boxplots) one year (black) and two years ahead (grey) and model fitted estimates of biomass in '000 t (blue points) for 4VWX silver hake from the logistic biomass dynamic model. The red boxplot represents the one year projected biomass for 2013 under catch scenario 2. The pink boxplots represent the two year ahead projected biomasses under catch scenario 2.

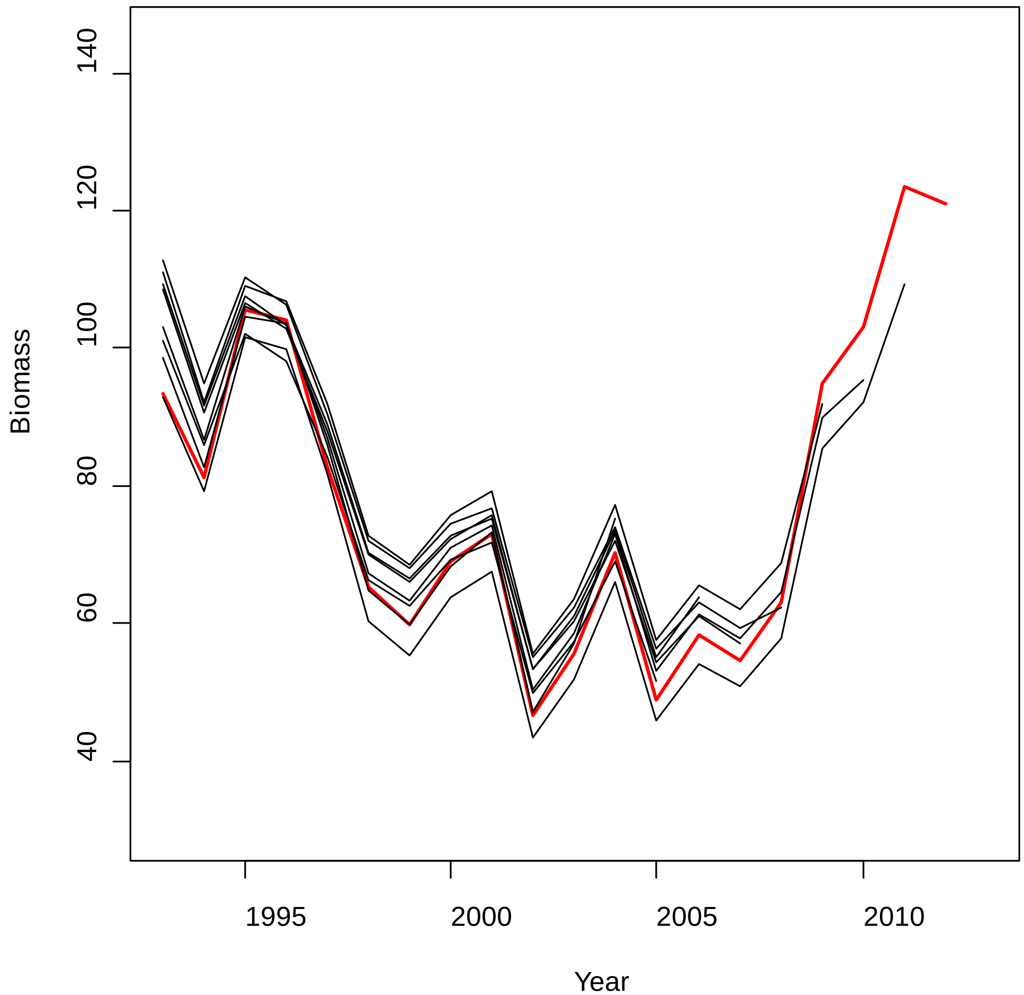

Figure 12: Retrospective plot showing the coherence of the estimated biomasses (x10^3 mT) model over the recent years. The model was run removing a single year of data from the terminal end of the data series (black lines) and the full suite of data (red line).

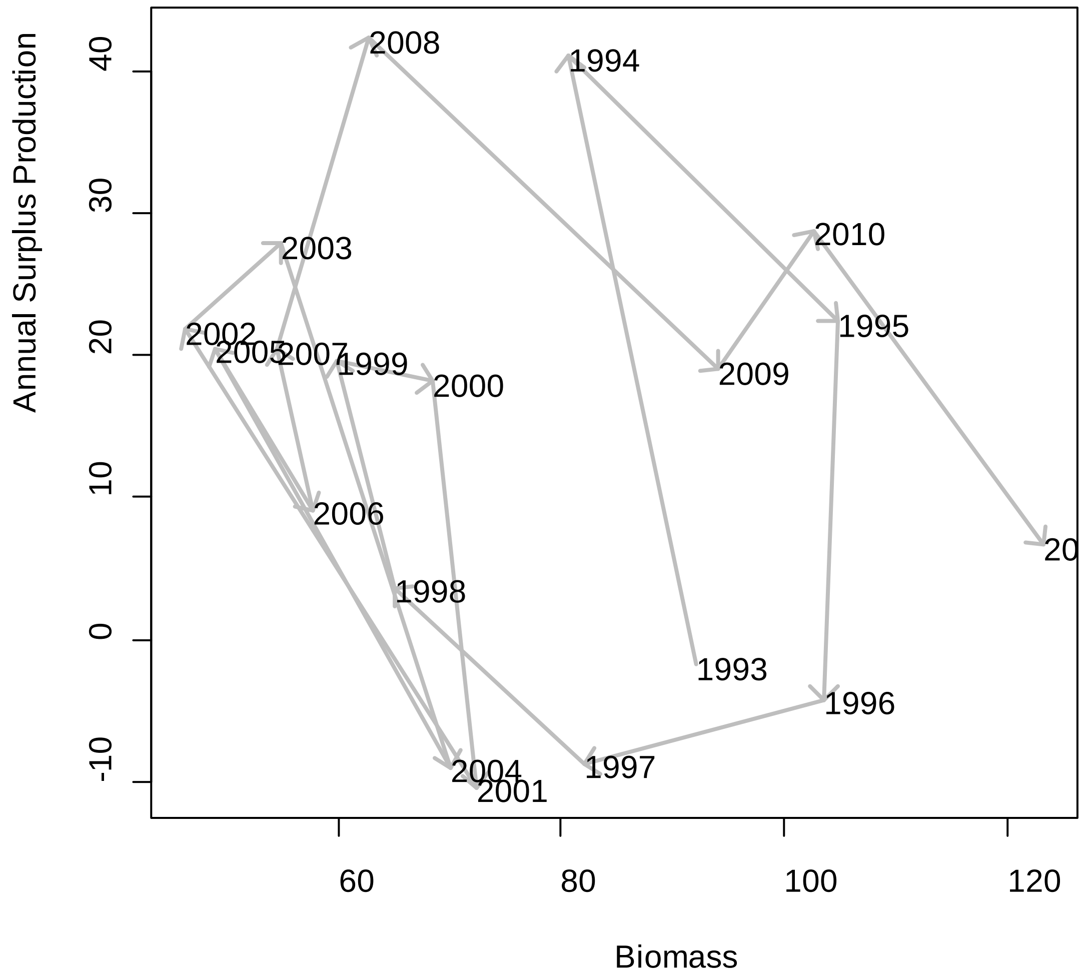

Figure 13: Annual surplus production in relation to biomass from the biomass dynamic model of 4VWX silver hake.

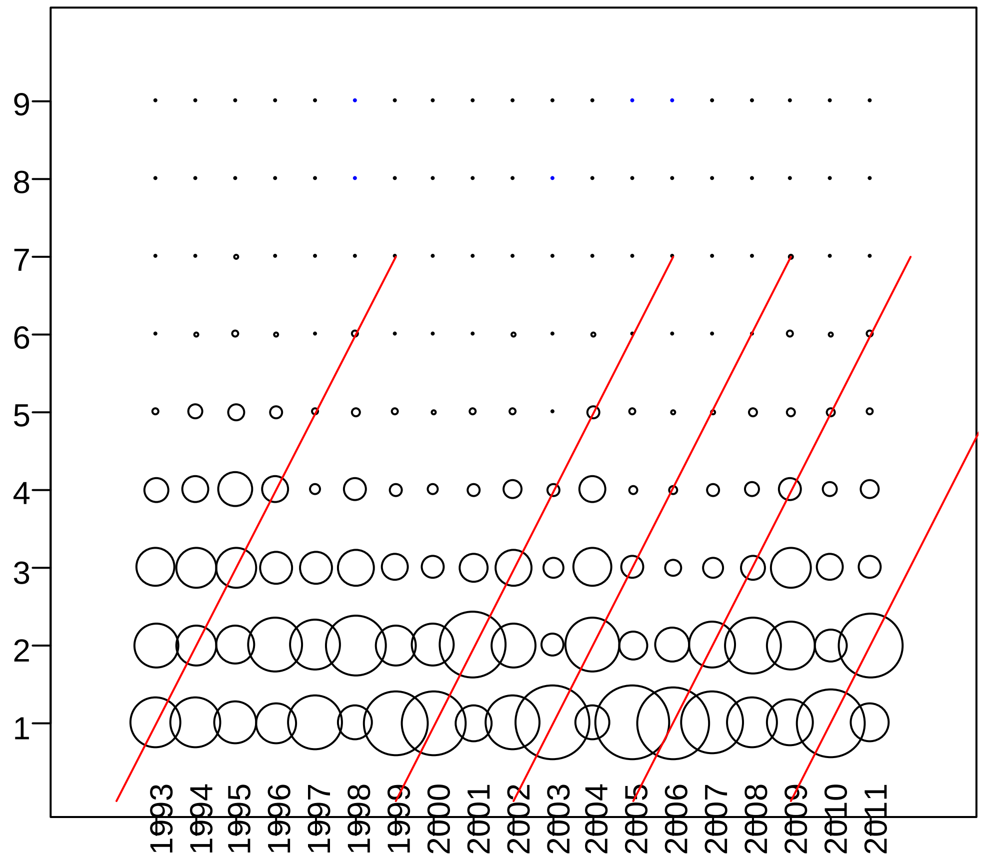

Figure 14: Proportions of numbers at age from the summer RV survey. The size of circle represents the relative proportion and the lines track year classes.

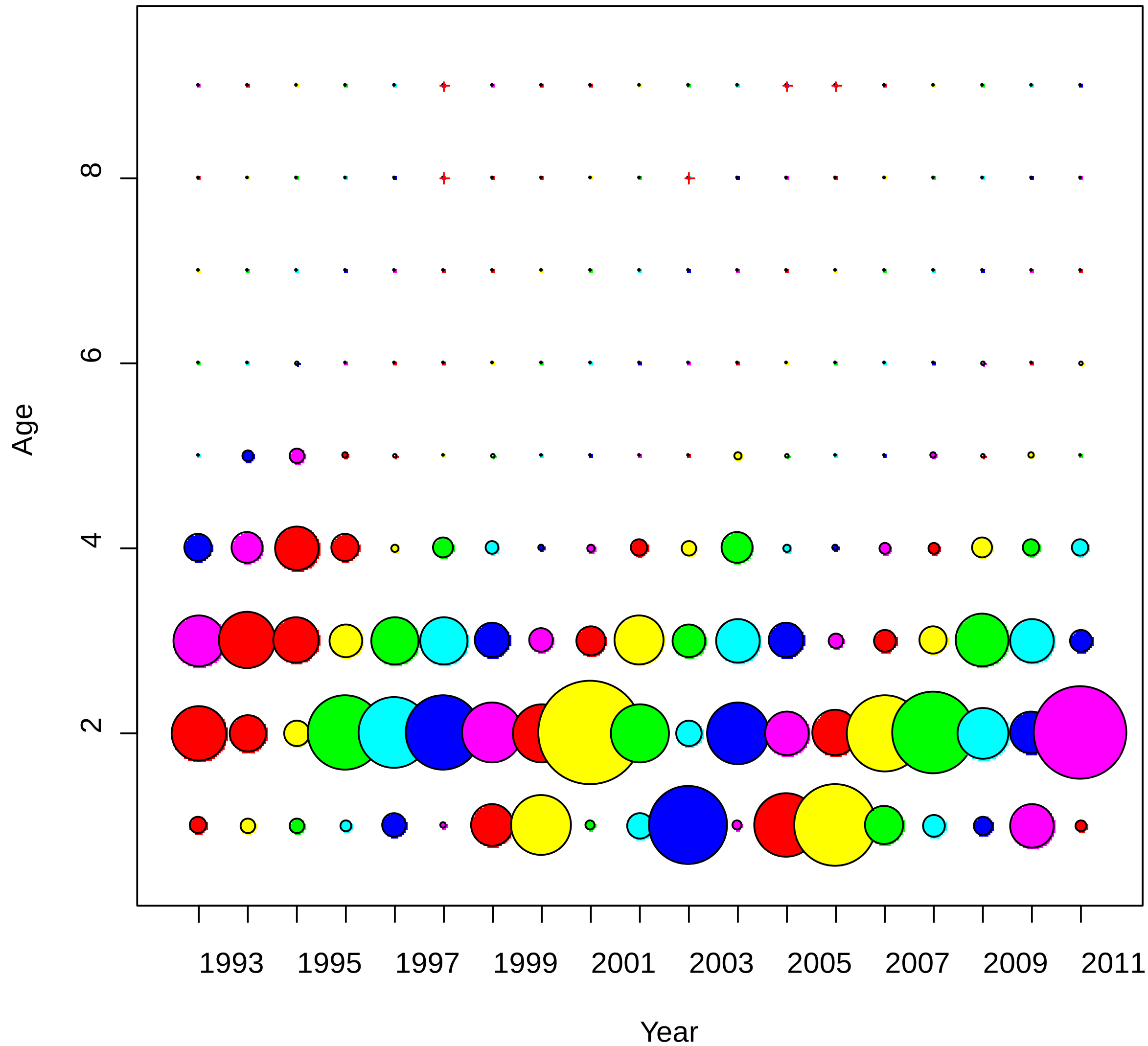

Figure 15: Proportions of total biomass at age from the summer RV survey. The size of circle represents the relative proportion and the colors track year classes.

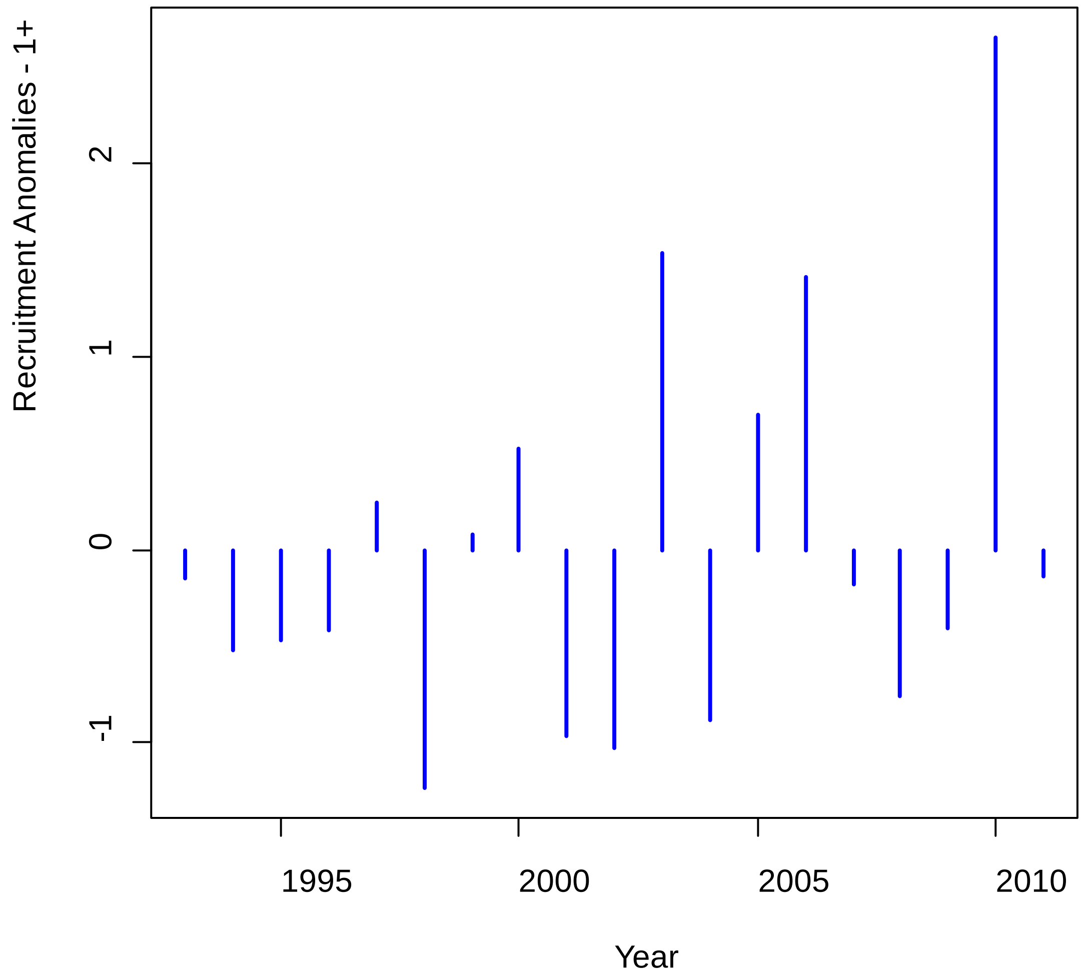

Figure 16: Recruitment anomalies estimated from the numbers at age 1 from the summer RV survey.

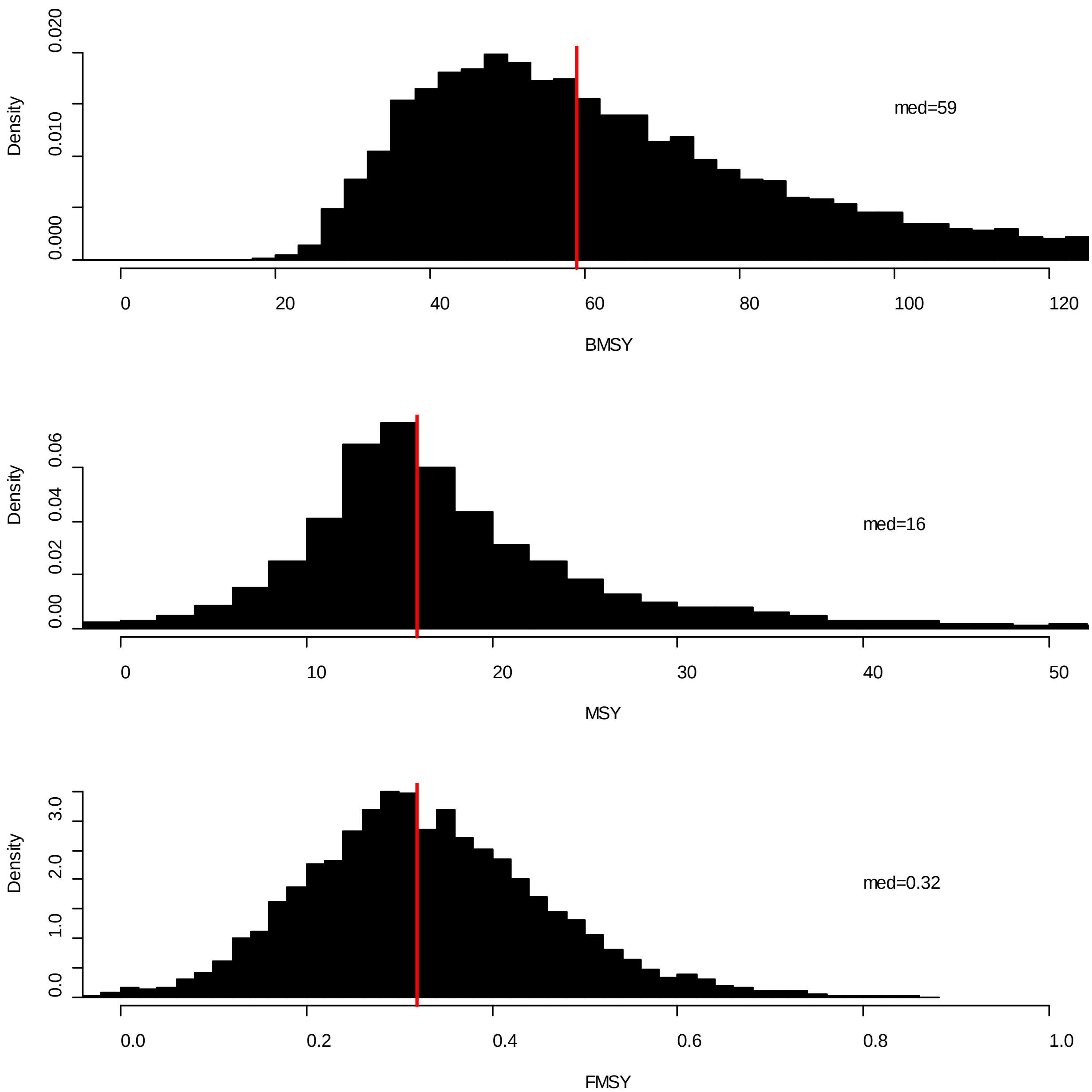

Figure 17: Estimated stochastic MSY reference points for 4VWX silver hake from the biomass dynamic model incorporating process uncertainty in the estimates.

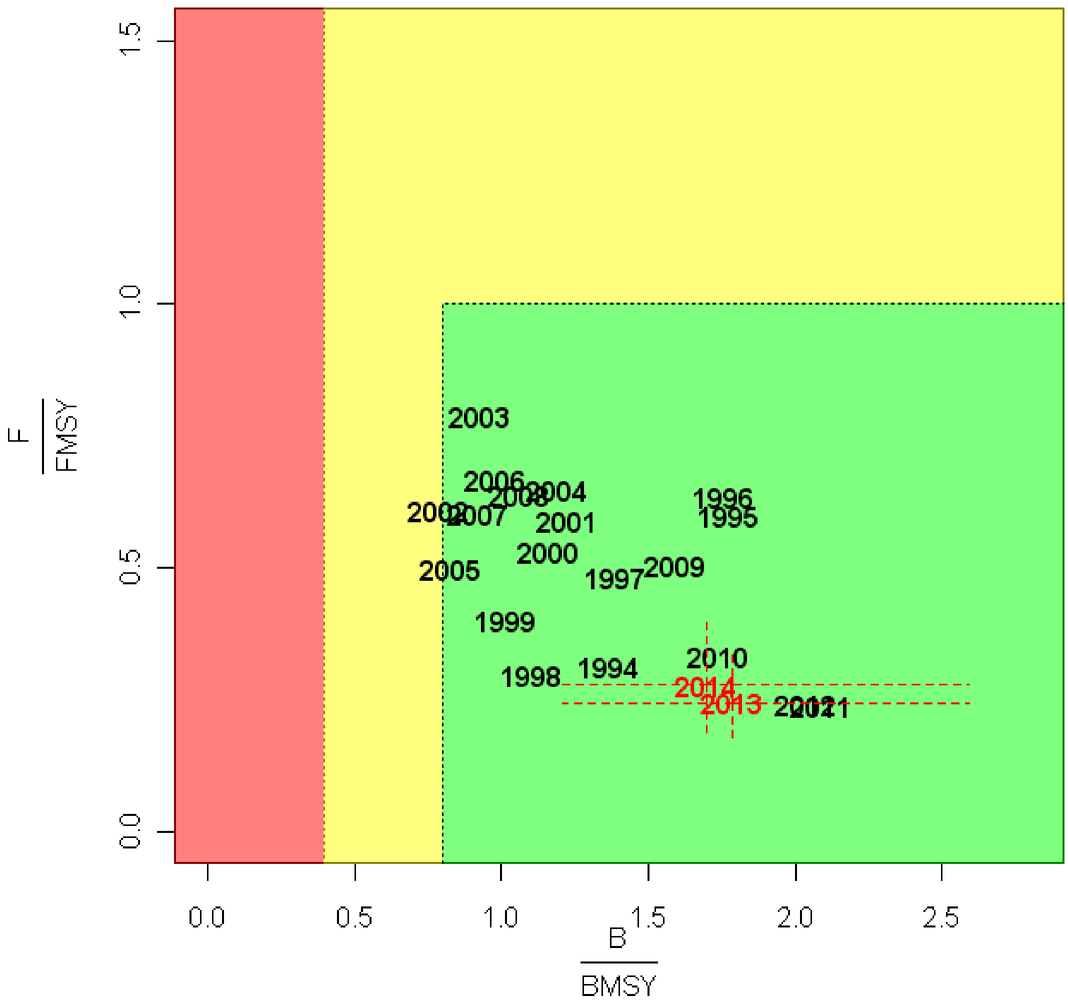

Figure 18: Phase plot of the ratio of current year fishing mortality (F) to F_{MSY} and biomass (B) to B_{MSY}. With one (2013) and two year (2014) projections under catch scenario 2, landings at 9989 t. Lines around 2013 and 2014 represent the 50% credible intervals for F and B.

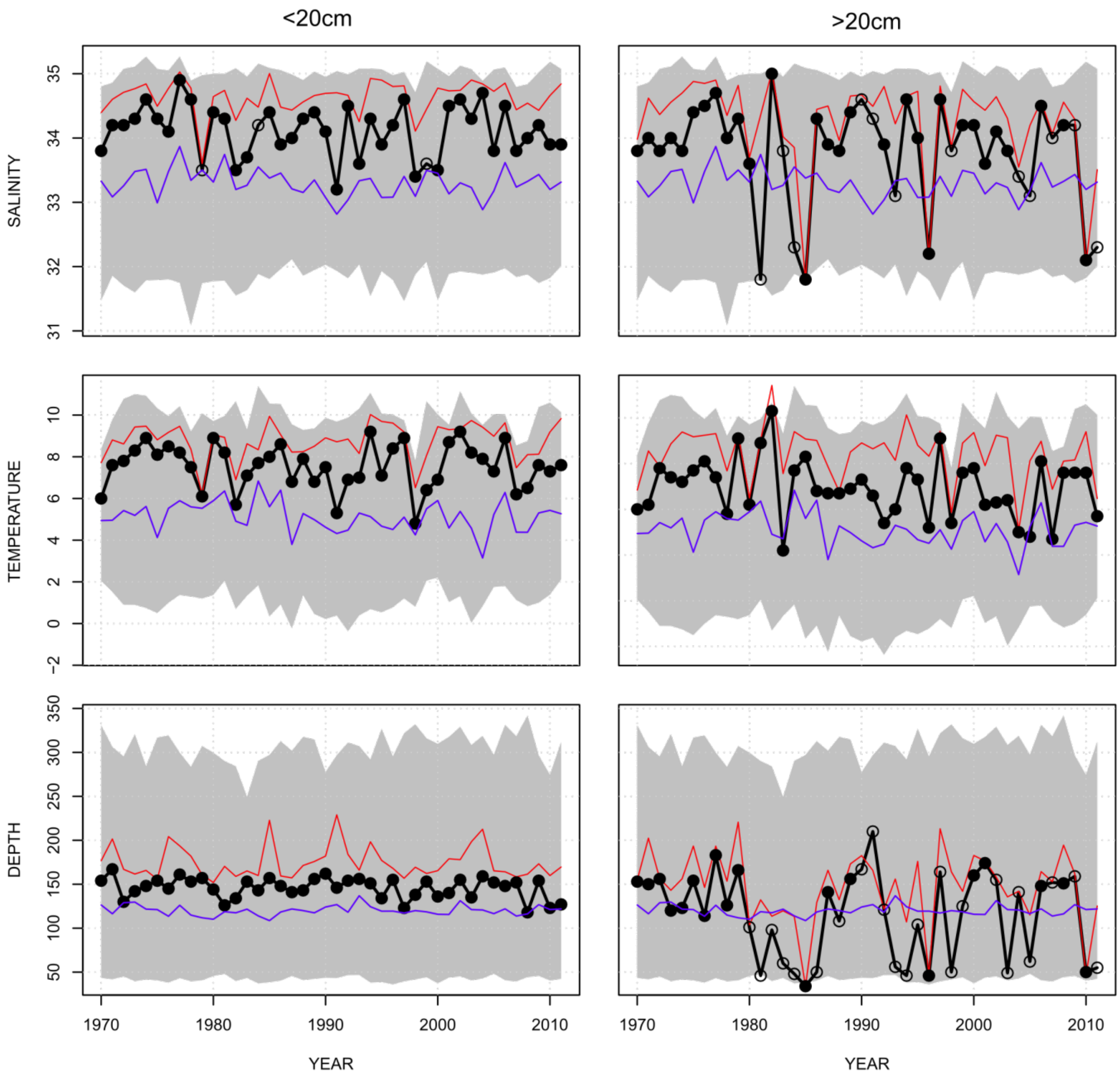

Figure 19: Time series of habitat preferences of silver hake as obtained from the RV summer survey series strata 440-483 between 1970 and 2011. Circles represent the location of maximum deviation of cumulative distributions from catch weighted effort and effort. Filled circles represent statistically significant habitat associations and open circles represent non significant associations. Red line indicates the median habitat occupied by silver hake. Purple line is the median sampled habitat. Shaded polygon in background is the 95th percentile for range of sampled habitat.

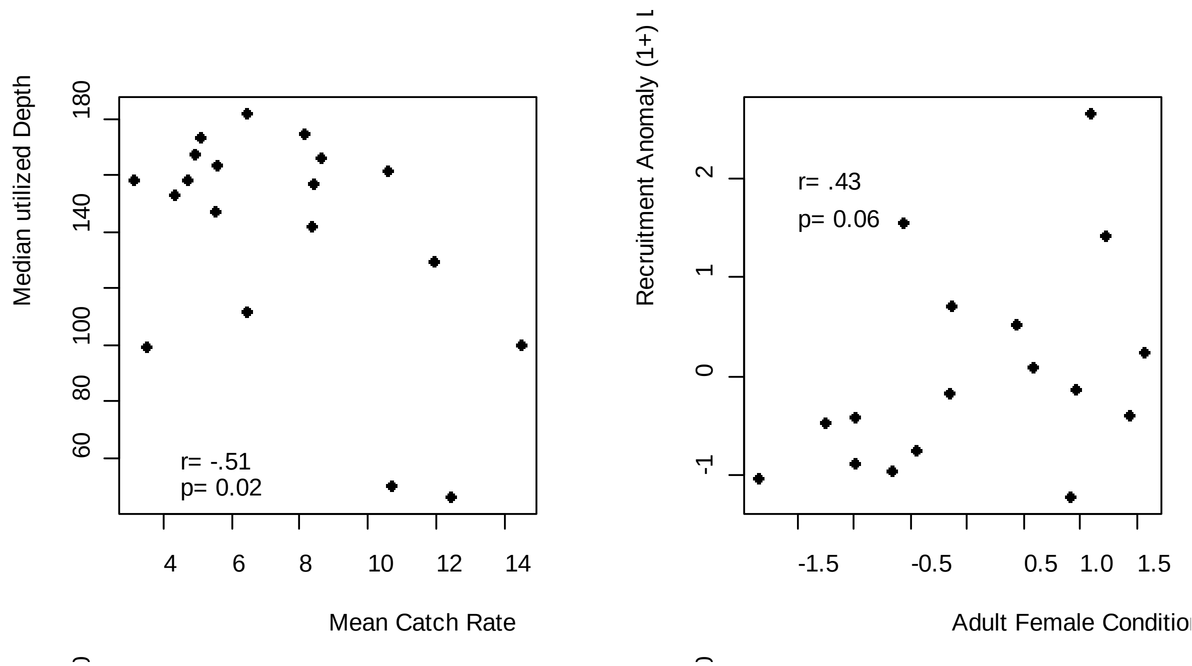

Figure 20: Relationships between median utilized depth and stratified catch rate (left), lagged recruitment anomalies and female condition (right). Data for these comparisons were taken from the summer RV surveys. r indicate the Pearson correlation coefficient and p is the respective p-value of the relationship.

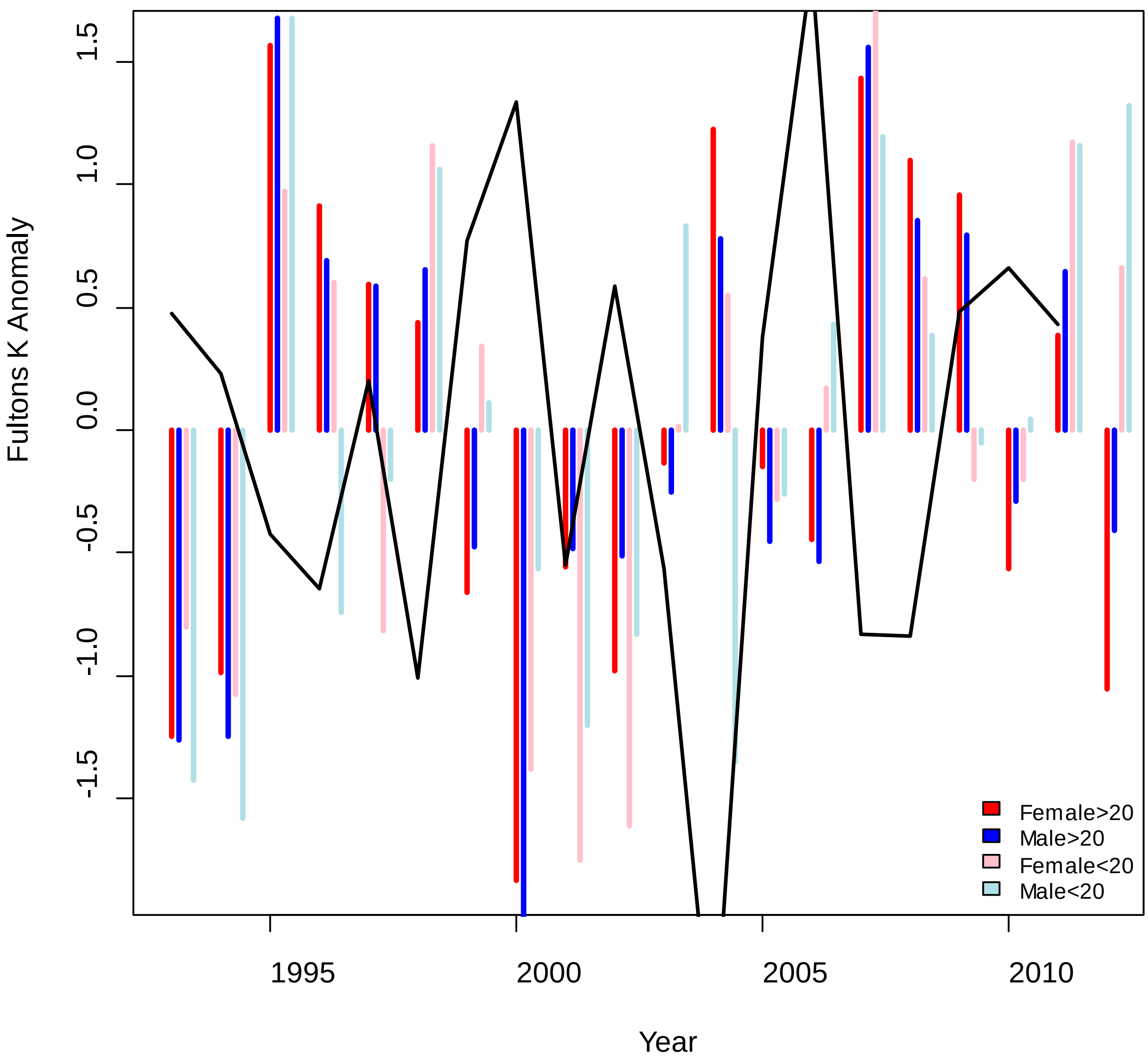

Figure 21: Fultons K anomaly and water temperature anomaly correlation between -0.64 and -0.58 for all except males <20 cm where there was no correlation.

APPENDIX 1

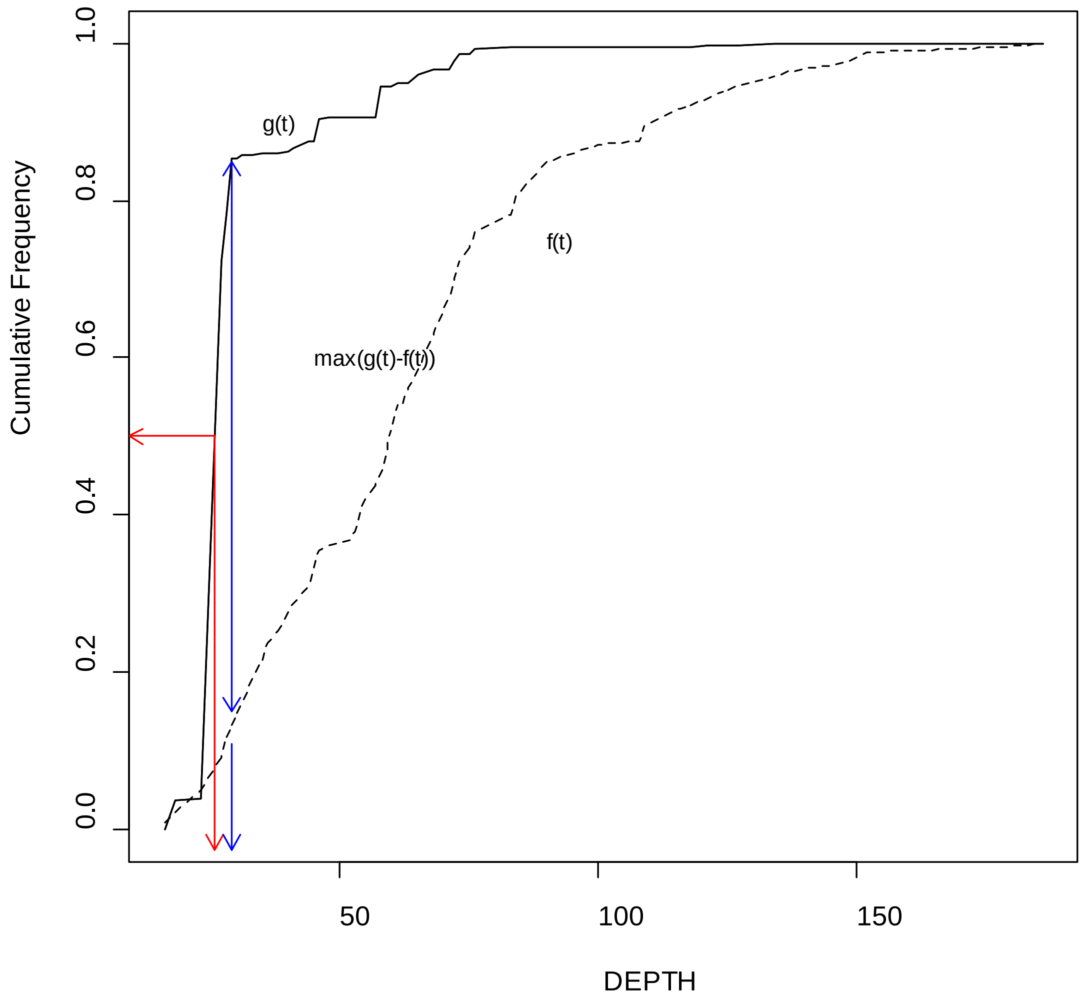

Figure A1: Example cumulative distribution functions of effort and catch from the summer RV survey. Red arrow indicates median depth of catch weighted sampling, blue arrows indicate the location of the maximum difference between the distribution of effort and catch curves.