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2007 STOCK ASSESSMENT AND PROJECTIONS FOR WESTERN ATLANTIC BLUEFIN TUNA USING A BSP AND OTHER SRA METHODOLOGY

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SUMMARY

This paper applies the ICCAT catalogued software BSP to evaluate recent trends in abundance of the western stock of Atlantic bluefin tuna (Thunnus thynnus) *and to evaluate the potential future trends in abundance from alternative total allowable catch policies. Data on stock mixing are not utilized and the models are fitted to stock trend data obtained west of 45°W. A prior for a key parameter, the intrinsic rate of increase, r, is formulated based on analysis of demographic data. The model utilizes ICCAT Task 1 records of catch biomass from the 1950s and is fitted to various combinations of fishery-independent and fishery-dependent stock trend indices for bluefin tuna to evaluate the sensitivity of results to the different datasets. The prior distribution for r was centred at 0.11. The posterior distribution for r was centred at lower values, i.e., 0.03-0.06, indicating that the population will decline with fishing mortality rates larger than these values. The estimates of the maximum sustainable yield were about 1100-2200 t depending on the dataset to which BSP was fitted. These estimates are generally less than that given by the ICCAT 2006 assessment which applied ADAPT VPA to catch-age data and stock trend indices dating back to the 1970s. The BSP also indicates that overfishing is still occurring and that the stock was overfished in 2006 and 2007 with respect to F_{MSY} and B_{MSY} reference points. Estimates of recent abundance trends are less optimistic than those from the 2006 ICCAT assessment. For example the estimated catch that could be taken without causing further decline was 2100 tons in the 2006 ICCAT assessment; the estimates obtained from BSP ranged from about 330 to 1620 tons depending on the indices to which BSP was fitted. Results were less sensitive to applying different priors for model parameters than to the set of stock trend indices to which the model was fitted. The only fishery independent stock trend index, i.e. the Gulf of Mexico larval survey index, gave among the least optimistic results, whereas runs fitted to the combination of the indices derived from commercial catch rate data gave the most optimistic predictions. The latter however were still less optimistic than the ICCAT assessment which was fitted to a combination of the larval and commercial indices. Projection results are considerably more pessimistic than those obtained from the 2006 ICCAT assessment. Those obtained by fitting BSP to the larval index indicated that increases in stock size could be expected if the TAC was lowered to about 300 tons. The most optimistic of the BSP runs that utilized a combination of the fishery dependent stock trend indices indicated that the maximum TAC that could still lead to increases in stock size was about 1600 tons. A BSP model was also fitted to conventional tagging data and a BSP model with a prior for harvest rates in the 1980s based on catch-at-age data gave results intermediate between produced by ICCAT BSP software and the 2006 ICCAT assessment.*

RÉSUMÉ

Le présent document applique le logiciel catalogué par l'ICCAT, BSP, afin d'évaluer les récentes tendances de l'abondance du stock occidental de thon rouge de l'Atlantique (Thunnus thynnus*) ainsi que les futures tendances potentielles de l'abondance à partir de politiques alternatives de prises totales admissibles. Les données sur le mélange des stocks ne sont pas utilisées et les modèles sont ajustés aux données de tendance des stocks obtenues à l'ouest de 45ºW. Une valeur préférentielle pour un paramètre clef, le taux d'augmentation intrinsèque, r, est formulée sur la base de l'analyse des données démographiques. Le modèle utilise les registres de la Tâche I de l'ICCAT de la capture en poids des années 1950 et est ajusté aux diverses combinaisons d'indices de tendances des stocks indépendants et dépendants des pêcheries de thon rouge, dans le but d'évaluer la sensibilité des résultats aux différents jeux de données. La distribution a priori pour r se centrait sur 0,11. La distribution a posteriori pour r se centrait sur des valeurs inférieures, c'est-à-dire 0,03-0,06, indiquant que la population diminuera avec des taux de mortalité de pêche supérieurs à ces valeurs. Les estimations de la prise maximale équilibrée s'élevaient à environ 1.100-2.200 t, en fonction du jeu de données auquel le BSP était ajusté. Ces estimations sont généralement inférieures à celles fournies par l'évaluation de 2006 de l'ICCAT, laquelle appliquait ADAPT VPA aux données de prise par âge et des indices de tendance des stocks*

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remontant aux années 1970. Le BSP indique aussi qu'il y a encore surpêche et que le stock était surexploité en 2006 et 2007 par rapport aux points de référence F_{PME} et B_{PME}. Les estimations des récentes tendances de l'abondance sont moins optimistes que celles de l'évaluation de 2006 de l'ICCAT. A titre d'exemple, l'évaluation de 2006 de l'ICCAT estimait à 2.100 t la prise qui pouvait être réalisée sans provoquer une nouvelle chute ; les estimations obtenues du BSP s'inscrivaient dans une échelle de 330 à 1-620 t en fonction des indices auxquels le BSP était ajusté. Les résultats ont été moins sensibles à l'application de différentes valeurs préférentielles pour les paramètres du modèle qu'au jeu d'indices de tendance des stocks auquel le modèle avait été ajusté. Le seul indice de tendance des stocks indépendant des pêcheries, c'est-à-dire l'indice de la prospection larvaire du Golfe du Mexique, a fourni un des résultats les moins optimistes, tandis que les passages ajustés à l'association d'indices obtenus des données de taux de capture commerciale ont donné les prédictions les plus optimistes. Ces derniers étaient néanmoins moins optimistes que l'évaluation de l'ICCAT qui était ajustée à une association d'indices larvaires et commerciaux. Les résultats de la projection sont considérablement plus pessimistes que ceux obtenus de l'évaluation de l'ICCAT de 2006. Ceux obtenus en ajustant le BPS à l'indice larvaire ont indiqué que si le TAC était ramené à environ 300 t, on pouvait s'attendre à ce que la taille du stock augmente. Le passage du BSP le plus optimiste qui utilisait une association d'indices de tendance des stocks dépendant des pêcheries indiquait que le TAC maximum qui pouvait encore entraîner des augmentations de la taille du stock se chiffrait à environ 1.600 t. Un modèle de BSP également ajusté à des données de marquage conventionnel et un modèle de BSP doté d'une valeur préférentielle pour la mortalité par pêche des années 1980 basés sur les données de prise par âge ont donné des résultats intermédiaires entre le logiciel BSP produit par l'ICCAT et celui issu de l'évaluation de 2006 de l'ICCAT.

RESUMEN

*Este documento aplica el software del catálogo de ICCAT, BSP, para evaluar las tendencias recientes en la abundancia del stock occidental de atún rojo del Atlántico (*Thunnus thynnus*) y para evaluar las futuras tendencias potenciales en la abundancia a partir de políticas alternativas de captura total admisible. Los datos sobre la mezcla del stock no se utilizan y los modelos se ajustan a los datos de las tendencias del stock obtenidos al Oeste de 45ºW. Se formula una distribución previa para un parámetro clave, la tasa intrínseca de incremento, r, basándose en el análisis de los datos demográficos. El modelo utiliza los registros de la Tarea I de ICCAT de biomasa de captura desde los 50 y está ajustado a varias combinaciones de índices de la tendencia del stock dependientes e independientes de la pesquería para el atún rojo con el objetivo de evaluar la sensibilidad de los resultados a los diferentes conjuntos de datos. La distribución previa de r se centró en 0,11. La distribución posterior de r se centró en valores menores, es decir, 0,03-0,06, indicando que la población descenderá con tasas de mortalidad por pesca superiores a estos valores. Las estimaciones del rendimiento máximo sostenible fueron de aproximadamente 1.100-2.200 t dependiendo del conjunto de datos al que se ajustara el BSP. Estas estimaciones son generalmente inferiores a la facilitada por la evaluación de ICCAT de 2006 que aplicó el ADAPT VPA a los datos de captura por edad y a los índices de tendencia del stock que se remontaban a los 70. El BSP indica también que se sigue produciendo sobrepesca y que el stock se encontraba sobrepescado en 2006 y 2007 con respecto a los puntos de referencia* F_{RMS} *y* B_{RMS}*. Las estimaciones de las tendencias de abundancia reciente son menos optimistas que las de la evaluación de ICCAT de 2006. Por ejemplo, la captura estimada que podría realizarse sin causar un mayor descenso era de 2.100 t en la evaluación de ICCAT de 2006; las estimaciones obtenidas del BSP oscilaban entre 330 y 1.620 t dependiendo de los índices a los que se ajustara el BSP. Los resultados eran menos sensibles a la aplicación de diferentes distribuciones previas para los parámetros del modelo que al conjunto de índices de tendencia del stock al que se ajustó el modelo. El único índice de la tendencia del stock independiente de la pesquería, el índice de la encuesta larval del Golfo de México, produjo resultados de los menos optimistas, mientras que los ensayos ajustados a la combinación de índices derivados de los datos de tasas de captura comerciales produjeron las predicciones más optimistas. Sin embargo, estos últimos eran todavía menos optimistas que la evaluación de ICCAT que se ajustó a una combinación de los índices larvales y comerciales. Los resultados de la proyección eran considerablemente más pesimistas que los obtenidos en la evaluación de ICCAT de 2006. Los obtenidos ajustando el BSP al índice larval indicaban que podrían esperarse aumentos en el tamaño del stock si el TAC se redujera hasta aproximadamente 300 t. El ensayo más optimista del BSP que utilizaba una combinación de los índices de tendencia del stock dependientes de la pesquería indicaba que un TAC máximo que podría aún conducir a incrementos en el tamaño del stock sería de aproximadamente 1.600 t. Los resultados de un modelo BSP ajustado también a los datos de marcado convencional y un modelo BSP con una distribución previa para las tasas de captura en los 80 basado en datos de captura por*

edad producían resultados intermedios entre los producidos por el software BSP de ICCAT y la evaluación de ICCAT de 2006.

KEY WORDS

Bayesian surplus production model, western Atlantic bluefin tuna, BSP

1. Introduction

For the last few decades, ICCAT stock assessments of western Atlantic bluefin tuna (*Thunnus thynnus*) have been carried out with applications of ADAPT VPA cohort analyses to data from the 1970s which have indicated that the stock is overfished and overfishing has been occurring. Assessments since the year 2000 however have incorrectly predicted increases in stock abundance with the catches that were subsequently taken when successive assessments have instead found only continued declines in abundance and since 2003 catches have fallen short of the total allowable catch by increasing amounts. Reasons why ADAPT has over-predicted the stock's ability to recover may include applying overly optimistic values for recent and future predicted recruitment. VPA may provide overly optimistic recruitment values for example from incorrectly assuming (a) input values for terminal fishing mortality rates that are too low, (b) that the mean value for future recruitment is best predicted by the mean of recent estimates of recruitment and independent of spawning stock size, or (c) that fishery dependent stock trend indices to which the VPA is tuned are unbiased (Walters and Maguire 1996). We apply an alternative stock assessment methodology to more fully account for uncertainty in the stock assessment and projections. This alternative assessment however still does not account for stock mixing and other information available in currently available mark-recapture data.

Surplus production models (SPMs) which model only surplus production and stock biomass and ignore age structure have often been applied in stock assessments. The most common implementation has been in the form of a stock reduction analyses (SRAs) whereby the model projects from the fishery's beginning to the present using the entire catch time series and is fitted to stock trend indices. While the approach may be prone to bias from ignoring age-structured processes, simulation evaluations using age structured models to simulate data have shown that this relatively simple model can often reliably estimate stock abundance trends and provide reliable predictions of future stock trends (Ludwig and Walters 1985; Punt 1993; Kirkwood 1996). This, combined with the simplicity of the model and the small number of parameters to estimate in it when compared to age-structured models, have made it attractive to stock assessment scientists, especially when age-structured data and information are relatively sparse yet catch biomass and stock trend indices are available.

This paper applies the catalogued ICCAT software, BSP (McAllister and Babcock 2001), to evaluate historic trends in abundance of the western stock of Atlantic bluefin tuna (*Thunnus thynnus*) and to evaluate the potential future trends in abundance from alternative total allowable catch (TAC) policies. A prior for a key parameter, the intrinsic rate of increase, *r*, is formulated with a methodology that utilizes demographic data for the fish stock of interest (McAllister *et al.* 2001a). The model utilizes ICCAT Task 1 records of catch biomass from the 1950s and is fitted in separate runs to fishery independent and fishery dependent stock trend indices for mature bluefin tuna to evaluate the sensitivity of results to the different datasets. Stock projections from 2008 to 2022 are carried out to evaluate the potential consequences for stock rebuilding of alternative fixed TAC policies.

2. Methods

The stock assessment model applied is the Schaefer surplus production function (Hilborn and Walters 1992). The version applied is deterministic and applies continuous fishing mortality rate equations (Prager 1994).

$$B_t = B_{t-1} + B_{t-1} r \left(1 - \frac{B_{t-1}}{K}\right) - C_t \qquad (1)$$

where B_t is stock biomass in year t, r is the intrinsic rate of increase, K is the average unfished stock size or carrying capacity, and C_t is the catch in year t. For details on the BSP stock assessment methodology and software we refer readers to McAllister and Babcock (2001) and McAllister *et al.* (2000; 2001a). The catch biomass data are presumed to be accurate and are shown in **Table 1**. The parameters estimated include average unfished stock size or "carrying capacity" (K), the intrinsic rate of increase (r), the stock size in 1950 relative to carrying capacity ($P_0 = B_{50}/K$), and the constant of proportionality for each stock trend index (q). An informative prior is assumed for P0:

$$P_0 \sim \text{lognormal}\left(\ln(1), \sigma^2_{P_0}\right). \quad (2)$$

A noninformative prior is presumed for q, i.e., the prior density for q proportional to 1/q (Walters and Ludwig 1994). The prior for K is uniform over a large range of values outside of the area of support by the data (i.e., between 500t and 200,000t).

We reformulated the demographic approach in McAllister *et al*. (2001a) for computing an informative prior pdf for *r* so that the inputs conform to those more commonly available for exploited fish stocks. The Euler-Lotka equation (Lotka 1907) is numerically solved for r with the integration over ages starting at age 0:

$$1 = \int_{a=0}^{\infty} l_a m_a \exp(-a \times r) da \quad (2a)$$

where l_a is the fraction of animals surviving from age 0 to age *a* where the fraction is set at 1 for l_0, and m_a is the number of age 0 offspring expected to be produced by an individual of age *a*

$$l_a = l_0 \exp(-a \times M) \quad (2b)$$

It can be shown that, providing that there is no reproduction in age 0, a computation in which the integration starts at age 1 and l_1 is set to 1 and m_a is specified in terms of age 1 recruits is analytically equivalent to equation 1a. This latter formulation is more convenient for fisheries modelling because most exploited fish species do not reproduce at age 0 and estimates of recruits per ton of spawners for age 1 recruits at spawner abundance approaching zero ($\widetilde{R}_S$) and the expected mass-at-age of spawners, W_a, are more commonly available than the survival of age 0 to 1 fish and the expected production of age 0 fish per spawner. m_a is thus obtained by:

$$m_a = \widetilde{R}_S W_a G_a \quad (3)$$

where $\widetilde{R}_S$ is age 1 recruits produced per ton of spawners when spawner abundance approaches zero, W_a is the mass per fish of age *a* in tons, and G_a is the fraction of animals of age *a* that are mature.

The computation thus requires a value for the rate of natural mortality for ages 1 and older (*M*), the fraction mature at age, the number of age 1 recruits produced per ton of spawners, and the mass per fish in tons for each age. Senescence was presumed at age 30 years. This computation utilizes the same RV for *M* as in the computations for initial harvest rate (see below). The rate of natural mortality, *M*, was treated as a lognormal random variable with a median of 0.14 yr^{-1} (ICCAT 2003) and the value for the standard deviation in the natural logarithm of *M* set at 0.2. $\widetilde{R}_S$ is assumed to be a uniformly distributed random variable with a minimum of 5 and a maximum of 12 age-1 recruits per ton of spawners. The bounds for $\widetilde{R}_S$ were obtained from McAllister *et al.* (2001b) based on stock recruit data from 1970-1993. The bounds reflect values slightly lower than the minimum value and slightly larger than the maximum value estimated for $\widetilde{R}_S$ from the set of scenarios considered ranging from Beverton-Holt and 2-line stock recruit functions and a shift versus no shift in carrying capacity in 1981.

The fraction mature at age, G_a, can be treated as a random variable based on results from reproductive studies. However, in this case, a recent study of size frequency distributions and age at maturity in the Gulf of Mexico with large sample sizes from harvests since the 1980s has provided a precise estimate of the fraction mature at age (Diez and Turner 2006). The values for G_a that were applied are shown in **Table 2**. This is a marked update from previous ICCAT assessments in which knife-edge maturity was assumed at age 8. This also required the estimates of recruits per ton of spawners to be adjusted to account for the revised maturity schedule. The mean and standard deviations (SD) for *r* were 0.113 and 0.031 **(Table 3)**. The histogram for *r* can be closely approximated by a normal pdf **(Figure 1)**.

The catch biomass data for western Atlantic bluefin tuna ranged from 1950 to 2005 and were obtained from the ICCAT Task I database for this stock and include catches from the various fleets that reported catches of this species west of 45 degrees west and also estimates of dead discard provided to ICCAT **(Table 1)**. As ICCAT records extended only to 2005, estimates of total catch biomass for 2006 and 2007 are based on reports on the Canadian Department of Fisheries and Oceans, US NOAA and other websites indicating catches of western Atlantic bluefin tuna in these years. The values presumed were 1552 tons in 2006 and 1500 tons in 2007.

The stock trend indices to which the BSP model was fitted included only those that indexed the larger sized fish in the stock so that the BSP tracked mainly the mature and near mature components of the population **(Table 4)**. These indices were obtained from ICCAT (2007) and included the Gulf of Mexico larval index (representing ages 10+), the US Gulf of Mexico and east coast Florida pelagic long line index (ages 10+), Canadian Gulf of Saint Lawrence (CGSL) index (age 13+), Canadian south west Nova Scotia index (ages 7-10), and the Japanese longline in ICCAT Area 2 of the north eastern Atlantic (ages 2-9). Some of the indices show very different trends **(Figure 1)**. For example, the Canadian modified GSL index shows a several-fold increase since the early 1990s whereas the larva index shows a several-fold decrease. The Canadian 4XU SW NS index and US PL LL GOM indices show large declines since the late 1980s and no trend since the early 1990s. Possible reasons for inconsistencies are many but could include (1) the indices are accurately tracking different stock components, e.g., different age groups, or different spawning stock components and (2) some of the indices such as the Canadian ones indicate changes in habitat use over time, e.g., a larger fraction of the stock foraging the Gulf of Saint Lawrence in the last decade.

Fitting a stock assessment model to all of the available stock trend indices even if some show inconsistent trends is common (e.g., ICCAT 2007). However, this tends to hide uncertainty in the stock trend over time since the net effect of fitting a model to several different indices is to average of the trends shown by the different indices, even when some show entirely different trends in abundance. In contrast, some have advocated that when stock trend indices show very different trends, the assessment model should be fitted to them separately to more fully account for uncertainty in historic trends in stock size (Punt and Hilborn 1997).

To evaluate the effects on stock assessment results of fitting the assessment model to all indices combined versus subsets of them and applying different weightings t the different sets, seven different combinations of indices were formed for different BSP model runs **(Table 5)**. Possibly the most reliable index of Gulf of Mexico (GOM) spawning stock abundance is the GOM larval research survey index. This is a fishery independent index of larval abundance in which sampling gear and sampling protocol have been consistently applied since the mid 1970s. In this paper, I treat the GOM larval index as the "base case" stock trend time series to which runs with other combinations of indices are compared. In contrast, the other indices are all fishery dependent indices obtained from statistically analysing commercial catch per unit effort data (cpue) from various fishing fleets in different areas. Even when area, season and vessel effects are estimated and removed from the cpue time series, misreporting of catch and effort records from various fishing fleets, changes in species targeting, fleet distribution, and gear innovations can still cause biases in the cpue stock trend indices (Walters and Maguire 1996; Walters 2003). Six additional BSP model runs were made that were fitted to different combinations of the five stock trend indices. Some included different combinations of only the commercial cpue indices (runs 2-3). Some included the larval index and some or all of the cpue indices (runs 4-7). Some assigned different weights to the larval and cpue series (runs 4-5).

The sensitivity of results to alternative prior specifications for r and the ratio of stock size to carrying capacity in 1950 were also evaluated with the BSP fitted to the larval index and then to the combined set of indices (runs 8-11, and 12-13, respectively, **Table 5**).

In most of the runs, the value for the variance parameter σ the lognormal likelihood function of the stock trend data was fixed for each time series based by rounding up maximum likelihood estimates obtained by fitting a deterministic surplus production model to each stock trend index separately in Excel (see **Table 5**). Where more weight was to be given to the larval index, the value for σ was increased from 0.5 to 1.0 for the cpue stock trend indices but kept at 0.5 for the stock trend indices.

Projections were done from 2007-2022 to evaluate the potential future stock trends resulting from alternative fixed TAC policies. Median stock biomass of approximately age 8+ fish and stock biomass to stock biomass at

MSY trajectories with 90% PIs were computed for each TAC policy under the different stock trend index options.

The retrospective analyses were carried out for the most recent years in which stock assessments had been carried out, i.e., 2000, 2002 and 2006. This was to evaluate whether there are systematic patterns of apparent over or under estimation of abundance and fishing mortality rates in the final year and whether projections from past stock assessments tend to recurrently be overly optimistic or overly pessimistic. Retrospective patterns are evaluated in assessments carried out with the larval index only versus all five indices in the same assessment with equal weighting **(Table 5)**.

The importance function utilized in importance sampling was a multivariate t log distribution with the median set to the posterior modal estimate for each estimated parameter and the marginal variances set values the same as or slightly larger than the prior variance, and covariances set to 0. This resulted in very well behaved importance sampling with the maximum weight dropping progressively as the number of importance samples increased. The main stopping rule for importance sampling approximations to the target posterior probability distributions included the following. The maximum relative probability weight assigned to a single draw was set to 0.5% and the number of draws of parameters that resulted in non-zero stock size to the present had to exceed 50,000. Importance functions with different marginal variance values were utilized for the same estimation to ensure that the posterior results obtained were insensitive to the importance function used in importance sampling. 5000 resampled importance draws were utilized in the stock projections.

For results from an application of a new state-space BSP approach that is fitted to conventional tagging data for western Atlantic bluefin tuna data, please see **Appendix 1**.

3. Results

Posterior means and posterior CVs (in parentheses) are provided for the estimated quantities unless stated otherwise. Under the base case estimation, the BSP was fitted to the Gulf of Mexico larval survey index (run 1). The model fitted the data without any serious autocorrelation in deviations between observed and predicted values **(Figure 2)**. However, the first two data points in the time series were considerably higher than the model predicted values. The posterior mean for the intrinsic rate of increase *r,* 0.06, was considerably less than the prior mean of 0.113, but the posterior SD was only slightly less than the prior SD than the prior for *r* (**Table 6** and **Figures 2, 3**). The posterior mean for the average unfished stock size, *K*, 148,000 t (21%) was in contrast, considerably more precise than the prior for *K*. The posterior mean for MSY is 2210 t (34%), less than that that obtained by the VPA in the 2006 ICCAT assessment **(Table 6, Figure 3)**.

The stock status results **(Table 6a, Figures 4, 5)** suggest that stock size is low relative to its unfished stock size (K) and its B_{MSY} reference point, i.e., under the base case estimation, it is currently at about 5% (42%) of K and about 10% (42%) of stock biomass at B_{MSY}. These estimates are considerably more pessimistic than those obtained from the cohort analyses in the 2006 stock assessment that indicate that the stock is at about 41% of B_{MSY} (**Table 6** and **Figure 4**). The estimate of F_{2007}/ F_{MSY} is about 10 (108%) which is over quadruple the ICCAT (2007) estimate for the year 2005. The estimate of the replacement yield (the amount that can be harvested so that the stock will not increase or decrease in the next year) is 380 tons (51%) much less than the ICCAT (2007) estimate of 2300t. Stock status results were very similar when the prior mean for stock size relative to *K* in 1950 was changed from 1.0 to 0.8. Stock size varied by a factor of nearly two when the prior mean for *r* was increased and decreased by one prior SD (Runs 10 and 11) but was still very low in both instances, i.e. at 5500 and 9600 tons for the low r and high r scenarios, respectively **(Table 6b)**.

Fifteen-year projections (2008-2022) were made on the basis of differing levels of constant total allowable catch ranging from 0 tons up to about 2000 tons. The results for the base case run are summarized in **Table 7**, Figure 5 (B_y/B_{MSY}) and Figure 6 (F_y/F_{MSY}). Upward median trajectories of B_y/B_{MSY} occur only in cases where the TAC is 300 tonnes or less. Similarly, sustainable rates of F_y/F_{MSY} (approximately <2) are achievable in the future where TAC is 300 tonnes or less. At the levels of TAC of 400t or more, the median B_y/B_{MSY} falls steadily in future years and F_y/F_{MSY} exceeds 2 and increases in all future years. The projection with a TAC of zero gives B_y/B_{MSY} of 35% in 2022 with a 5% chance of being less than 20% of B_{MSY} in 2022. Changing the prior mean for stock size relative to carrying capacity in 1950 from 1 to 0.8 gave similar results **(Table 7)**. Projections results were also very similar when the prior mean for r was decreased to 0.08 and increased to 0.15, i.e., here the TAC also needed to be decreased to 400 tons to achieve increases in future stock size.

In contrast, the assessment runs in which BSP was fitted to commercial cpue data only provided considerably more optimistic estimates of stock status (Table 6a). When the most optimistic index, CAN GSL was excluded (run 2), the estimates of current stock size were over three times higher at about 40,000 t (44%) and stock depletion considerably less, i.e., at 0.21 (27%). The estimated ratio F_{07}/F_{MSY} was 2.7 (110%). Including the CAN GSL index (run 3) gave even more optimistic results, for example, with current stock size at 69,000 t (53%). Including both the larval survey index and all of the cpue indices but giving more weight to the larval index (run 4) gave results for stock status intermediate between run 1 and runs 2 and 3 **(Table 6)**. Giving equal weight to the larval index and cpue indices gave similar results to run 2. Using both the larval index and the cpue indices, giving them equal weight but excluding the CAN GSL index (run 6) gave slightly more optimistic results than run 4 but much more optimistic than run 1 where only the larval index was utilized. Excluding the JLL and CAN GSL index but including the larval index and CAN 4X SWNS and GOM PLL indices gave results similar to run 1 with replacement yield at only 330 t. The more optimistic estimates of K where BSP was fitted to cpue data resulted in the more optimistic estimates of stock status.

Stock projections were markedly more optimistic when BSP was fitted to either cpue data alone or a combination of cpue data and the larval index **(Table 7)**. The most optimistic projections that included the cpue data and the CAN GSL index indicated that increases in stock size could be achieved over a 15-year period with greater than 50% probability with TACs up to 1600 kt. A larger than 50% chance of rebuilding to B_{MSY} could be obtained in 15 years or less with TAC policies of 300 tons or less. The runs based on combinations of the larval index and cpue data (runs 4-7) suggested that increases in stock size could be achieved with greater than 50% probability over a 15-year period with TACs no larger than 300-1100 t.

Retrospective analyses for BSP fitted to the larval index suggested a slight retrospective pattern of under-estimation of surplus production in that carrying capacity estimates increased by about 5% per assessment from the 2000 to the 2002 assessment and also from the 2002 to 2006 assessment. The replacement yield estimate for the final year remained very similar in all years, i.e., low at about 300-400 tons whereas in each assessment it showed a decrease over the last several years. The BSP fitted to all five indices showed little difference in parameter estimates between the 2000 and 2002 assessments and a marked increase in estimates of carrying capacity, stock biomass and most of all replacement yield (doubling) between the 2002 and 2006 assessments, presumably due to the marked increase in the GSL index in the most recent years. However, the replacement yield estimate for the 2006 assessment, i.e., about 1200t, was still much less than that in the ICCAT 2006 assessment.

4. Discussion

This paper presents results obtained with the ICCAT catalogued stock assessment software, BSP. The base case results in which the model is fitted to the 1977-2005 Gulf of Mexico bluefin tuna larval survey index indicate that stock size is at about 5% of unfished conditions and 10% of B_{MSY} with a total exploitable stock biomass of about 5,000 tons **(Figure 2)**. The estimated replacement yield for 2007-8 is very small at about 380 tons (posterior CV = 51%). The TAC would need to be lowered markedly from 2100 t to about 300 tons to provide more than a 50% chance of having the stock increase over the next 15 years. Even if the catch was decreased to zero, the stock could be expected to approach only about 20% of B_{MSY} in 2022. The estimate of MSY provided by BSP of 2200 tons is less than that provided in the 2006 ICCAT assessment (3200 tons). Base case BSP results on stock status and projections are markedly less optimistic than the ICCAT 2006 assessment results. The latter indicated that the replacement yield was about 2300 tons, stock size in 2004 was at 41% of B_{MSY}. With catches of 2100 tons or less the stock was predicted to increase from the year 2007. In contrast, catches in 2006 and 2007 appear to be much less than the TAC of 2100 tons and the base case BSP model results show only continued declines in stock size to the year 2007.

Unlike the ICCAT ADAPT VPA model which models the stock starting in 1970, the BSP model tracks abundance from the early 1950s to the year 2007 under the assumption that the stock started near to unfished conditions in the early 1950s. This appears to be reasonable since in the early 1950s reported catches were relatively low at about 1000 tons, much less than those in the 1960s and 1970s. Stock status and projection results were very similar when the prior mean for initial stock size relative to unfished stock size was changed from 1.0 to 0.8. Results were also very similar when the prior mean for r was decreased to 0.08 and increased to 0.15.

The BSP modelling ignores the issue of stock mixing between eastern and western Atlantic spawning stocks (ICCAT 2002). Recent findings from electronic tagging studies shows considerable mixing of Mediterranean spawning bluefin tuna in the western Atlantic (Block 2001; 2005). Thus the Task 1 catch biomass estimates for the western Atlantic include both western and eastern spawning bluefin tuna stocks. If the annual catches were to be corrected for the fraction of western spawning Atlantic bluefin tuna, it is likely that the estimates of stock size for the western stock would be lower than those provided in this paper, presuming that the relative abundance of Mediterranean spawning fish has not increased markedly over time.

The BSP model also assumes inputted catch biomass values to be accurate and that there is no process error in the surplus production function. Given recent findings of under-reporting of catches of eastern and southern bluefin tuna (ICCAT 2007), potential inaccuracy of ICCAT catch records for western Atlantic tuna are also plausible but as yet unquantifiable. It would appear that interannual changes in surplus production could be expected to deviate in a stochastic manner from deterministic predictions of the surplus production function as in Myer and Millar (1999). In another paper (McAllister and Carruthers 2008, *in press*), I apply a variant of Meyer and Millar (1999) also to catch biomass and stock trend data for western Atlantic bluefin tuna to evaluate the sensitivity of results to the form of the surplus production function and to including process error in surplus production. The current application also presumes stationarity in key population dynamics parameters since 1950. The latter paper also explores the sensitivity of results to this assumption.

In contrast to results provided by fitting the BSP model to the larval survey index, the estimates of historic stock trends, stock status and stock projection results were markedly more optimistic when the BSP model was also fitted to commercial catch per unit effort data. For example, when the model was fitted to the four time series of cpue data, leaving out the larval index, the current stock size was at about 33% of carrying capacity, rather than only 5%, and stock size was 69,000 tons rather than only 8,000 tons. Stock projections indicated that TACs as large as 1600 tons could be expected to result in increases in stock size over the next 15 years. However, even if the TAC was set to zero, the stock biomass could be expected to reach only about 87% of B_{MSY} in the next 15 years. The most run with all indices weighted equally indicated that even if the TAC was decreased to zero stock size would reach only 66% of B_{MSY} within about 15 years. All BSP runs were however considerably less optimistic than the 2006 ICCAT assessment run.

This application utilized demographic data and information available for Atlantic bluefin tuna to formulate a prior probability distribution for r. Given the high median age at maturity of about 11.5 years, the prior mean for r is quite low at about 0.11. Given the relatively high degree of certainty in the recent updated estimate of the median age at maturity, the prior distribution for r is quite precise with a prior SD of 0.03. This is despite the considerable uncertainty in the rate of natural mortality (prior CV of about 0.2) and in the recruits per unit of spawner biomass at the lowest stock size. Together with the stock trend indices to which the model was fitted and the relatively uninformative prior for K, this informative prior for r resulted reasonably precise estimates of stock trends and current status.

The paper demonstrates that results for this assessment are less sensitive to implementing variants to the informative prior pdfs for r and B_{1950}/ K than they are to fitting the model to different stock trend indices. This is perhaps due to the long time series of catches and the moderately informative stock trend index applied which extends for about three decades and shows large decreases near to when catch removals are largest. This paper demonstrates that in contrast estimates of stock status and stock projection results are highly sensitive to the set of stock trend indices utilized in the stock assessment and the amount of weighting given to the different stock trend indices. This is not a new finding for the western Atlantic bluefin tuna assessment (e.g., ICCAT 1999; McAllister *et al.* 2001b) and has given rise to considerable acrimony in past assessments of this stock. The paper also demonstrates that the assessment results are far more sensitive to the stock trend index assumed than the prior means applied for key input parameters. The paper supports previous recommendations that (1) stock assessment models should not be fitted to combinations of stock trend indices that show different trends in abundance but instead should be fitted only to sets of stock trend indices that show consistent trends and (2) results from fitting the model to different sets of stock trend indices should be communicated to fisheries managers to convey the uncertainty in the assessment resulting from inconsistent stock trend indices (Schnute and Hilborn 1993).

Age-structured methods based on cohort analysis have used in the stock assessment of Atlantic bluefin for the last few decades (ICCAT 1999, 2003, 2007). While these methods capture the age-dependent features of Atlantic bluefin tuna, they appear to have over-predicted recent recruitment and the propensity of the western stock to rebuild with the total allowable catches that have been adopted by ICCAT, especially in assessments since the year 2000. Although a long time series of catch-age data (starting in the mid-1970s) and several different age-dependent stock trend indices are available, the predictive ability of cohort-based stock assessments may be compromised by several different factors. For example, it is well known that the precision from VPA is least for the estimates of recruit abundance in the most recent years. VPAs can also, for a variety of reasons, exhibit retrospective patterns in estimation of recruitment such that the methods give forecasts that consistently turn out to be more optimistic than the estimated stock response after the policy has been implemented, especially if stock size is low and fishing mortality rates are high (Walters and Maguire 1996; Pastoors 2005). Even if there is intensive sampling of commercial catches for length frequency and accurate age-length keys, information about cohort strength may be limited due to considerable overlap of length modes of adjacent cohorts. Additional errors in VPA stock assessments can occur due to incorrect assumptions about terminal fishing mortality rates and about fishing mortality at age for incomplete cohorts at the end of the catch-age time series. The precise reason for why the ICCAT VPA assessments have incorrectly predicted increases in stock size when stock size has only continued to decrease are not entirely clear.

This paper indicates one possible source of positive bias in recent VPA assessments which is to tune the VPA model to a large number of stock trend indices some of which indicate very different trends in stock size. The effect of this is to estimate with high precision a stock trend which is approximately the average trend across the various indices. This estimated trend can be incorrect and inconsistent with the stock trend indices that deviate from the mean. If a pair of indices are assumed to track the same stock component but show inconsistent trends, they cannot both be correct and averaging the result as is achieved by fitting a model to both indices at the same time will produce an incorrect stock trend estimate, for example, showing no change when the stock is actually decreasing or vice versa. Thus one potential reason for ICCAT assessments overly optimistic stock projections has been that it has been finding a mean stock trend through the commercial cpue indices when in fact many of these are too optimistic. This paper effectively demonstrates the overly precise and possibly incorrect estimates of stock trend can be obtained by fitting a stock assessment model to combinations of inconsistent stock trend indices. It demonstrates that a much wider variety of plausible results can be obtained by fitting the model to groups of indices that show different stock trends and that inconsistency in stock trend indices creates far more uncertainty in assessment results than uncertainty over the values for stock assessment model parameters. In the case of Western Atlantic bluefin tuna, the paper suggests that the stock status and projection results from recent ICCAT VPA assessments of this stock may be too optimistic and that it is plausible that stock status could be far lower than given by the 2006 assessment and that increases in stock size are possible with TACs that are far smaller than the one recently adopted for the western stock in 2006.

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Table 1. Total catch biomass of western Atlantic bluefin tuna in thousands of tonnes. Source for years 1950-2005 is the ICCAT Task I database available at the ICCAT website. See text for the approximations 2006-7. Catch biomass is in 000's of tons.

Year	*Catch biomass*	*Year*	*Catch biomass*
1950	1.007	1979	6.255
1951	1.096	1980	5.801
1952	0.629	1981	5.771
1953	1.084	1982	1.445
1954	0.823	1983	2.542
1955	0.544	1984	2.292
1956	0.247	1985	2.685
1957	0.546	1986	2.322
1958	1.207	1987	2.592
1959	1.57	1988	3.011
1960	1.032	1989	2.867
1961	1.62	1990	2.798
1962	5.799	1991	2.9919
1963	13.838	1992	2.2817
1964	18.679	1993	2.368
1965	14.171	1994	2.113
1966	8.09	1995	2.423
1967	5.94	1996	2.495
1968	3.176	1997	2.334
1969	3.012	1998	2.657
1970	5.466	1999	2.772
1971	6.591	2000	2.775
1972	3.948	2001	2.785
1973	3.871	2002	3.319
1974	5.393	2003	2.347
1975	5.032	2004	2.107
1976	5.883	2005	1.829
1977	6.694	2006	1.552
1978	5.763	2007	1.500

Table 2. Demographic parameters used to compute a prior pdf for the intrinsic rate of increase, r.

age	*mass at age (in kg)*	*fraction mature at age*
1	2.5	0.000
2	8.5	0.000
3	18.9	0.000
4	33.9	0.000
5	53.4	0.000
6	77.0	0.000
7	104.0	0.000
8	134.0	0.006
9	166.2	0.037
10	200.3	0.142
11	235.5	0.360
12	271.5	0.640
13	307.9	0.858
14	344.2	0.963
15	380.1	0.994
16	415.4	1.000
17	449.9	1.000
18	483.5	1.000
19	515.9	1.000
20	547.1	1.000
21	577.0	1.000
22	605.5	1.000
23	632.7	1.000
24	658.6	1.000
25	683.1	1.000
26	706.2	1.000
27	728.1	1.000
28	748.7	1.000
29	768.0	1.000
30	786.2	1.000

Table 3. Prior means and SDs of model parameters.

Parameter	*Prior density function*	*Comments*
K	Uniform(50, 200)	Units in thousands of tons
q	Proportional to 1/q	This was applied for each index
P_0	Lognormal(ln(1), 0.2^2)	This indicates that the stock was at near carrying capacity in 1950.
r	Normal(0.113, 0.030^2)	The relatively low prior mean comes largely from the late median age at maturity of 11.5 years and relatively low estimates of recruits per ton of spawner biomass at the origin of the stock-recruit function.

Table 4. Stock trend indices for western Atlantic bluefin tuna. These include the Gulf of Mexico (GOM) larval index (indexing ages 10+), the US pelagic long line index from the Gulf of Mexico and Florida east coast (US PLL GOM REP MEANS) (ages 10+), Canadian Modified Gulf of Saint Lawrence (CAN Modified GSL) Index (ages 13+), Canadian south west Nova Scotia index (CAN 4XU SWNS) (age 7-10), and Japanese long line in the north western Atlantic (JLL AREA 2 (WEST)). "-1" entries indicate no index available for that year.

	CAN Modified GLS	*CAN 4XU SWNS*	*JLL AREA 2 (WEST)*	*GOM larval Index*	*US PLL GOM REP MEANS*
1976	-1	-1	0.317	-1	-1
1977	-1	-1	1	2.277	-1
1978	-1	-1	0.487	4.675	-1
1979	-1	-1	0.374	-1	-1
1980	-1	-1	0.595	-1	-1
1981	-1	-1	0.842	0.734	-1
1982	1.667	-1	0.266	1.319	-1
1983	2.489	-1	0.127	1.231	-1
1984	1.47	-1	0.412	0.339	-1
1985	0.551	-1	0.52	-1	-1
1986	0.692	-1	0.057	0.451	-1
1987	0.403	-1	0.237	0.332	3.27
1988	0.771	1.84	0.433	1.052	1.963

1989	0.767	3.212	0.367	1.148	2.369
1990	0.441	2.04	0.269	0.32	1.495
1991	0.804	1.321	0.346	0.205	2.027
1992	0.836	1.21	0.505	0.519	0.689
1993	1.021	0.336	0.466	0.43	0.497
1994	0.329	1.122	0.603	0.472	0.419
1995	1.196	0.772	0.333	0.343	0.527
1996	0.405	0.371	0.845	0.949	0.275
1997	0.413	0.236	0.544	0.41	0.369
1998	0.762	0.376	0.329	0.116	0.391
1999	1.092	0.978	0.279	0.518	0.77
2000	0.931	0.163	0.311	0.297	0.911
2001	1.045	0.623	0.204	0.389	0.503
2002	0.906	1.038	0.277	0.15	0.392
2003	1.273	1.027	0.231	0.579	0.667
2004	2.231	0.626	0.417	0.371	0.874
2005	2.03	0.71	0.474	0.113	0.59

Table 5. Details on the alternative stock assessment runs made using the BSP software.

Run	*Type*	*Details*	*Comments*
1	Base case	Fitted to larval index only (□ set at 0.5)	This is perhaps the most reliable stock trend index since only this one comes from a scientific research survey and thus makes this the most reliable assessment run. This is the least optimistic run.
2	Sensitivity	Fitted to commercial cpue indices excluding CAN GSL (□ set at 0.4)	This run indicates what the commercial cpue indices excluding the most optimistic one say about stock status.
3	Sensitivity	Fitted to commercial cpue indices including CAN GSL (□ set at 0.4)	This run indicates what the commercial cpue indices including the most optimistic one say about stock status. This is the most optimistic run.
4	Sensitivity	Fitted to larval index (□ set at 0.5), commercial cpue indices including CAN GSL (□ set at 1)	This run indicates what the commercial cpue indices together with the larval index say about stock status with more weight put on the larval index.
5	Sensitivity	Fitted to larval index (□ set at 0.5), commercial cpue indices including CAN GSL (□ set at 0.5)	This run indicates what the commercial cpue indices together with the larval index say about stock status with the same weight put on the larval index.
6	Sensitivity	Fitted to larval index (□ set at 0.5), commercial cpue indices excluding CAN GSL (□ set at 0.5)	This run indicates what the commercial cpue indices, excluding the most optimistic one, together with the larval index say about stock status with the same weight put on the larval index.
7	Sensitivity	Fitted to larval index (□ set at 0.5), commercial cpue indices excluding CAN GSL and JLL (□ set at 0.5)	This run indicates what the commercial cpue indices, excluding the most optimistic ones, together with the larval index say about stock status with the same weight put on the larval index
8	Sensitivity	Fitted to larval index only but with the prior mean for initial stock size at 80% of carrying capacity rather than at 100% (□ set at 0.5)	This run evaluates the sensitivity of stock status results to the prior for initial stock size relative to carrying capacity in 1950.
9	Sensitivity	Fitted to larval index only but with the prior mean for initial stock size at 120% of carrying capacity rather than at 100% (□ set at 0.5)	This run evaluates the sensitivity of stock status results to the prior for initial stock size relative to carrying capacity in 1950.
10	Sensitivity	Fitted to larval index only but with the prior mean for r at 0.15 rather than 0. 113 (□ set at 0.5)	This run evaluates the sensitivity of stock status results to the prior mean for r.
11	Sensitivity	Fitted to larval index only but with the prior mean for r at 0.08 rather than 0. 113 (□ set at 0.5)	This run evaluates the sensitivity of stock status results to the prior mean for r.

12	Sensitivity	Fitted to all five indices but with the prior mean for r at 0.15 rather than 0. 113 (□ set at 0.5)	This run evaluates the sensitivity of stock status results to the prior mean for r and also indices used.
13	Sensitivity	Fitted to all five indices but with the prior mean for r at 0.08 rather than 0. 113 (□ set at 0.5)	This run evaluates the sensitivity of stock status results to the prior mean for r and also indices used.
14	Retrospective analysis	Fitted to larval index (□ set at 0.5) for data up to 1999 presuming that it is the stock assessment in the year 2000.	The retrospective analysis attempts to evaluate whether there are systematic patterns of apparent over or under estimation of abundance in the final year and whether projections from past stock assessments tend to recurrently be overly optimistic or overly pessimistic. Retrospective patterns are evaluated in assessments carried out with the larval index only versus all five indices in the same assessment with equal weighting.
15	Retrospective analysis	Fitted to larval index (□ set at 0.5) for data up to 2001 presuming that it is the stock assessment in the year 2002.	As above.
16	Retrospective analysis	Fitted to larval index (□ set at 0.5) for data up to 2005 presuming that it is the stock assessment in the year 2006.	As above.
17	Retrospective analysis	Fitted to all fives indices (□ set at 0.5) for data up to 1999 presuming that it is the stock assessment in the year 2000.	As above.
18	Retrospective analysis	Fitted to all fives indices (□ set at 0.5) for data up to 2001 presuming that it is the stock assessment in the year 2002.	As above.
19	Retrospective analysis	Fitted to all fives indices (□ set at 0.5) for data up to 2005 presuming that it is the stock assessment in the year 2006.	As above.

Table 6a. Comparisons of estimates of various stock assessment quantities between estimations using different sets of indices and weightings. escriptions of the settings for each run are provided in Table 5. Shown are posterior mean and percent coefficient of variation (100% x standard deviation/ mean) for key parameters and stock status indicators for western Atlantic bluefin tuna. B_{07} and C_{07} are the recruited stock biomass and catch biomass in 2007, RepY is the replacement yield in 2007. D Biomass values are in tons.

	Run 1		*Run 2*		*Run 3*		*Run 4*		*Run 5*		*Run 6*		*Run 7*	
	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV
K	148,000	21	183,000	27	199,900	30	153,980	22	168,950	24	168.83	24	195,720	24
r	0.06	46	0.05	55	0.045	54	0.06	48	0.05	51	0.05	55	0.03	75
MSY	2,210	34	1,850	40	1960	38	2,170	34	1,990	36	1,860	41	1,100	61
B_{07}	7,610	50	39,910	44	68,700	53	17,610	38	33,160	37	23.09	35	16,710	28
B_{07}/K	0.05	42	0.21	27	0.33	29	0.11	27	0.19	23	0.14	23	0.09	28
B_{1950}	153,000	21	187,000	24	21,000	29	160,020	22	178,160	23	174,590	21	195,010	15
B_{07}/B_{1950}	0.05	43	0.21	25	0.31	27	0.11	28	0.18	22	0.13	23	0.09	22
C_{07}/MSY	0.88	116	1.2	123	0.98	105	0.91	121	1.00	113	1.20	137	2.63	120
F_{07}/F_{MSY}	9.7	108	2.65	110	1.49	88	4.07	109	2.52	96	4.35	127	15.83	128
B_{07}/ B_{MSY}	0.10	42	0.43	27	0.66	29	0.23	27	0.39	23	0.27	23	0.18	28
C_{07}/ RepY	5.65	114	1.71	113	1.13	95	2.35	117	1.59	106	2.57	130	9.08	133
B_{MSY}	74,000	21	91,440	27	99,900	30	76,990	22	84,470	24	84,420	24	97,860	24
RepY	380	51	1180	36	1,620	30	830	36	1,190	32	830	38	330	62

Table 6b. Comparisons of estimates of various stock assessment quantities between estimations using different priors for runs with the larval index only and all five indices. Descriptions of the settings for each run are provided in Table 5. Shown are posterior mean and percent coefficient of variation (100% x standard deviation/ mean) for key parameters and stock status indicators for western Atlantic bluefin tuna. B_{07} and C_{07} are the recruited stock biomass and catch biomass in 2007, RepY is the replacement yield in 2007. Biomass values are in tons.

	Run 8		*Run 9*		*Run10*		*Run 11*		*Run 12*		*Run 13*	
	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV
K	165,528	27	138,007	17	121,995	17	175,189	24	137,187	21	200,272	25
r	0.06	49	0.07	45	0.10	33	0.04	63	0.08	38	0.03	64
MSY	2,336	34	2,128	34	2,995	21	1,576	49	2,705	24	1,427	49
B_{07}	7,683	50	7,683	50	5,512	51	9,631	49	24,080	35	42,315	35
B_{07}/K	0.05	42	0.05	43	0.04	43	0.06	43	0.17	19	0.21	26
$E(B_{1950})$	137,028	24	169,996	20	127,239	23	173,304	19	144,733	24	205,356	21
$E(B_{07}/B_{1950})$	0.06	42	0.05	44	0.04	46	0.05	41	0.17	22	0.20	21
$E(C_{07}/MSY)$	0.85	125	0.92	120	0.53	46	1.61	133	0.61	66	1.70	120
F_{07}/F_{MSY}	10.40	120	9.26	103	7.00	54	15.84	129	1.76	51	3.96	114
B_{07}/ B_{MSY}	0.09	42	0.11	43	0.09	43	0.11	43	0.35	19	0.42	26
C_{07}/ RepY	5.99	110	5.45	110	4.24	61	9.16	136	1.07	54	2.56	117
B_{MSY}	82,764	27	69,004	17	60,997	17	87,595	24	68,593	21	100,136	25
RepY	366	52	387	50	449	47	285	59	1,510	21	894	45

Table 6c. Comparisons of estimates of various stock assessment quantities between estimations from retrospective analyses for the assessment years 2000, 2002, and 2006 for runs with the larval index only (runs 14-16) and all five indices (runs 17-19). Descriptions of the settings for each run are provided in Table 5. Shown are posterior mean and percent coefficient of variation (100% x standard deviation/ mean) for key parameters and stock status indicators for western Atlantic bluefin tuna. B_{07} and C_{07} are the recruited stock biomass and catch biomass in 2007, RepY is the replacement yield in 2007. Biomass values are in tons.

	Run 14		***Run 15***		***Run16***		***Run 17***		***Run 18***		***Run 19***	
	Mean	*%CV*	*Mean*	*%CV*	*Mean*	*%CV*	*Mean*	*%CV*	*Mean*	*%CV*	*Mean*	*%CV*
K	133,969	18	139,707	19	149,182	21	140,406	20	142,995	20	169,056	24
r	0.08	39	0.07	42	0.06	48	0.07	41	0.07	42	0.05	52
MSY	2,528	28	2,388	31	2,176	35	2,420	29	2,374	30	1,979	36
B_{fin}	8,342	47	9,221	48	8,890	44	14,400	35	12,016	42	33,571	37
B_{fin}/K	0.06	41	0.07	40	0.06	36	0.10	24	0.08	31	0.20	22
$E(B_{1950})$	137,498	22	144,821	22	154,013	22	143,668	22	145,958	22	178,733	23
$E(B_{fin}/B_{1950})$	0.06	42	0.06	42	0.06	36	0.10	26	0.08	31	0.19	22
$E(C_{fin}/MSY)$	1.29	91	1.70	98	0.97	128	1.37	96	1.69	94	1.04	113
F_{fin}/F_{MSY}	11.82	91	14.56	89	8.83	118	6.77	80	10.37	68	2.58	95
B_{fin}/ B_{MSY}	0.12	41	0.13	40	0.12	36	0.20	24	0.17	31	0.39	22
C_{07}/ RepY	7.62	99	9.62	93	5.03	111	4.04	82	6.46	77	1.63	104
B_{MSY}	66,984	18	69,853	19	74,591	21	70,203	20	71,498	20	84,528	24
RepY	493	49	479	50	433	45	795	28	602	32	1,187	32

Table 7. Posterior median and 90% PIs for stock status indicators for western Atlantic bluefin tuna after 5 and 10 years. Descriptions of the settings for each run are provided in Table 5. Biomass values are in thousands of tons (kt).

Run 1.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.06	0.12	1	0	0.92	1	0
	0.1	0.06	0.12	1	0	0.79	1	0
	0.2	0.05	0.11	1	0	0.59	1	0.01
	0.3	0.05	0.1	1	0	0.4	1	0.04
	0.4	0.05	0.09	1	0	0.25	1	0.06
	0.5	0.04	0.09	1	0	0.15	0.99	0.09
	0.6	0.04	0.08	1	0	0.09	0.88	0.15
	0.7	0.04	0.07	1	0	0.04	0.74	0.19
	0.8	0.03	0.07	1	0	0.02	0.59	0.26
	0.9	0.03	0.06	1	0	0.01	0.41	0.32
	1	0.03	0.06	1	0	0.01	0.25	0.38
10 -year	0	0.08	0.16	0.99	0	0.99	1	0
	0.1	0.08	0.15	0.99	0	0.91	1	0
	0.2	0.07	0.13	0.99	0	0.74	1	0.03
	0.3	0.06	0.11	1	0	0.51	1	0.07
	0.4	0.05	0.1	1	0	0.33	1	0.15
	0.5	0.04	0.08	1	0	0.2	0.82	0.25
	0.6	0.03	0.07	1	0	0.11	0.59	0.36
	0.7	0.03	0.06	1	0	0.06	0.41	0.46
	0.8	0.02	0.05	1	0	0.03	0.24	0.57
	0.9	0.02	0.04	1	0	0.01	0.13	0.64
	1	0.02	0.03	1	0	0.01	0.06	0.71

Run 2. TAC Policies from 0 to 1 kt (thousand of tons).

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.25	0.49	0.21	0	0.99	1	0
	0.2	0.24	0.49	0.22	0	0.97	1	0
	0.4	0.24	0.48	0.26	0	0.91	1	0
	0.6	0.23	0.47	0.3	0	0.86	1	0
	0.8	0.23	0.46	0.34	0	0.78	1	0
	1	0.22	0.44	0.38	0	0.66	1	0
	1.2	0.22	0.43	0.44	0	0.5	1	0
	1.4	0.21	0.42	0.48	0	0.32	0.79	0
	1.6	0.21	0.41	0.52	0	0.15	0.02	0
	1.8	0.2	0.4	0.56	0	0.06	0	0
	2	0.19	0.39	0.6	0	0.02	0	0
10 -year	0	0.29	0.58	0.06	0	1	1	0
	0.2	0.28	0.57	0.08	0	0.98	1	0
	0.4	0.27	0.54	0.12	0	0.93	1	0
	0.6	0.26	0.52	0.17	0	0.88	1	0
	0.8	0.25	0.49	0.23	0	0.8	1	0
	1	0.23	0.47	0.31	0	0.68	1	0
	1.2	0.22	0.44	0.4	0	0.52	0.99	0
	1.4	0.21	0.41	0.5	0	0.32	0.54	0
	1.6	0.19	0.39	0.59	0	0.15	0.06	0
	1.8	0.18	0.36	0.67	0	0.05	0	0
	2	0.17	0.34	0.74	0	0.01	0	0

Run 3. TAC Policies from 1.2 to 2.2 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.37	0.74	0	0.08	1	1	0
	0.2	0.37	0.74	0	0.08	0.99	1	0
	0.4	0.36	0.73	0	0.08	0.97	1	0
	0.6	0.36	0.72	0	0.07	0.95	1	0
	0.8	0.35	0.71	0.01	0.07	0.91	1	0
	1	0.35	0.7	0.01	0.06	0.87	1	0
	1.2	0.34	0.69	0.01	0.06	0.8	1	0
	1.4	0.34	0.68	0.02	0.06	0.71	1	0
	1.6	0.33	0.67	0.02	0.05	0.6	0.13	0
	1.8	0.33	0.66	0.03	0.05	0.44	0	0
	2	0.32	0.65	0.04	0.05	0.26	0	0
10 -year	0	0.42	0.84	0	0.15	1	1	0
	0.2	0.42	0.83	0	0.14	0.99	1	0
	0.4	0.41	0.81	0	0.12	0.98	1	0
	0.6	0.39	0.79	0	0.1	0.95	1	0
	0.8	0.38	0.77	0	0.09	0.92	1	0
	1	0.37	0.74	0	0.08	0.87	1	0
	1.2	0.36	0.72	0.01	0.07	0.81	1	0
	1.4	0.35	0.7	0.01	0.06	0.72	0.93	0
	1.6	0.34	0.68	0.02	0.05	0.59	0.3	0
	1.8	0.33	0.65	0.04	0.05	0.42	0.03	0
	2	0.32	0.63	0.07	0.04	0.24	0	0

Run 4. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.14	0.28	0.95	0	0.99	1	0
	0.2	0.13	0.27	0.95	0	0.95	1	0
	0.4	0.13	0.26	0.97	0	0.86	1	0
	0.6	0.12	0.24	0.97	0	0.7	1	0
	0.8	0.11	0.23	0.98	0	0.44	1	0
	1	0.11	0.21	0.98	0	0.22	0.99	0
	1.2	0.1	0.2	0.99	0	0.09	0.75	0
	1.4	0.09	0.19	0.99	0	0.03	0.1	0
	1.6	0.09	0.17	0.99	0	0.01	0	0.01
	1.8	0.08	0.16	1	0	0	0	0.02
	2	0.07	0.14	1	0	0	0	0.04
10 -year	0	0.18	0.36	0.69	0	1	1	0
	0.2	0.17	0.34	0.77	0	0.97	1	0
	0.4	0.15	0.3	0.85	0	0.9	1	0
	0.6	0.14	0.27	0.91	0	0.75	1	0
	0.8	0.12	0.24	0.95	0	0.49	0.99	0
	1	0.1	0.2	0.97	0	0.25	0.83	0.01
	1.2	0.09	0.17	0.98	0	0.09	0.33	0.04
	1.4	0.07	0.14	0.99	0	0.03	0.05	0.1
	1.6	0.05	0.11	0.99	0	0.01	0	0.24
	1.8	0.04	0.08	1	0	0	0	0.37
	2	0.03	0.06	1	0	0	0	0.52

Run 5 TAC Policies from 1.2 to 2.2 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.23	0.45	0.28	0	0.99	1	0
	0.2	0.23	0.45	0.3	0	0.98	1	0
	0.4	0.22	0.44	0.34	0	0.94	1	0
	0.6	0.21	0.43	0.4	0	0.89	1	0
	0.8	0.21	0.41	0.46	0	0.81	1	0
	1	0.2	0.4	0.52	0	0.7	1	0
	1.2	0.19	0.39	0.58	0	0.51	1	0
	1.4	0.19	0.38	0.64	0	0.3	0.76	0
	1.6	0.18	0.37	0.7	0	0.14	0.02	0
	1.8	0.18	0.35	0.74	0	0.05	0	0
	2	0.17	0.34	0.77	0	0.01	0	0
10 -year	0	0.28	0.55	0.07	0	1	1	0
	0.2	0.27	0.54	0.09	0	0.99	1	0
	0.4	0.25	0.51	0.14	0	0.96	1	0
	0.6	0.24	0.48	0.22	0	0.9	1	0
	0.8	0.23	0.45	0.3	0	0.83	1	0
	1	0.21	0.43	0.42	0	0.71	1	0
	1.2	0.2	0.4	0.54	0	0.53	0.98	0
	1.4	0.18	0.37	0.66	0	0.3	0.52	0
	1.6	0.17	0.34	0.76	0	0.14	0.07	0
	1.8	0.16	0.31	0.84	0	0.04	0	0
	2	0.14	0.28	0.89	0	0.01	0	0

Run 6. TAC Policies from 2.4 to 3.2 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.16	0.32	0.9	0	0.97	1	0
	0.2	0.16	0.31	0.91	0	0.93	1	0
	0.4	0.15	0.3	0.93	0	0.84	1	0
	0.6	0.14	0.29	0.95	0	0.69	1	0
	0.8	0.14	0.27	0.96	0	0.49	1	0
	1	0.13	0.26	0.97	0	0.27	1	0
	1.2	0.12	0.25	0.98	0	0.1	0.96	0
	1.4	0.12	0.24	0.98	0	0.02	0.15	0
	1.6	0.11	0.22	0.99	0	0	0	0
	1.8	0.11	0.21	0.99	0	0	0	0
	2	0.1	0.2	0.99	0	0	0	0
10 -year	0	0.19	0.39	0.57	0	0.99	1	0
	0.2	0.18	0.37	0.66	0	0.94	1	0
	0.4	0.17	0.34	0.76	0	0.88	1	0
	0.6	0.16	0.31	0.86	0	0.73	1	0
	0.8	0.14	0.28	0.93	0	0.53	1	0
	1	0.13	0.25	0.96	0	0.3	0.98	0
	1.2	0.11	0.23	0.98	0	0.11	0.52	0
	1.4	0.1	0.2	0.99	0	0.02	0.06	0
	1.6	0.08	0.17	1	0	0	0	0.03
	1.8	0.07	0.14	1	0	0	0	0.08
	2	0.05	0.11	1	0	0	0	0.17

Run 7. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.09	0.19	1	0	0.77	1	0
	0.1	0.09	0.18	1	0	0.63	1	0
	0.2	0.09	0.18	1	0	0.48	1	0
	0.3	0.09	0.17	1	0	0.33	1	0
	0.4	0.08	0.17	1	0	0.21	1	0
	0.5	0.08	0.16	1	0	0.12	1	0
	0.6	0.08	0.16	1	0	0.07	1	0
	0.7	0.08	0.15	1	0	0.03	1	0
	0.8	0.07	0.15	1	0	0.01	1	0
	0.9	0.07	0.14	1	0	0	0.99	0
	1	0.07	0.14	1	0	0	0.9	0
10 -year	0	0.11	0.21	0.99	0	0.91	1	0
	0.1	0.1	0.2	1	0	0.77	1	0
	0.2	0.09	0.19	1	0	0.59	1	0
	0.3	0.09	0.18	1	0	0.43	1	0
	0.4	0.08	0.17	1	0	0.27	1	0
	0.5	0.08	0.16	1	0	0.17	1	0
	0.6	0.07	0.14	1	0	0.09	1	0
	0.7	0.07	0.13	1	0	0.05	0.97	0
	0.8	0.06	0.12	1	0	0.02	0.83	0.01
	0.9	0.05	0.11	1	0	0.01	0.48	0.02
	1	0.05	0.1	1	0	0	0.18	0.05

Run 8. TAC Policies from 1.2 to 2.2 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.05	0.11	1	0	0.92	1	0
	0.1	0.05	0.11	1	0	0.77	1	0
	0.2	0.05	0.1	1	0	0.58	1	0.02
	0.3	0.05	0.09	1	0	0.37	1	0.04
	0.4	0.04	0.09	1	0	0.22	1	0.09
	0.5	0.04	0.08	1	0	0.13	1	0.12
	0.6	0.04	0.07	1	0	0.07	0.89	0.17
	0.7	0.03	0.07	1	0	0.04	0.75	0.22
	0.8	0.03	0.06	1	0	0.02	0.61	0.27
	0.9	0.03	0.06	1	0	0.01	0.44	0.33
	1	0.03	0.05	1	0	0.01	0.25	0.37
10 -year	0	0.07	0.15	0.99	0	0.98	1	0
	0.1	0.07	0.14	0.99	0	0.9	1	0
	0.2	0.06	0.12	1	0	0.7	1	0.03
	0.3	0.05	0.1	1	0	0.49	1	0.1
	0.4	0.04	0.09	1	0	0.3	1	0.18
	0.5	0.04	0.08	1	0	0.17	0.87	0.27
	0.6	0.03	0.06	1	0	0.1	0.65	0.36
	0.7	0.03	0.05	1	0	0.05	0.42	0.44
	0.8	0.02	0.04	1	0	0.03	0.24	0.55
	0.9	0.02	0.04	1	0	0.01	0.13	0.64
	1	0.02	0.03	1	0	0.01	0.05	0.72

Run 9. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.06	0.13	1	0	0.93	1	0
	0.1	0.06	0.12	1	0	0.8	1	0
	0.2	0.06	0.12	1	0	0.61	1	0
	0.3	0.05	0.11	1	0	0.4	1	0
	0.4	0.05	0.1	1	0	0.25	1	0
	0.5	0.05	0.09	1	0	0.14	0.99	0
	0.6	0.04	0.09	1	0	0.08	0.88	0
	0.7	0.04	0.08	1	0	0.04	0.75	0
	0.8	0.04	0.07	1	0	0.02	0.6	0
	0.9	0.03	0.07	1	0	0.01	0.43	0
	1	0.03	0.06	1	0	0.01	0.26	0
10 -year	0	0.09	0.17	0.99	0	0.99	1	0
	0.1	0.08	0.16	0.99	0	0.91	1	0
	0.2	0.07	0.14	0.99	0	0.74	1	0
	0.3	0.06	0.12	1	0	0.53	1	0
	0.4	0.05	0.11	1	0	0.32	1	0
	0.5	0.04	0.09	1	0	0.19	0.83	0
	0.6	0.04	0.07	1	0	0.1	0.62	0
	0.7	0.03	0.06	1	0	0.05	0.42	0
	0.8	0.03	0.05	1	0	0.03	0.25	0
	0.9	0.02	0.04	1	0	0.01	0.13	0
	1	0.02	0.03	1	0	0.01	0.05	0

Run 10. TAC Policies from 1.2 to 2.2 kt

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.06	0.12	1	0	0.99	1	0
	0.1	0.06	0.12	1	0	0.91	1	0
	0.2	0.05	0.11	1	0	0.74	1	0
	0.3	0.05	0.1	1	0	0.53	1	0
	0.4	0.04	0.09	1	0	0.39	1	0
	0.5	0.04	0.08	1	0	0.25	0.97	0
	0.6	0.04	0.07	1	0	0.15	0.79	0
	0.7	0.03	0.06	1	0	0.08	0.62	0
	0.8	0.03	0.06	1	0	0.05	0.47	0
	0.9	0.03	0.05	1	0	0.03	0.32	0
	1	0.02	0.04	1	0	0.01	0.2	0
10 -year	0	0.1	0.19	0.96	0	1	1	0
	0.1	0.09	0.18	0.97	0	0.98	1	0
	0.2	0.08	0.15	0.98	0	0.87	1	0
	0.3	0.06	0.13	0.99	0	0.65	1	0
	0.4	0.05	0.1	0.99	0	0.47	1	0
	0.5	0.04	0.09	1	0	0.32	0.79	0
	0.6	0.03	0.07	1	0	0.19	0.56	0
	0.7	0.03	0.05	1	0	0.11	0.35	0
	0.8	0.02	0.04	1	0	0.06	0.22	0
	0.9	0.02	0.03	1	0	0.04	0.12	0
	1	0.01	0.03	1	0	0.02	0.07	0

Run 11. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.06	0.12	1	0	0.77	1	0
	0.1	0.06	0.12	1	0	0.59	1	0
	0.2	0.05	0.11	1	0	0.36	1	0.01
	0.3	0.05	0.1	1	0	0.21	1	0.02
	0.4	0.05	0.1	1	0	0.13	1	0.04
	0.5	0.05	0.09	1	0	0.06	1	0.07
	0.6	0.04	0.09	1	0	0.03	0.93	0.1
	0.7	0.04	0.08	1	0	0.02	0.82	0.13
	0.8	0.04	0.08	1	0	0.01	0.67	0.17
	0.9	0.04	0.07	1	0	0	0.5	0.22
	1	0.03	0.07	1	0	0	0.3	0.28
10 -year	0	0.07	0.14	1	0	0.93	1	0
	0.1	0.07	0.13	1	0	0.75	1	0
	0.2	0.06	0.12	1	0	0.52	1	0.02
	0.3	0.05	0.11	1	0	0.29	1	0.06
	0.4	0.05	0.09	1	0	0.16	1	0.12
	0.5	0.04	0.08	1	0	0.09	0.87	0.2
	0.6	0.03	0.07	1	0	0.04	0.65	0.29
	0.7	0.03	0.06	1	0	0.02	0.46	0.39
	0.8	0.03	0.05	1	0	0.01	0.26	0.47
	0.9	0.02	0.04	1	0	0	0.12	0.54
	1	0.02	0.04	1	0	0	0.04	0.62

R***un12. TAC Policies from 1.2 to 2.2 kt***

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.23	0.45	0.23	0	1	1	0
	0.2	0.23	0.45	0.24	0	1	1	0
	0.4	0.22	0.44	0.31	0	0.99	1	0
	0.6	0.21	0.42	0.4	0	0.99	1	0
	0.8	0.2	0.41	0.48	0	0.97	1	0
	1	0.2	0.39	0.57	0	0.93	1	0
	1.2	0.19	0.38	0.66	0	0.83	1	0
	1.4	0.18	0.36	0.75	0	0.65	0.93	0
	1.6	0.17	0.34	0.8	0	0.42	0.16	0
	1.8	0.16	0.33	0.84	0	0.21	0	0
	2	0.16	0.31	0.88	0	0.07	0	0
10 -year	0	0.31	0.62	0.02	0	1	1	0
	0.2	0.3	0.6	0.03	0	1	1	0
	0.4	0.28	0.57	0.05	0	0.99	1	0
	0.6	0.27	0.53	0.09	0	0.99	1	0
	0.8	0.25	0.49	0.18	0	0.97	1	0
	1	0.23	0.46	0.31	0	0.93	1	0
	1.2	0.21	0.42	0.44	0	0.85	1	0
	1.4	0.19	0.38	0.6	0	0.66	0.81	0
	1.6	0.17	0.34	0.73	0	0.41	0.28	0
	1.8	0.15	0.3	0.85	0	0.19	0.03	0
	2	0.13	0.26	0.92	0	0.06	0	0.01

Run 13. TAC Policies from 0 to 1.2 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.23	0.46	0.28	0	0.97	1	0
	0.2	0.23	0.46	0.3	0	0.9	1	0
	0.4	0.22	0.45	0.34	0	0.81	1	0
	0.6	0.22	0.44	0.39	0	0.69	1	0
	0.8	0.21	0.43	0.43	0	0.54	1	0
	1	0.21	0.42	0.49	0	0.38	1	0
	1.2	0.2	0.41	0.53	0	0.22	1	0
	1.4	0.2	0.4	0.56	0	0.1	0.53	0
	1.6	0.19	0.39	0.61	0	0.04	0	0
	1.8	0.19	0.38	0.65	0	0.01	0	0
	2	0.18	0.37	0.67	0	0	0	0
10 -year	0	0.26	0.52	0.15	0	0.99	1	0
	0.2	0.25	0.51	0.18	0	0.92	1	0
	0.4	0.24	0.48	0.23	0	0.84	1	0
	0.6	0.23	0.46	0.3	0	0.72	1	0
	0.8	0.22	0.44	0.38	0	0.57	1	0
	1	0.21	0.42	0.46	0	0.39	1	0
	1.2	0.2	0.4	0.56	0	0.23	0.93	0
	1.4	0.19	0.37	0.64	0	0.11	0.24	0
	1.6	0.18	0.35	0.71	0	0.04	0.01	0
	1.8	0.16	0.33	0.78	0	0.01	0	0
	2	0.15	0.31	0.82	0	0	0	0

Run 14. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.07	0.14	1	0	0.87	1	0
	0.1	0.07	0.14	1	0	0.78	1	0
	0.2	0.07	0.13	1	0	0.59	1	0.01
	0.3	0.06	0.13	1	0	0.42	1	0.03
	0.4	0.06	0.12	1	0	0.32	1	0.05
	0.5	0.05	0.11	1	0	0.2	1	0.07
	0.6	0.05	0.1	1	0	0.13	1	0.1
	0.7	0.05	0.09	1	0	0.08	0.93	0.14
	0.8	0.04	0.09	1	0	0.05	0.84	0.19
	0.9	0.04	0.08	1	0	0.03	0.73	0.26
	1	0.04	0.07	1	0	0.02	0.64	0.3
10 -year	0	0.1	0.21	0.95	0	0.99	1	0
	0.1	0.1	0.2	0.96	0	0.94	1	0
	0.2	0.09	0.18	0.97	0	0.82	1	0.02
	0.3	0.08	0.15	0.98	0	0.63	1	0.06
	0.4	0.07	0.13	0.98	0	0.46	1	0.09
	0.5	0.06	0.12	0.99	0	0.33	1	0.17
	0.6	0.05	0.1	0.99	0	0.21	0.87	0.27
	0.7	0.04	0.08	0.99	0	0.13	0.68	0.36
	0.8	0.04	0.07	0.99	0	0.08	0.53	0.46
	0.9	0.03	0.06	1	0	0.05	0.4	0.54
	1	0.02	0.05	1	0	0.03	0.29	0.62

Run 15. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.07	0.15	1	0	0.77	1	0
	0.1	0.07	0.14	1	0	0.65	1	0
	0.2	0.07	0.13	1	0	0.5	1	0.02
	0.3	0.06	0.13	1	0	0.37	1	0.04
	0.4	0.06	0.12	1	0	0.23	1	0.06
	0.5	0.06	0.11	1	0	0.16	1	0.09
	0.6	0.05	0.1	1	0	0.09	1	0.12
	0.7	0.05	0.1	1	0	0.05	0.96	0.15
	0.8	0.05	0.09	1	0	0.03	0.88	0.19
	0.9	0.04	0.08	1	0	0.01	0.79	0.23
	1	0.04	0.08	1	0	0.01	0.73	0.26
10 -year	0	0.1	0.2	0.97	0	0.96	1	0
	0.1	0.1	0.19	0.97	0	0.88	1	0
	0.2	0.09	0.17	0.98	0	0.75	1	0.03
	0.3	0.08	0.15	0.98	0	0.57	1	0.07
	0.4	0.07	0.13	0.99	0	0.42	1	0.12
	0.5	0.06	0.12	0.99	0	0.28	1	0.18
	0.6	0.05	0.1	0.99	0	0.17	0.97	0.25
	0.7	0.04	0.09	1	0	0.11	0.79	0.32
	0.8	0.04	0.07	1	0	0.06	0.62	0.41
	0.9	0.03	0.06	1	0	0.04	0.47	0.5
	1	0.03	0.05	1	0	0.02	0.34	0.6

Run 16. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.07	0.14	1	0	0.94	1	0
	0.1	0.07	0.14	1	0	0.87	1	0
	0.2	0.06	0.13	1	0	0.73	1	0
	0.3	0.06	0.12	1	0	0.52	1	0.01
	0.4	0.06	0.12	1	0	0.35	1	0.02
	0.5	0.05	0.11	1	0	0.2	1	0.03
	0.6	0.05	0.1	1	0	0.1	0.95	0.06
	0.7	0.05	0.09	1	0	0.06	0.88	0.09
	0.8	0.04	0.09	1	0	0.03	0.77	0.12
	0.9	0.04	0.08	1	0	0.01	0.63	0.17
	1	0.04	0.07	1	0	0.01	0.44	0.21
10 -year	0	0.09	0.19	0.99	0	0.98	1	0
	0.1	0.09	0.18	0.99	0	0.94	1	0
	0.2	0.08	0.16	0.99	0	0.83	1	0
	0.3	0.07	0.14	1	0	0.66	1	0.02
	0.4	0.06	0.12	1	0	0.45	1	0.06
	0.5	0.05	0.11	1	0	0.26	0.92	0.11
	0.6	0.05	0.09	1	0	0.16	0.75	0.19
	0.7	0.04	0.08	1	0	0.07	0.59	0.28
	0.8	0.03	0.06	1	0	0.04	0.4	0.37
	0.9	0.03	0.05	1	0	0.02	0.21	0.45
	1	0.02	0.04	1	0	0.01	0.09	0.56

Run 17. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.12	0.25	0.99	0	0.98	1	0
	0.2	0.12	0.24	0.99	0	0.94	1	0
	0.4	0.11	0.22	1	0	0.82	1	0
	0.6	0.1	0.21	1	0	0.54	1	0
	0.8	0.1	0.19	1	0	0.23	1	0
	1	0.09	0.18	1	0	0.06	1	0
	1.2	0.08	0.16	1	0	0.01	0.98	0
	1.4	0.07	0.15	1	0	0	0.9	0.01
	1.6	0.06	0.13	1	0	0	0.64	0.04
	1.8	0.06	0.11	1	0	0	0.28	0.07
	2	0.05	0.1	1	0	0	0.05	0.15
10 -year	0	0.17	0.34	0.78	0	0.99	1	0
	0.2	0.16	0.31	0.87	0	0.97	1	0
	0.4	0.14	0.27	0.95	0	0.92	1	0
	0.6	0.12	0.24	0.98	0	0.72	1	0
	0.8	0.1	0.2	0.99	0	0.38	1	0
	1	0.08	0.16	1	0	0.11	0.94	0.03
	1.2	0.06	0.12	1	0	0.02	0.7	0.12
	1.4	0.04	0.08	1	0	0	0.33	0.27
	1.6	0.03	0.06	1	0	0	0.08	0.46
	1.8	0.02	0.03	1	0	0	0.01	0.64
	2	0.01	0.02	1	0	0	0	0.78

Run 18. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.09	0.19	1	0	0.94	1	0
	0.2	0.09	0.18	1	0	0.78	1	0
	0.4	0.08	0.16	1	0	0.41	1	0.01
	0.6	0.07	0.15	1	0	0.14	1	0.01
	0.8	0.07	0.13	1	0	0.02	0.97	0.04
	1	0.06	0.12	1	0	0	0.92	0.07
	1.2	0.05	0.1	1	0	0	0.82	0.13
	1.4	0.04	0.09	1	0	0	0.68	0.2
	1.6	0.04	0.08	1	0	0	0.45	0.27
	1.8	0.03	0.06	1	0	0	0.21	0.35
	2	0.03	0.05	1	0	0	0.07	0.43
10 -year	0	0.13	0.26	0.97	0	0.99	1	0
	0.2	0.11	0.23	0.98	0	0.94	1	0
	0.4	0.09	0.19	0.99	0	0.7	1	0.01
	0.6	0.08	0.15	1	0	0.31	0.99	0.06
	0.8	0.06	0.12	1	0	0.07	0.86	0.14
	1	0.04	0.09	1	0	0.01	0.67	0.27
	1.2	0.03	0.06	1	0	0	0.41	0.42
	1.4	0.02	0.04	1	0	0	0.15	0.6
	1.6	0.01	0.02	1	0	0	0.04	0.76
	1.8	0.01	0.01	1	0	0	0.01	0.85
	2	0	0.01	1	0	0	0	0.92

Run 19. TAC Policies from 0 to 1 kt.

Horizon	*Policy*	*E(Bfin/K)*	*E(Bfin/Bmsy)*	*P(Bfin<0.2K)*	*P(Bfin>Bmsy)*	*P(Bfin>Bcur)*	*P(Ffin<Fcur)*	*P(Bfin<0.01K)*
5 -year	0	0.23	0.46	0.26	0	0.99	1	0
	0.2	0.23	0.45	0.27	0	0.98	1	0
	0.4	0.22	0.44	0.32	0	0.95	1	0
	0.6	0.22	0.43	0.39	0	0.9	1	0
	0.8	0.21	0.42	0.44	0	0.82	1	0
	1	0.2	0.41	0.51	0	0.7	1	0
	1.2	0.2	0.39	0.57	0	0.52	1	0
	1.4	0.19	0.38	0.63	0	0.3	0.92	0
	1.6	0.18	0.37	0.7	0	0.14	0.06	0
	1.8	0.18	0.36	0.74	0	0.04	0	0
	2	0.17	0.34	0.77	0	0.01	0	0
10 -year	0	0.28	0.56	0.05	0	1	1	0
	0.2	0.27	0.54	0.07	0	0.98	1	0
	0.4	0.26	0.51	0.12	0	0.96	1	0
	0.6	0.24	0.49	0.2	0	0.91	1	0
	0.8	0.23	0.46	0.28	0	0.83	1	0
	1	0.21	0.43	0.39	0	0.72	1	0
	1.2	0.2	0.4	0.52	0	0.54	0.99	0
	1.4	0.19	0.37	0.65	0	0.3	0.62	0
	1.6	0.17	0.34	0.76	0	0.14	0.09	0
	1.8	0.16	0.32	0.84	0	0.04	0	0
	2	0.14	0.29	0.89	0	0.01	0	0

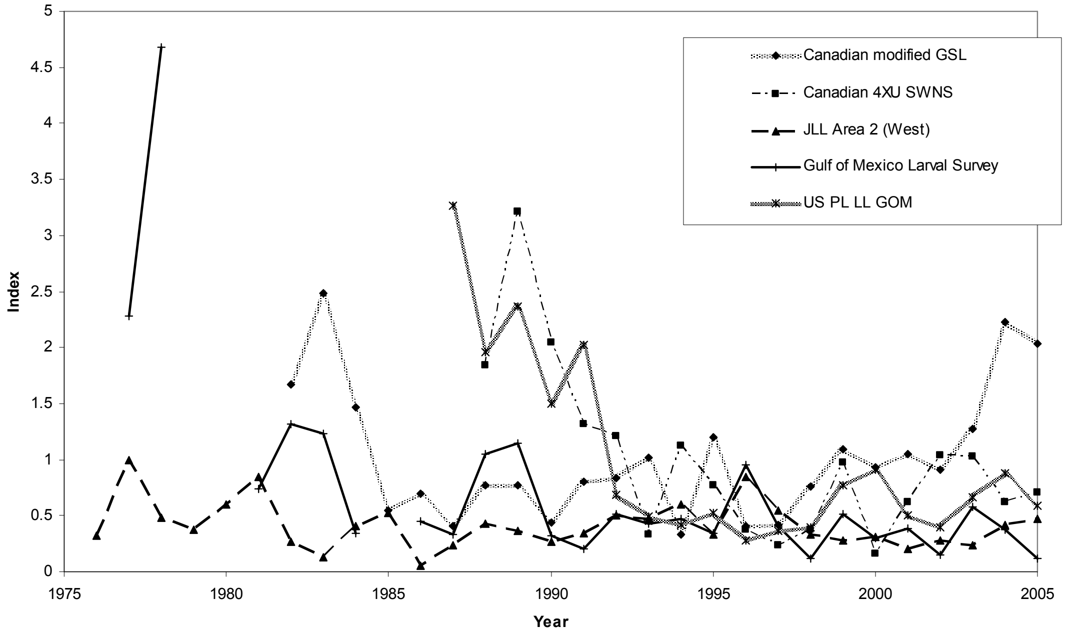

Figure 1. A plot of five of the stock trend indices utilized in the 2006 ICCAT stock assessment of western Atlantic bluefin tuna.

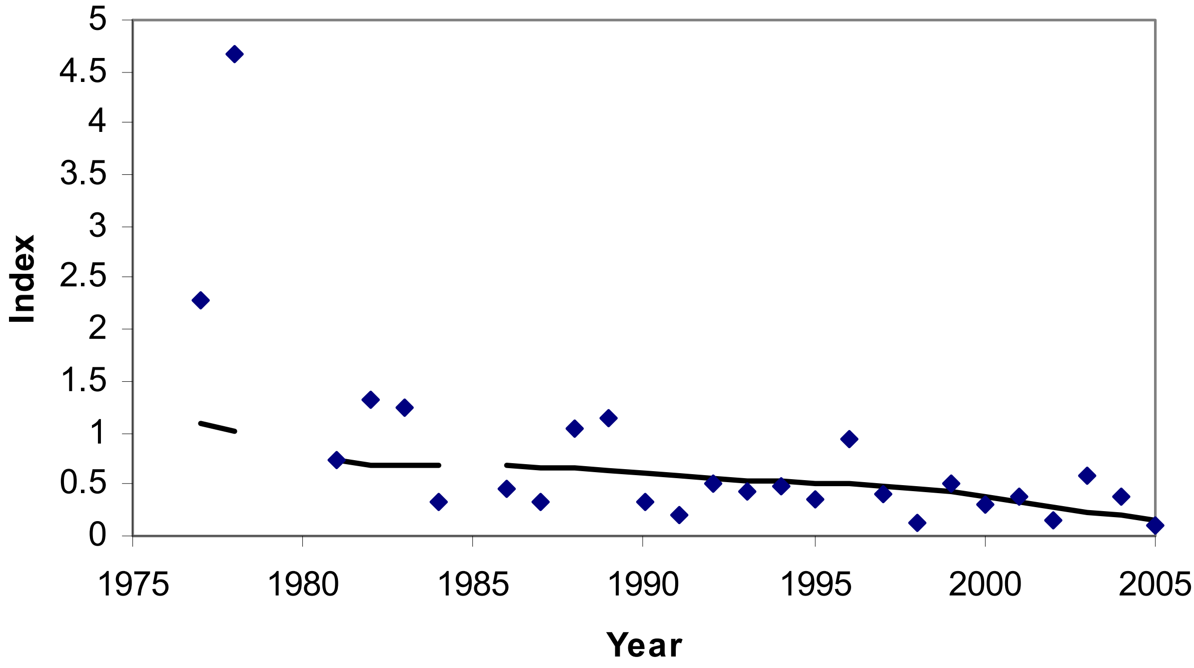

Figure 2. A plot of the model predicted and observed Gulf of Mexico stock trend index. The posterior modal parameter estimates from run number 1 were applied to obtain the model predicted index values.

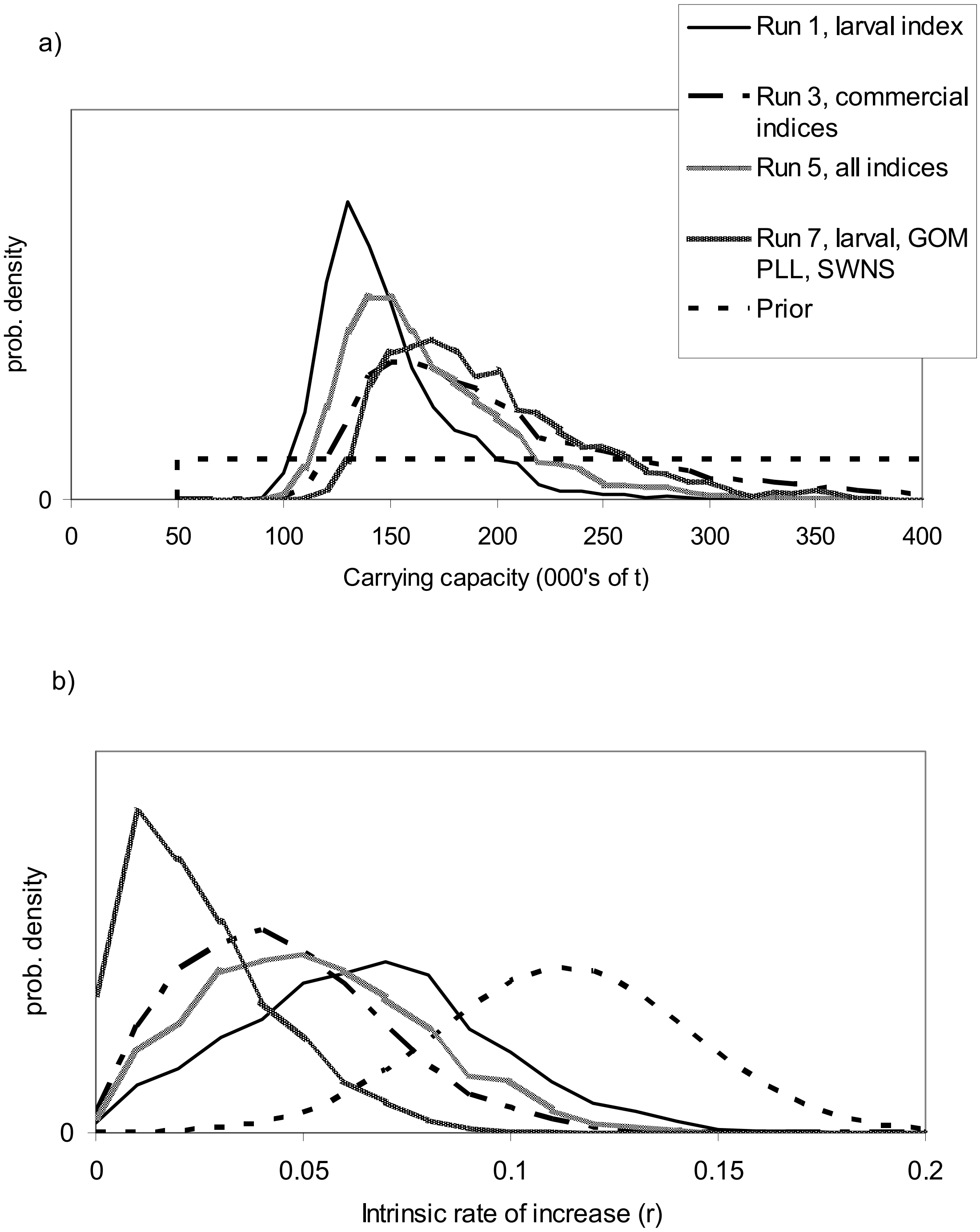

Figure 3. Prior and posterior densities for the intrinsic rate of increase and carrying capacity for western Atlantic bluefin tuna. Results are shown for run 1 (base case, fitted to the larval index only), run 2 (fitted to commercial catch rate data excluding the Canadian Gulf of Saint Laurence Index), and run 6 (fitted to the larval index and the same commercial cpue data as in run 2.

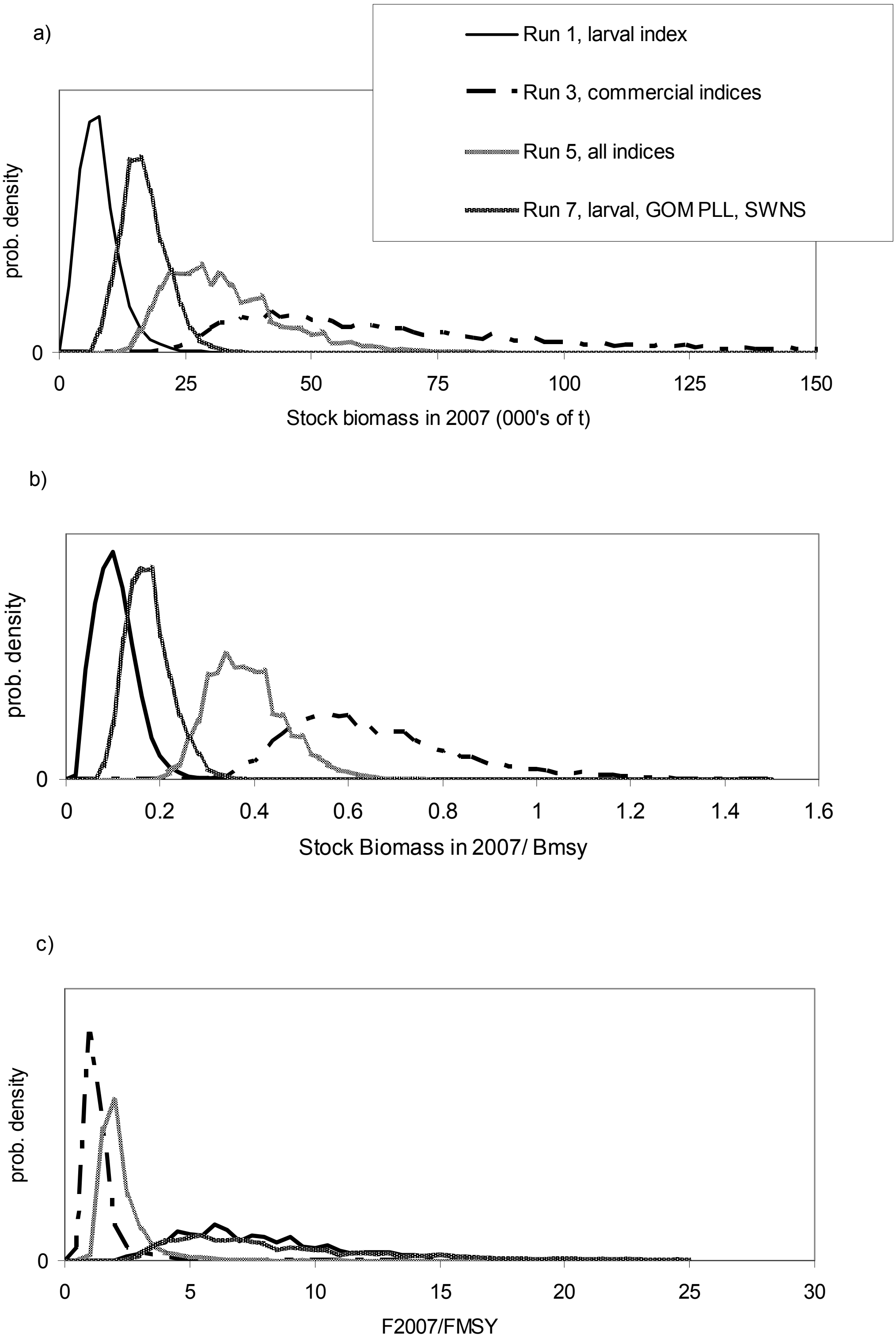

Figure 4. Posterior densities for stock biomass in 2007, stock biomass in 2007 relative to stock biomass at MSY (B(2007)/ BMSY), and the fishing mortality rate in 2007 relative to that at MSY (F(2007)/ FMSY). Results are shown for run 1 (base case, fitted to the larval index only), run 2 (fitted to commercial catch rate data excluding the Canadian Gulf of Saint Laurence Index), and run 6 (fitted to the larval index and the same commercial cpue data as in run 2. Results from these three runs are plotted to show the sensitivity of stock status results to fitting the BSP model to different sets of stock trend indices.

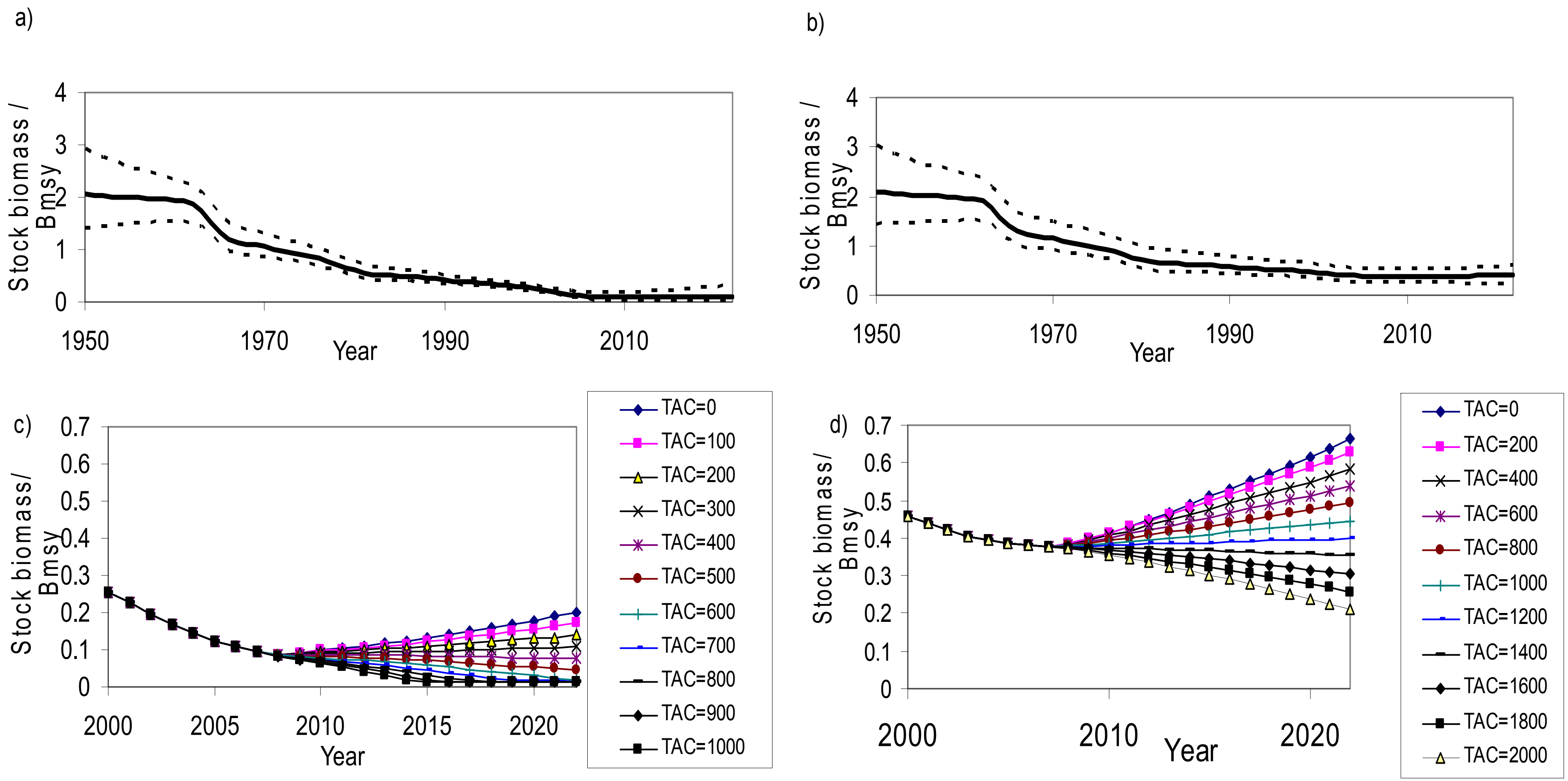

Figure 5. Stock projections of stock biomass relative to BMSY showing 90% probability intervals (dotted lines) and posterior median (solid line) for years from 1950-2022 for a (a) 200 ton TAC policy implemented from 2008 for Run 1 with BSP fitted to the larval index only, and (b) 1200 ton TAC policy implemented from 2008 for Run 5 with BSP fitted to all four indices. . Posterior medians of B/ BMSY for years from 2000-2022 are shown for several different TAC policies for (c) Run 1 and (d) Run 2.

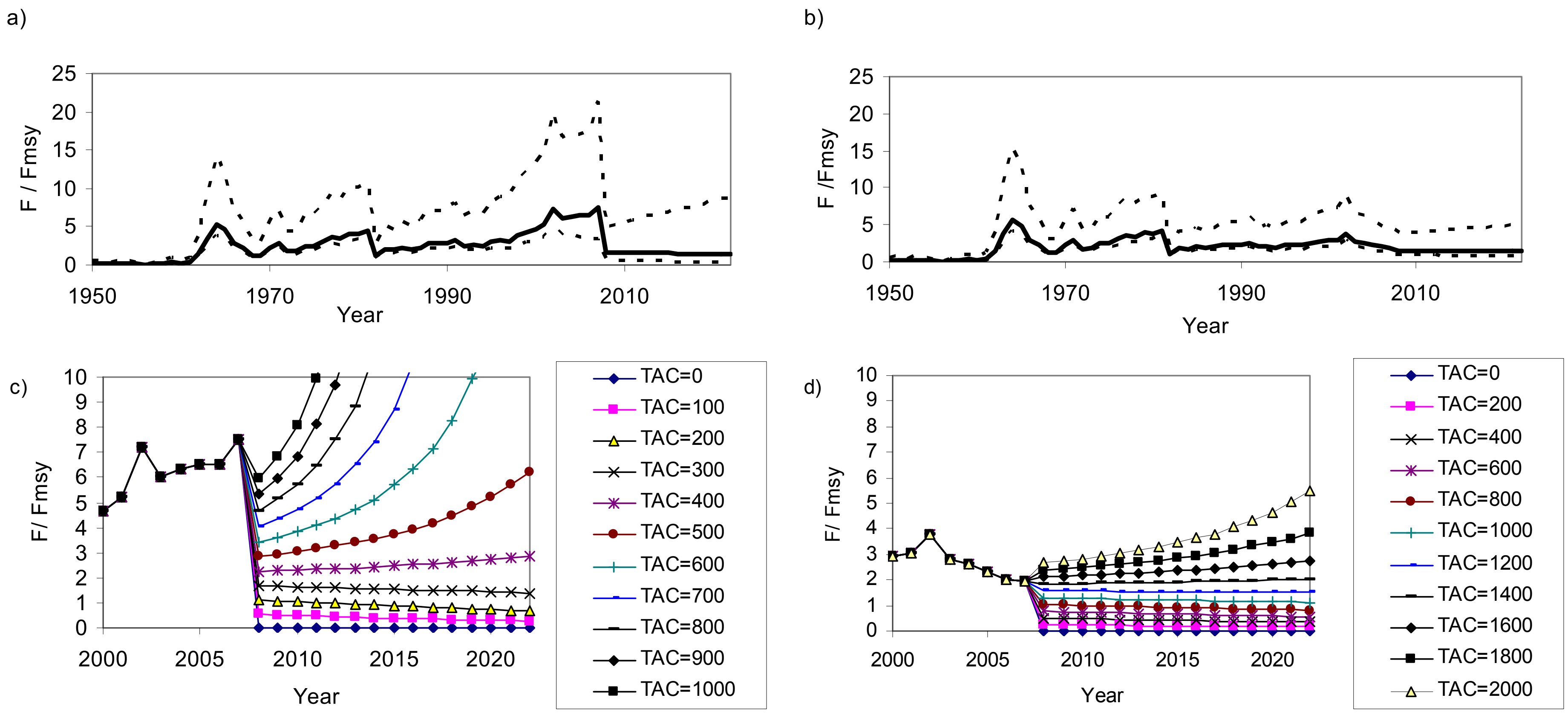

Figure 6. Medians and 90% PIs of F/ FMSY from 1950-2022 from stock projections a (a) 200 ton TAC policy implemented from 2008 for Run 1 with BSP fitted to the larval index only, and (b) 1200 ton TAC policy implemented from 2008 for Run 5 with BSP fitted to all four indices. Posterior medians of F/ FMSY for years from 2000-2022 are shown for several different TAC policies for (c) Run 1 and (d) Run 2.

Appendix 1

An integrated BSSSP – Mark recapture model

Introduction

In this section we describe a tag-recapture probability model that infers exploitation rate given sufficiently informative priors for reporting rates, tag loss rate (long term Type-II tag shedding rate + instantaneous natural mortality) and tag failure rate (short term tag induced mortality and short term Type I tag shedding rate) (Pollock *et al*., 2004). By including a likelihood function for observed catches, the BSSSP and MR models can be integrated, allowing both component models and data to inform yearly harvest rates. The benefit of such an approach is that a larger amount of available data is utilised in the estimation of model parameters and the influence of the component models and data on the posterior estimates is weighted by their relative informational quality. Additionally, the tagging data are used here to update surplus production parameters that allow stock projections based on different management scenarios.

The concept of integrating mark-recapture analyses with conventional population dynamics models has been established for some time (Patterson, 1999; Punt *et al*., 2000). Today, fisheries stock assessment software such as CASAL (C++ Algorithmic Stock Assessment Laboratory; Bull *et al.,* 2005) and MULTIFAN-CL (Fournier *et al.,* 1998) provide such modelling solutions. The practical implications of employing both catch, relative abundance and tagging data into a single analysis was simulation tested by Martell and Walters (2002) and recently applied by Polacheck *et al.* (2006) in their catch-at-age and mark-recapture analysis of Southern bluefin tuna (*Thunnus maccoyii)*. In this model, the conventional tagging data that are available for Atlantic bluefin tuna are employed alongside the relative abundance indices of the base case BSSSP model and observed catches to inform exploitation rates.

A multinomial tag recapture model.

The probability p of recapturing and observing a tag released in year y_{rel}, in year-at-liberty y_{lib}, may be calculated:

(the first year at liberty)

(1) $$p_{y_{rel},1} = H_{y_{rel}} \cdot \lambda \cdot \exp(-L/2) \cdot (1-f)$$

For the first year-at-liberty. The tag loss rate, L is halved to account for an average time at liberty of half a year.

(years at liberty greater than one and less than the maximum)

(2) $$p_{y_{rel},y_{lib}} = H_{y_{yrel}+y_{lib}-1} \cdot \lambda \cdot (\exp(-L))^{y_{lib}-1} \cdot \exp(-L/2) \cdot (1-f) \cdot \prod_{y=y_{rel}}^{y_{rel}+y_{lib}-2} 1-(H_y)$$

(the maximum years-at-liberty, y_{libmax})

(3) $$p_{y_{rel},y_{lib\max}} = 1 - \sum_{y_{lib}=1}^{y_{lib\max}-1} P_{y_{rel},y_{lib}}$$

Where H is the harvest rate, λ is the reporting rate, f is the tag failure rate (Type I tag shedding + short term tag induced mortality) L is the tag loss rate (natural mortality rate plus type II tag shedding rate).

Observed recaptures $K,$ could then be included in the following likelihood function:

(4) $$K_{y_{rel},1:y_{lib\max}} \sim MN\left(P_{y_{rel},1:y_{lib\max}}, R_{y_{rel}}\right)$$

Where '*MN*' refers to the multinomial model, *R* is the number of tags that were released in year y_{rel} and the plus group of observed recaptures is calculated:

(5) $$K_{y_{rel}, y_{lib\,max}} = R_{y_{rel}} - \sum_{y_{lib}}^{y_{lib\,max}-1} K_{y_{rel}, y_{lib}}$$

In order to ensure that the tagging data remain relevant to the Western stock, only tags released and recapture west of the current management boundary are employed in these analyses. In comparison to a sequential mark-recapture model that includes process error in the number of predicted tags at liberty, the multinomial probability model runs much (up to 15 times) faster.

Integrating the surplus production and mark-recapture models

Harvest rates are used to predict recaptures in the mark-recapture equations (1) and (2) and the prediction of catch in the equation:

(6) $$C_y^{pred} = \log\left(B_y \cdot H_y\right)$$

Observed catch now enters the model to inform harvest rate via the likelihood function:

(7) $$C_y^{obs} \sim LN\left(C_y^{pred}, \sigma^C\right)$$

Where *LN* represents the log-normal probability density function and σ^C is the standard deviation of the observation model.

In combining the mark-recapture model with the surplus production model, the BSSSP equations remain largely unchanged. A key difference is that common yearly harvest rates are updated from an 'uninformative' prior (see Table 1 below) by both the multinomial mark-recapture probability model and the surplus production model. The bivariate prior distribution of *q* and *K* and the trivariate prior distribution of H_0, *r* and *M* are the same as the BSSSP model above. In this application the multivariate prior of *M* is ignored and instead, an independent prior for tag loss rate *L* is applied, which combines Type II (long-term) tag shedding rate with natural mortality. Additionally, a prior must also be prescribed for the tag reporting rate, *λ*. In this application, tag failure rate (short-term tag-induced mortality and short-term tag shedding) is not estimated and instead fixed at a level of 10 per cent. Long term tag induced mortality is assumed to be zero.

The instantaneous rate of Type II tag shedding was derived meta-analytically from double tagging studies undertaken on bluefin tuna and other large pelagic species (Hampton and Kirkwood, 1990; Hampton, 1997; Adam and Kirkwood, 2001; Adam and Sibert, 2002). Reporting rates estimates were calculated on the basis of a comparison between archival tag recapture rates and conventional tag recapture rates in the Western Atlantic from 1990 – 2006.

Table 1. The specification of prior distributions and fixed values for mark-recapture parameters

MR Parameter	Specification
reporting rate, λ	~ N(mean = 0.217, StDev=0.0716) (pre 1990) ~ N(mean = 0.098, StDev=0.0358) (1990 -2006) (these rates are constrained between 0.01 and 0.99)
Tag loss rate (long-term tag shedding rate + instantaneous natural mortality rate), L	~ $LogN$(med = 0.3, StDev = 0.06)
Harvest rate, H	~ U(0.001,0.6)
Standard deviation of the catch observation model, σ^c	~ U(0.1, 1000)
Tag failure rate (short- term tag shedding rate + short term tag induced mortality), f	0.1
Long-term tag induced mortality	0

Alternative model runs and projections

In order to determine how the prior specification key model parameters affect model outputs, the model is subject to a sensitivity analysis (Table 2). The harvest rate estimates derived by the mark-recapture model component are directly negatively proportional to reporting rate (Hearn *et al*., 1998). It is therefore important to establish the sensitivity of the model outputs to different prior assumptions about reporting rate. Reporting rate priors that are two thirds and 1.5 times that of the base case rate are investigated. Additionally, the assumption of a temporally inconsistent reporting rate is also investigated by undertaking a model run where reporting rate is not reduced during the period from 1990-2006. In a similar way, the sensitivity of model outputs to tag-loss rates that are 50% smaller and 50% larger than the base case is analysed. Finally, a long-term scenario is investigated where the tagging data and catch data available since 1950 are incorporated into the model. Under this scenario, the initial condition of the stock is considered to be pristine (*i.e.* $P_{1950} = 1$)

Table 2. The model scenarios and projections

Scenario	Characteristics
Base case	Prior for reporting rate λ has mean 0.217 and CV = 0.33. From 1990-2006 reporting rate is 0.45 that of the prior.
Low reporting rate	Prior for reporting rate has mean 0.3255 and CV = 0.33. From 1990-2006 reporting rate is 0.45 that of the prior.
High reporting rate	Prior for reporting rate has mean 0.1445 and CV = 0.33. From 1990-2006 reporting rate is 0.45 that of the prior.
Low tag loss rate	Prior for tag loss rate has mean 0.2 and CV = 0.2
High tag loss rate	Prior for tag loss rate has mean 0.45 and CV = 0.2
Consistent reporting rate	Prior for reporting rate has mean 0.217 and CV = 0.33 for all years
Long-term model	Prior for reporting rate has mean 0.217 and CV = 0.33. From 1990-2006 reporting rate is 0.45λ. The model runs from 1950 – 2006 and includes all tagging and catch data over this period. The model is run from an initial relative stock size of 1. (*I.e.* P = 1)
Projections	(in each scenario the following projections are carried out)
500 tonne TAC	10 years
1000 tonne TAC	10 years
2000 tonne TAC	10 years
3000 tonne TAC	10 years

Results of the base case and constant reporting rate scenarios

The integrated model estimates a relatively low carrying capacity of approximately 80,000 tonnes (90% PI = 65,000 – 100,000 tonnes; Table 3 below). This represents a negative update in the prior and a substantial increase in precision (Figure 1). The intrinsic rate of increase is updated modestly under the base case scenario exhibiting a posterior of slightly lower central tendency of greater precision than the prior. Consequently, the posterior estimate of Maximum Sustainable Yield (MSY is derived directly from *K* and *r*) is much more precise than the prior. Under the base case scenario, MSY is estimated to have a mean of 2,200 tonnes and a 90 per cent probability interval bounded by 1,700 and 2,700 tonnes. Similarly to carrying capacity, the posterior for the constant *q* that scales relative abundance to biomass, was both much more precise and lower than the prior.

Table 3. The results of the Base case BSSSP-MR run with and without constant reporting rate including projections

Base case scenario							**Constant reporting rate**						
TAC	**Parameter / Variable**	**Mean**	**StDev**	**5%**	**Median**	**95%**	**TAC**	**Parameter / Variable**	**Mean**	**StDev**	**5%**	**Median**	**95%**
	r	0.111559	0.024356	0.08103	0.1104	0.14331		*r*	0.111005	0.024702	0.0791	0.1113	0.1421
	K	81226.67	14844.24	64569	78780	101100		*K*	92484.69	17824.2	72839	89475	115600
	q	1.51E-05	2.52E-06	1.21E-05	1.49E-05	1.84E-05		*q*	1.24E-05	2.28E-06	9.74E-06	1.22E-05	1.54E-05
	H0	0.060395	0.014	0.04268	0.05982	0.078881		*H0*	0.060645	0.014033	0.042806	0.060655	0.07876
	MSY (tonnes)	2208.606	378.6319	1739.9	2198	2682		*MSY (tonnes)*	2498.517	451.8631	1938	2490	3067.1
	Tag loss rate	0.308701	0.01408	0.291	0.3085	0.3268		*Tag loss rate*	0.289177	0.013308	0.2722	0.2888	0.3062
	Reporting rate	0.19493	0.013084	0.1787	0.1945	0.2121		*Reporting rate*	0.20026	0.013403	0.1836	0.1997	0.2176
	Deviance	950.6694	9.698165	938.6	950.1	963.4		*Deviance*	978.855	10.16804	966.3	978.25	992.01
500t	*Pr(P[2016]> P[2006])*	0.985429					500t	*Pr(P[2016]> P[2006])*	0.987571				
1000t	*Pr(P[2016]> P[2006])*	0.906429					1000t	*Pr(P[2016]> P[2006])*	0.948714				
2000t	*Pr(P[2016]> P[2006])*	0.346286					2000t	*Pr(P[2016]> P[2006])*	0.661286				
3000t	*Pr(P[2016]> P[2006])*	0.052143					3000t	*Pr(P[2016]> P[2006])*	0.226143				
	B [1983]	36609.72	5479.315	30140	36060	43802		*B [1983]*	41210.5	6742.861	33379	40530	49630
	B [1990]	31198.77	4067.314	26270	30950	36491		*B [1990]*	36292.01	5384.918	29749	35880	43220
	B [2000]	27101.16	3774.933	22659	26720	31980		*B [2000]*	35370.63	5620.563	28410	35080	42781
	B [2006]	22821.47	5166.265	16920	22020	29730		*B [2006]*	35193.62	8248.586	25110	34590	45894
	H [1983]	0.072986	0.025597	0.043748	0.06977	0.1065		*H [1983]*	0.067922	0.02868	0.0368	0.06276	0.1044
	H [1990]	0.116391	0.029585	0.08211	0.1129	0.1551		*H [1990]*	0.11246	0.030469	0.076549	0.109	0.1517
	H [2000]	0.063897	0.011912	0.049099	0.06317	0.07996		*H [2000]*	0.045455	0.008773	0.03471	0.04484	0.05708
	H [2006]	0.054423	0.017611	0.03421	0.05189	0.07816		*H [2006]*	0.025065	0.008093	0.01544	0.02419	0.035721
	P [1983]	0.456973	0.060375	0.37749	0.458	0.53281		*P [1983]*	0.451725	0.060484	0.37509	0.4516	0.5254
	P [1990]	0.391722	0.061169	0.3125	0.39105	0.4696		*P [1990]*	0.400373	0.065244	0.3156	0.4006	0.4823
	P [2000]	0.341657	0.064382	0.262	0.3385	0.4223		*P [2000]*	0.391378	0.074657	0.29409	0.3894	0.48831
	P [2006]	0.288379	0.078144	0.2008	0.2776	0.3914		*P [2006]*	0.389614	0.100383	0.25949	0.3868	0.5226
500t	*B [2010]*	27405.75	7123.728	19080	26510	36881	500t	*B [2010]*	41788.91	10688.75	28569	41130	55791
	B [2016]	36456.86	10111.11	24268	35570	49872		*B [2016]*	52626.03	13467.65	35908	51875	69891
1000t	*B [2010]*	25911.44	7303.077	17480	24850	35700	1000t	*B [2010]*	40172.66	10663.65	27140	39405	54003
	B [2016]	31575.9	10557.63	19030	30600	45450		*B [2016]*	48024.63	13750.43	30620	47550	65701
2000t	*B [2010]*	22603.71	7098.259	14450	21630	32060	2000t	*B [2010]*	37200.09	10611.64	24259	36495	51100
	B [2016]	20789.35	10544.25	8174.7	19430	35041		*B [2016]*	39020.49	14263	20996	38420	57117
3000t	*B [2010]*	19419.63	7176.383	11350	18310	29162	3000t	*B [2010]*	33989.83	10773.15	20850	33425	48071
	B [2016]	10444.5	10235.89	754.19	7822	25030		*B [2016]*	28946.97	14997.1	9910.6	28375	47865
500t	*H [2010]*	0.019481	0.005059	0.013559	0.01886	0.026201	500t	*H [2010]*	0.012814	0.003549	0.008962	0.01216	0.017501
	H [2016]	0.014858	0.004492	0.010029	0.014055	0.020602		*H [2016]*	0.010185	0.00288	0.007154	0.009638	0.013921
1000t	*H [2010]*	0.041692	0.011882	0.02801	0.040245	0.057201	1000t	*H [2010]*	0.026825	0.007886	0.018519	0.02538	0.03685
	H [2016]	0.035959	0.017492	0.022	0.03268	0.05256		*H [2016]*	0.022815	0.007686	0.01522	0.02103	0.03266
2000t	*H [2010]*	0.097238	0.030181	0.06238	0.09248	0.13841	2000t	*H [2010]*	0.058783	0.019279	0.03914	0.054805	0.082442
	H [2016]	0.142147	0.160927	0.057088	0.1029	0.2447		*H [2016]*	0.061589	0.036959	0.035016	0.052055	0.095238
3000t	*H [2010]*	0.176196	0.065438	0.10289	0.16385	0.2643	3000t	*H [2010]*	0.09904	0.038609	0.062408	0.08975	0.1439
	H [2016]	1.345713	1.584829	0.1199	0.3835	3.978		*H [2016]*	0.246785	0.597107	0.062674	0.1057	0.3027
500t	*P [2010]*	0.347394	0.106857	0.22179	0.33375	0.49052	500t	*P [2010]*	0.463285	0.12945	0.2918	0.46105	0.63424
	P [2016]	0.462784	0.148279	0.2788	0.45075	0.66251		*P [2016]*	0.583206	0.15889	0.36659	0.58835	0.79121
1000t	*P [2010]*	0.328151	0.10588	0.2077	0.3139	0.4738	1000t	*P [2010]*	0.445026	0.127	0.27729	0.44145	0.61281
	P [2016]	0.40063	0.147574	0.2228	0.3835	0.60381		*P [2016]*	0.531905	0.159457	0.3146	0.5329	0.73704
2000t	*P [2010]*	0.286304	0.101729	0.1724	0.2697	0.42442	2000t	*P [2010]*	0.412323	0.12615	0.24709	0.4091	0.5788
	P [2016]	0.264426	0.142945	0.09969	0.2415	0.46491		*P [2016]*	0.432503	0.16237	0.21819	0.43185	0.64541
3000t	*P [2010]*	0.246105	0.100057	0.1364	0.2292	0.38291	3000t	*P [2010]*	0.376009	0.124251	0.2149	0.3709	0.53823
	P [2016]	0.133615	0.133925	0.009827	0.09731	0.32633		*P [2016]*	0.319839	0.165838	0.1047	0.3163	0.53746

On the advent of the data, prior estimates of both tagging parameters were strongly updated. Posterior reporting rate estimates were slightly more precise and considerably lower than the prior, suggesting that the data provide information of higher exploitation rates. In contrast, the tag loss rate parameter was slightly positively updated.

The base case model, estimates current biomass levels to be a fraction under 23,000 tonnes (with a 90 per cent probability interval of 17,000 – 30,000 tonnes), and approximately 30% of the estimated carrying capacity (95% PI: 0.18 - 0.46). Under projection, the model did not show strong recovery given a TAC of 2,000 tonnes and the estimated probability that biomass in 2016 is greater than 2006 was 0.35 (Figure 3). Recovery was more convincing in the case of a TAC of 1,000 tonnes (Pr(P_{2016}>P_{2006}) = 0.91) suggesting that an intermediate level could still offer a consistent upward biomass trajectory. However, even under a TAC of 1,000 tonnes the 5th percentile of biomass relative to K remained at a relatively low level of 0.2 after a 10 year projection.

The integrated model offered an time series of historical harvest rates (1983 - 2006) with little or no consistent trend (Figure 2). The harvest rates fluctuated between 0.05 and 0.17 throughout the time series with the lowest rates occurring at the start and end of the time series.

Given constant reporting rates (no recent reduction to 45% in the years 1999-2006), the model predicted very different model outputs from the base case scenario. In general, the model outputs of biomass were 10-20% less precise in the case of the constant reporting rate scenario (Table 3; Figure 2 and Figure 5). The mark-recapture model and data effectively infer harvest rates that are less than half of the base case scenario in the last eight years. It follows that in order to predict catches that were similar to those observed at these reduced harvest rates, the model provides posterior support for much larger carrying capacity of 92,500 tonnes (the 90 % PI 73,000 – 116,000 tonnes; Table 3, Figure 4). This more robust stock supports an elevated maximum sustainable yield of 2,500 tonnes (90 % PI: 1,940 – 3,070 tonnes). The result is that the model predicts a steady (but not conclusive) recovery at a TAC of 2,000 tonnes (Pr(P_{2016}>P_{2006})=0.66; Table 3, Figure 3). A total allowable catch of 3,000 tonnes produces to declining stock projections that are less steep than those of the base case scenario.

The reporting rate and tag loss rate parameters undertook a strong negative update (Figure 4). The negative update in reporting rate is consistent with the base case scenario. It is possible that the lower tag loss rate provides a larger population of tags at liberty to support the estimation of lower harvest rates in the final model years (due to the reduced reporting rate).

Figures of the Base case scenario

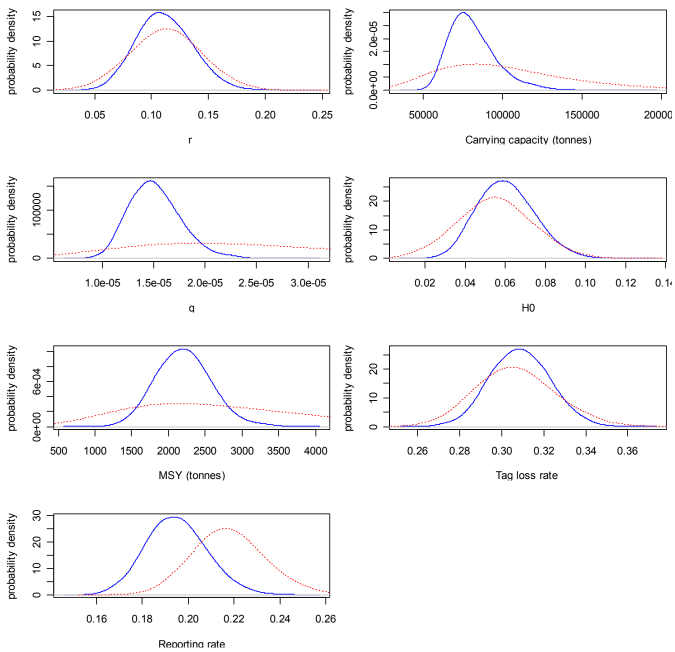

Figure 1. Posterior (solid blue line) versus prior (dotted red line) distributions of BSSSP-MR model parameters for the base case scenario.

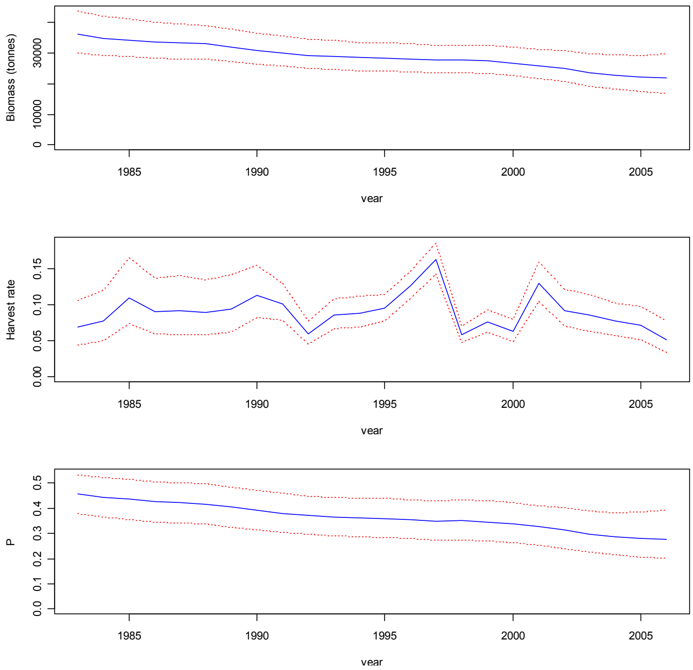

Figure 2. Posterior estimates of biomass, harvest rate and biomass relative to carrying capacity (P) for the base case scenario. The blue represent the median posterior estimate and the red dotted lines, the 90 per cent probability interval.

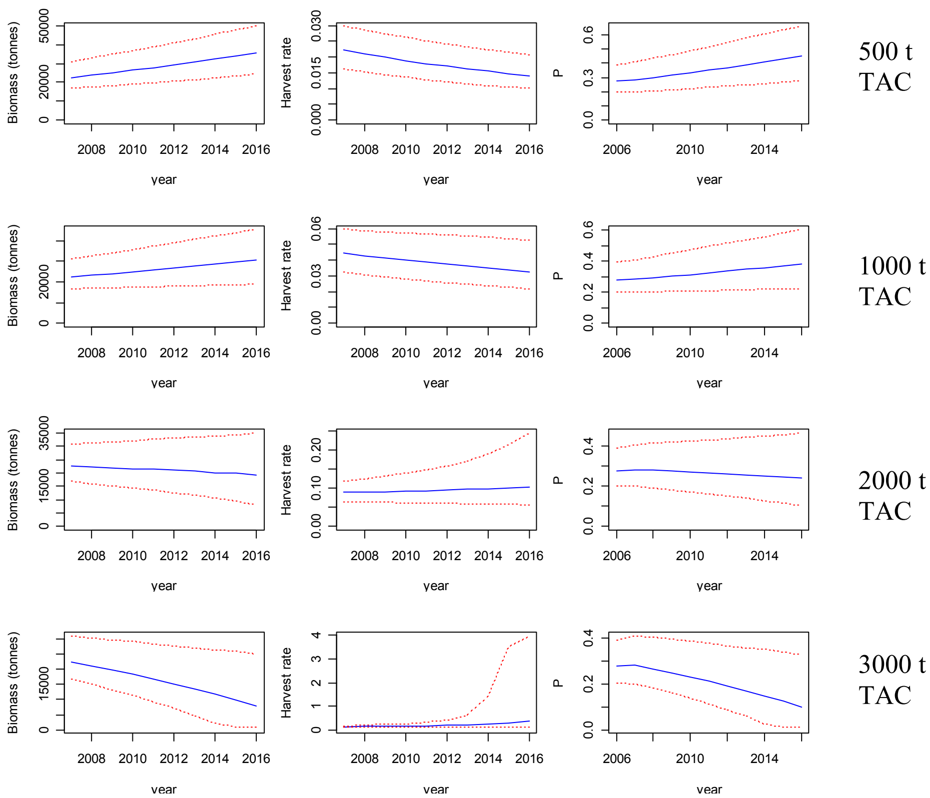

Figure 3. Biomass and harvest rate projections under different TAC strategies under the base case scenario. Each row represents a different level of TAC. The blue line represents the median of the posterior estimates, the dotted red lines, the 90 per cent probability interval.

Figures of the constant reporting rate scenario

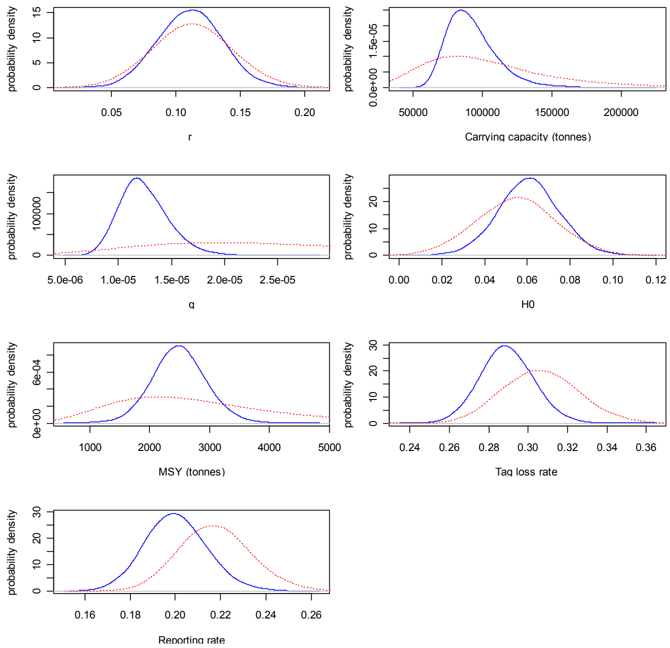

Figure 4. Posterior (solid blue line) versus prior (dotted red line) distributions of BSSSP-MR model parameters for the constant reporting rate scenario.

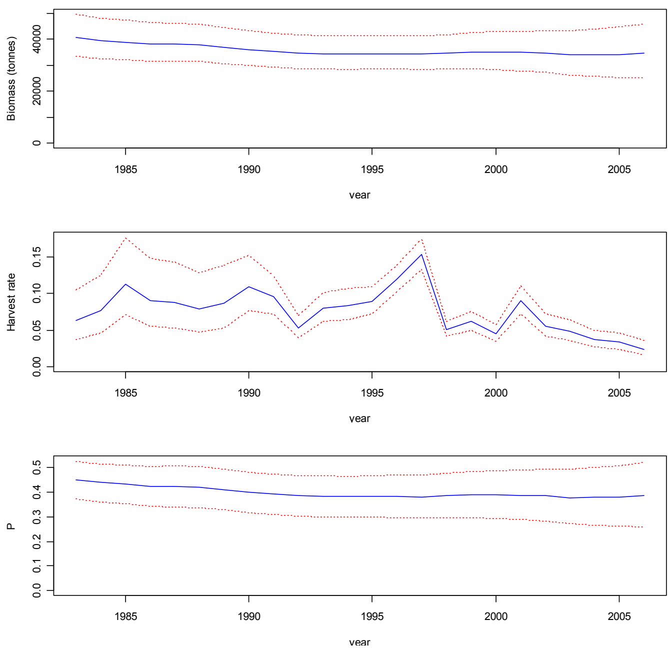

Figure 5. Posterior estimates of biomass, harvest rate and biomass relative to carrying capacity (*P*) under the constant reporting rate scenario. The blue represent the median posterior estimate and the red dotted lines, the 90 per cent probability interval.

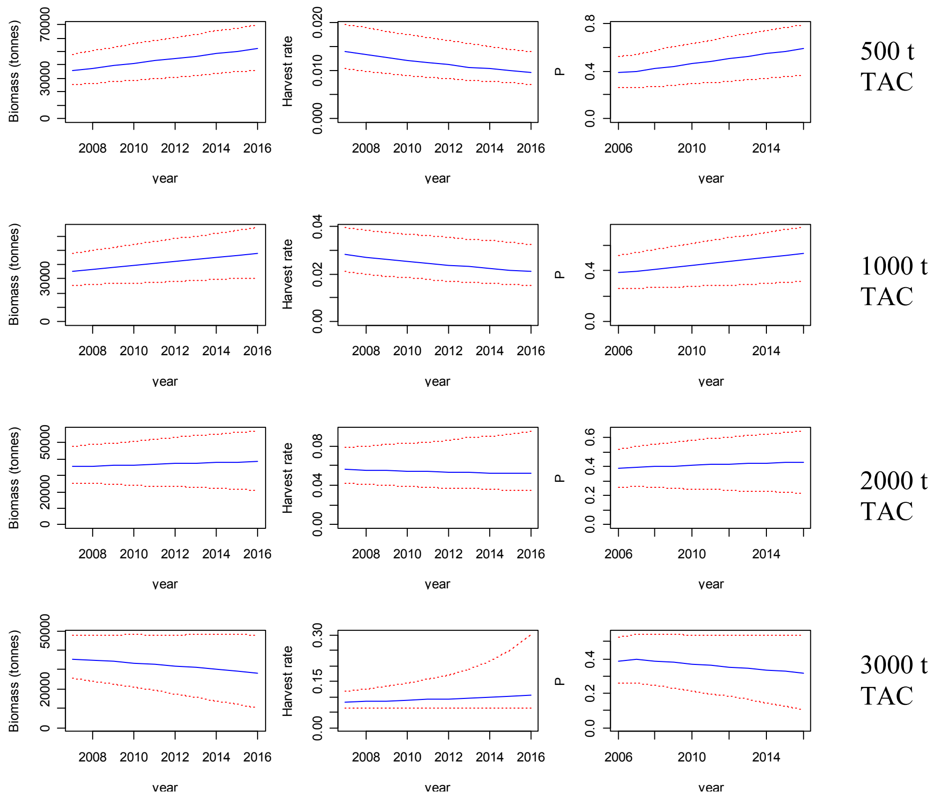

Figure 6. Biomass and harvest rate projections under different TAC strategies under the constant reporting rate scenario. Each row represents a different level of TAC. The blue line represents the median of the posterior estimates, the dotted red lines, the 90 per cent probability interval.

Results of high and low reporting rate scenario

The high and low reporting rate scenarios illustrate the strong effect that the prior for reporting rate has on the posterior model estimates (Table 4). At low reporting rates (66% of base case) the model estimates a smaller and more productive stock (K = 67,400 tonnes , r = 0.129) to explain the observed catches at higher harvest rates. This mechanic results in the estimation of a larger less productive stock (K = 91,600 tonnes, r = 0.109) given higher reporting rate priors (150% of base case). Despite the large difference in the direction of updates, the negative correlation of K and r provides a fairly consistent estimate of maximum sustainable yield between the two reporting rate models (low: 2,120 tonnes, high: 2,430 tonnes).

Model estimates of exploitation rate were strongly sensitive to reporting rate. Harvest rate posteriors fully reflected the alterations to the prior (relative percentage changes to the prior were exactly negatively correlated with harvest rate posteriors). The lower reporting rate prior lead to significantly more pessimistic stock projections than the base case which in turn, was less optimistic than the high reporting rate scenario. For example, given a TAC of 2000 tonnes the probability that the biomass relative to carrying capacity is greater in 2016 than in 2006 is 0.15, 0.34 and 0.64 for the low reporting rate, base case and high reporting rate scenarios, respectively.

The model predictions of biomass and biomass relative to K were the most precise in the case of the low reporting rate scenario (Figure 8 and Figure 11). Additionally, the negative update of the prior for reporting rate is least in the case of the low reporting rate scenario (Figure 7 and Figure 10), followed in magnitude by the base case and high reporting rate scenarios. This may suggest that with the base case prior specification the mark-recapture model and data provide lower estimates of exploitation rate than the BSSSP component.

Table 4. The results of the high and low reporting rate scenarios including projections

Low reporting rate							**High reporting rate**						
TAC	**Parameter / Variable**	**Mean**	**StDev**	**5%**	**Median**	**95%**	**TAC**	**Parameter / Variable**	**Mean**	**StDev**	**5%**	**Median**	**95%**
	r	0.128681	0.024258	0.097089	0.1287	0.1594		*r*	0.109109	0.024265	0.078192	0.1088	0.1413
	K	67374.61	11509.1	54787	65625	81332		*K*	91558.96	17983.44	71970	88660	114300
	q	1.97E-05	3.17E-06	1.59E-05	1.95E-05	2.39E-05		*q*	1.22E-05	2.25E-06	9.55E-06	1.20E-05	1.52E-05
	H0	0.070003	0.014002	0.0516	0.069855	0.08793		*H0*	0.058347	0.013779	0.040866	0.057765	0.07641
	MSY (tonnes)	2121.649	304.4876	1740	2124.5	2496		*MSY (tonnes)*	2430.521	437.0572	1896	2414	2976.1
	Tag loss rate	0.290103	0.013088	0.2737	0.29	0.3071		*Tag loss rate*	0.318076	0.014844	0.2993	0.3178	0.3374
	Reporting rate	0.141992	0.006444	0.1338	0.1417	0.1504		*Reporting rate*	0.24712	0.024314	0.2169	0.2458	0.2795
	Deviance	954.2189	10.28657	941.4	953.9	967.6		*Deviance*	948.881	9.507552	937.39	948.2	961.5
500t	*Pr(P[2016]> P[2006])*	0.982143					500t	*Pr(P[2016]> P[2006])*	0.990143				
1000t	*Pr(P[2016]> P[2006])*	0.799714					1000t	*Pr(P[2016]> P[2006])*	0.951714				
2000t	*Pr(P[2016]> P[2006])*	0.149429					2000t	*Pr(P[2016]> P[2006])*	0.637714				
3000t	*Pr(P[2016]> P[2006])*	0.003857					3000t	*Pr(P[2016]> P[2006])*	0.202571				
	B [1983]	30320.82	4317.356	25270	29870	35971		*B [1983]*	41894.75	6867.858	33830	41100	50940
	B [1990]	24619.94	3155.886	20840	24360	28721		*B [1990]*	37731.9	5713.405	30799	37175	45111
	B [2000]	19861.72	2512.435	16750	19680	23190		*B [2000]*	35586.86	5740.902	28610	35070	43211
	B [2006]	14550.87	3559.094	10359	14090	19530		*B [2006]*	33582.31	7226.6	24790	32950	43201
	H [1983]	0.088598	0.030873	0.053689	0.084395	0.1292		*H [1983]*	0.064368	0.022816	0.038628	0.06109	0.094065
	H [1990]	0.154849	0.038636	0.10899	0.15075	0.2075		*H [1990]*	0.094119	0.024508	0.064856	0.09176	0.1268
	H [2000]	0.091418	0.016345	0.071239	0.09027	0.1132		*H [2000]*	0.049281	0.010015	0.036939	0.04867	0.062511
	H [2006]	0.082481	0.026544	0.051418	0.07935	0.1175		*H [2006]*	0.038882	0.012848	0.02423	0.0369	0.05581
	P [1983]	0.454809	0.052736	0.391	0.455	0.5199		*P [1983]*	0.463775	0.060428	0.38849	0.4646	0.53901
	P [1990]	0.371232	0.053066	0.30469	0.3706	0.4388		*P [1990]*	0.419967	0.065301	0.3371	0.4191	0.50451
	P [2000]	0.30052	0.049761	0.2391	0.2981	0.3659		*P [2000]*	0.397328	0.072806	0.30719	0.3931	0.49382
	P [2006]	0.220691	0.061459	0.1475	0.2125	0.30461		*P [2006]*	0.37522	0.08757	0.2693	0.36715	0.49571
500t	*B [2010]*	17804.41	5276.714	11520	17170	25190	500t	*B [2010]*	39938.37	9387.33	28578	39180	52331
	B [2016]	25469.47	8322.657	15340	24760	36570		*B [2016]*	50787.59	12196.42	35789	50075	66504
1000t	*B [2010]*	16200.19	5288.47	9939.8	15570	23440	1000t	*B [2010]*	38407	9523.502	26987	37525	51060
	B [2016]	19889.58	8469.735	9432.7	19050	31290		*B [2016]*	46260.42	12602.18	30789	45360	62661
2000t	*B [2010]*	12878.53	5345.885	6504	12390	20171	2000t	*B [2010]*	35327.86	9383.436	23779	34640	47641
	B [2016]	8712.532	8121.877	632.49	7106	20631		*B [2016]*	36838	12989.18	20580	36080	53565
3000t	*B [2010]*	9546.558	5165.352	3583.8	8951.5	16820	3000t	*B [2010]*	32379.69	9385.016	20970	31440	44691
	B [2016]	2371.14	4058.812	555.2	706.6	7644.3		*B [2016]*	26941.2	13272.26	10279	25950	44390
500t	*H [2010]*	0.030648	0.009252	0.01985	0.02912	0.0434	500t	*H [2010]*	0.013239	0.003233	0.009554	0.01276	0.017501
	H [2016]	0.022012	0.008067	0.01367	0.0202	0.032591		*H [2016]*	0.010457	0.002717	0.007519	0.009985	0.01397
1000t	*H [2010]*	0.068719	0.023202	0.04266	0.06422	0.1006	1000t	*H [2010]*	0.027702	0.00712	0.01959	0.02665	0.037054
	H [2016]	0.062888	0.03668	0.03196	0.0525	0.106		*H [2016]*	0.023389	0.007133	0.01596	0.022045	0.032481
2000t	*H [2010]*	0.187238	0.086881	0.099154	0.1614	0.3075	2000t	*H [2010]*	0.060914	0.01741	0.041988	0.057735	0.084111
	H [2016]	1.087973	1.280463	0.096928	0.28145	3.1621		*H [2016]*	0.062971	0.029027	0.037337	0.05543	0.097191
3000t	*H [2010]*	0.477505	0.497997	0.1784	0.33515	0.83713	3000t	*H [2010]*	0.101139	0.031792	0.067119	0.09541	0.1431
	H [2016]	3.652427	1.799708	0.39248	4.246	5.4031		*H [2016]*	0.208401	0.462043	0.06758	0.1156	0.29192
500t	*P [2010]*	0.271291	0.091858	0.16359	0.25845	0.3978	500t	*P [2010]*	0.447249	0.115248	0.30379	0.44085	0.6031
	P [2016]	0.389281	0.143315	0.2148	0.37385	0.58641		*P [2016]*	0.569113	0.148852	0.37395	0.5675	0.76501
1000t	*P [2010]*	0.246654	0.089844	0.1414	0.2333	0.36921	1000t	*P [2010]*	0.429821	0.114776	0.2877	0.4226	0.5877
	P [2016]	0.304238	0.140289	0.13299	0.2854	0.49771		*P [2016]*	0.517953	0.148368	0.32399	0.5175	0.71432
2000t	*P [2010]*	0.196306	0.087913	0.093069	0.18655	0.3188	2000t	*P [2010]*	0.395117	0.111439	0.2569	0.38755	0.54931
	P [2016]	0.134319	0.128869	0.009784	0.1057	0.32581		*P [2016]*	0.41196	0.148274	0.21928	0.40655	0.61305
3000t	*P [2010]*	0.145208	0.082494	0.052009	0.1321	0.2637	3000t	*P [2010]*	0.361457	0.107846	0.22109	0.352	0.509
	P [2016]	0.036461	0.063767	0.009404	0.01021	0.1213		*P [2016]*	0.300262	0.147353	0.10837	0.2893	0.5028

Figures of the low reporting rate scenario

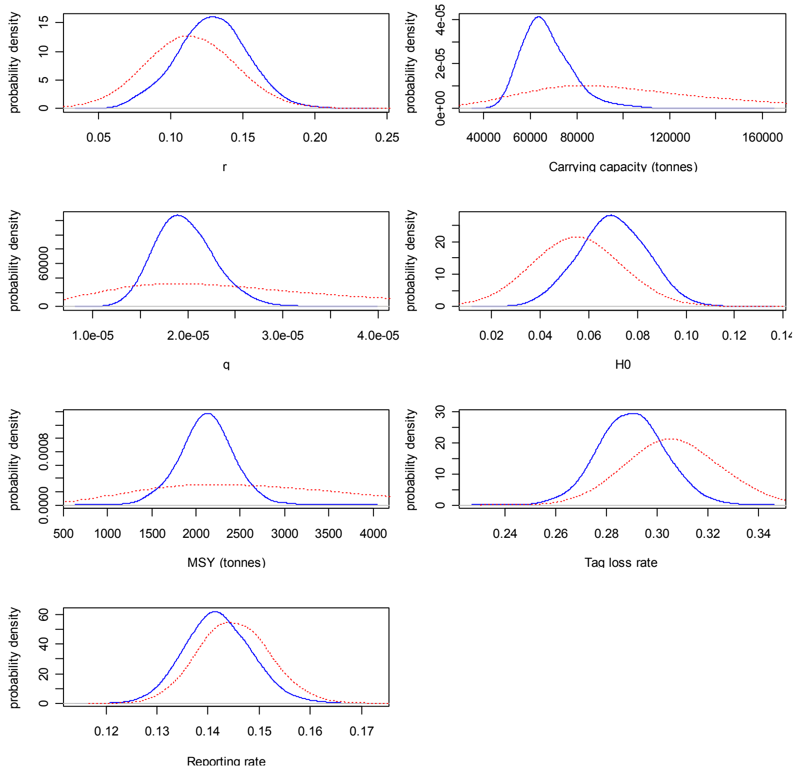

Figure 7. Posterior (solid blue line) versus prior (dotted red line) distributions of BSSSP-MR model parameters for the low reporting rate scenario.

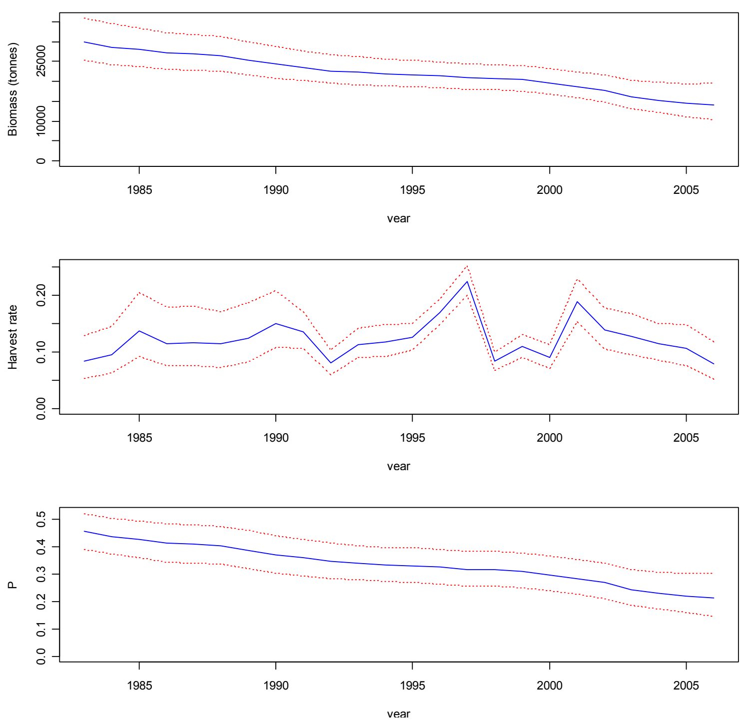

Figure 8. Posterior estimates of biomass, harvest rate and biomass relative to carrying capacity (*P*) under the low reporting rate scenario. The blue represent the median posterior estimate and the red dotted lines, the 90 per cent probability interval.

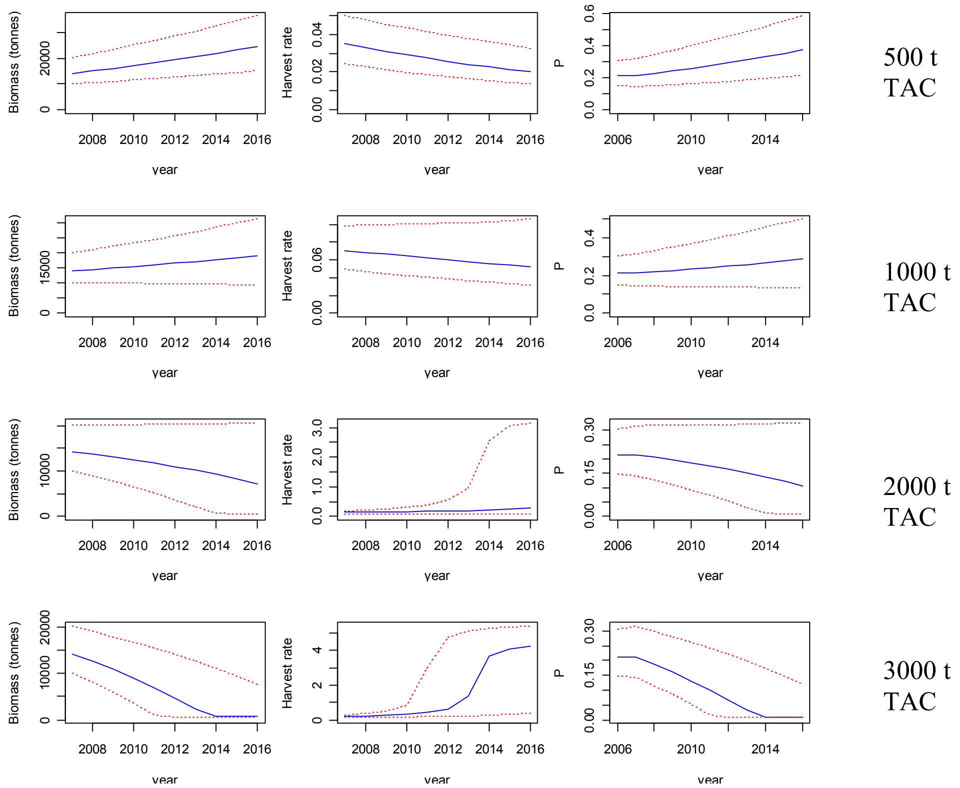

Figure 9. Biomass and harvest rate projections under different TAC strategies under the low reporting rate scenario. Each row represents a different level of TAC. The blue line represents the median of the posterior estimates, the dotted red lines, the 90 per cent probability interval.

Figures of the high reporting rate scenario

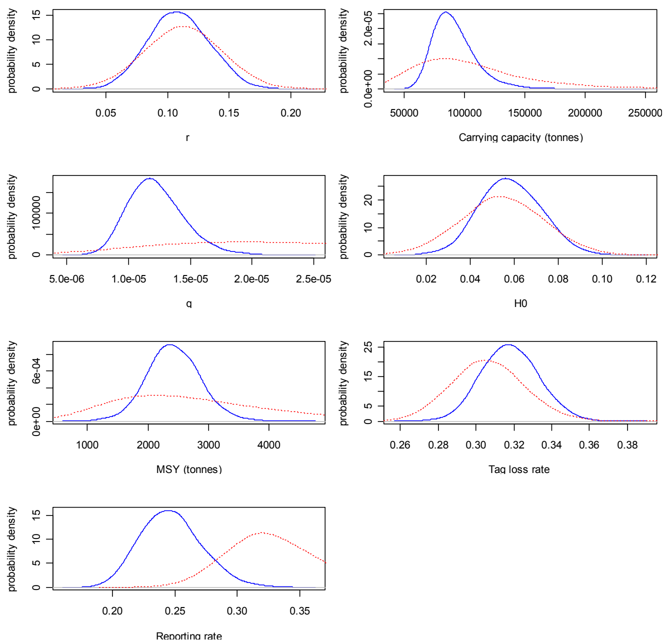

Figure 10. Posterior (solid blue line) versus prior (dotted red line) distributions of BSSSP-MR model parameters for the high reporting rate scenario.

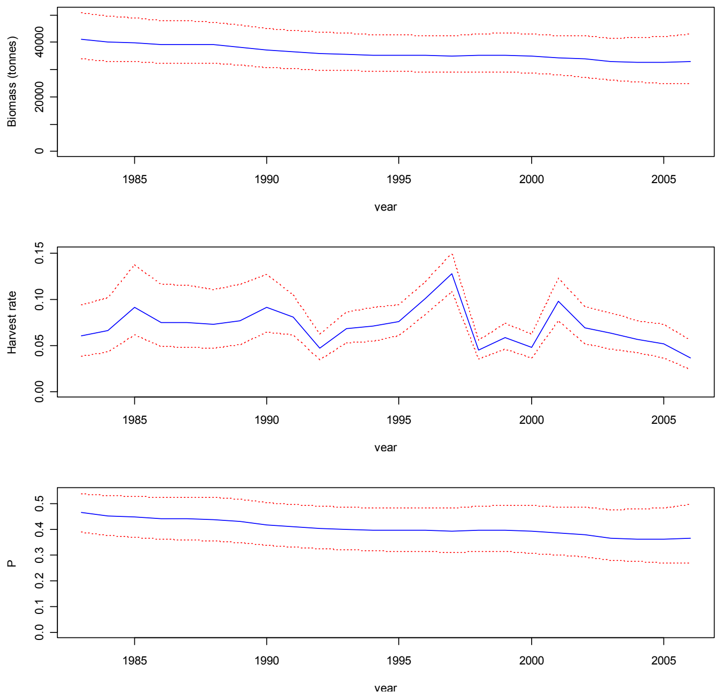

Figure 11. Posterior estimates of biomass, harvest rate and biomass relative to carrying capacity (*P*) under the high reporting rate scenario. The blue represent the median posterior estimate and the red dotted lines, the 90 per cent probability interval.

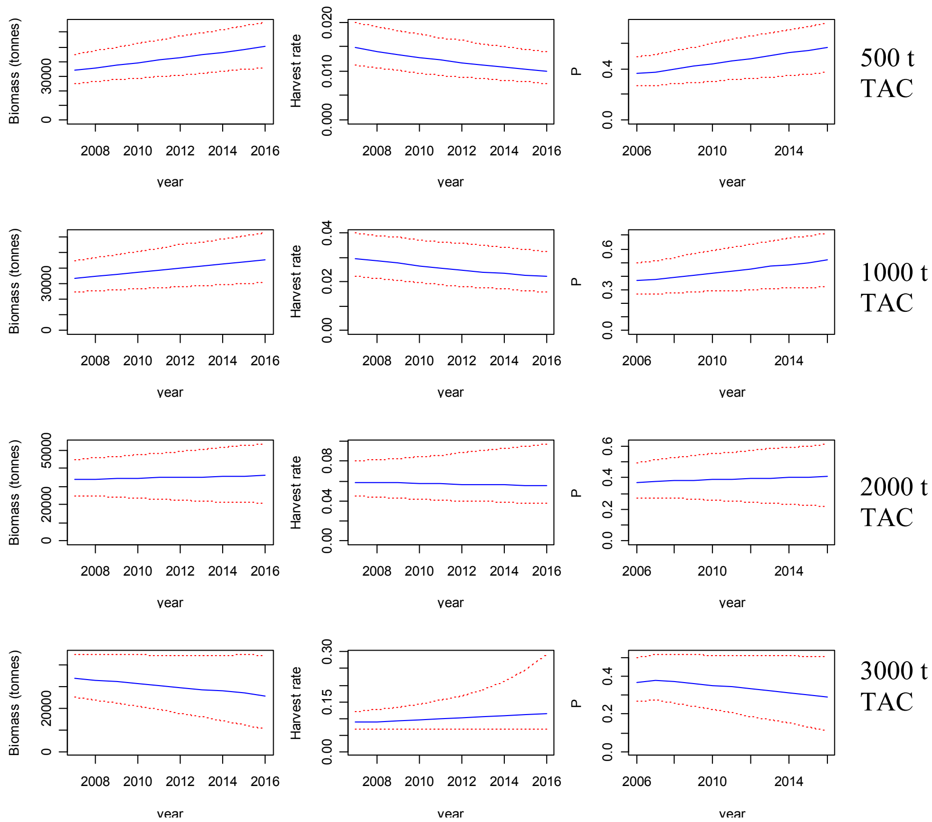

Figure 12. Biomass and harvest rate projections under different TAC strategies under the high reporting rate scenario. Each row represents a different level of TAC. The blue line represents the median of the posterior estimates, the dotted red lines, the 90 per cent probability interval.

Results of high and low tag loss rate scenarios

Altering the prior for tag shedding rate by 50 % made less difference to model outputs than similar proportional changes to reporting rates (Table 4 and Table 5). Both high and low tag loss rate scenarios estimate similar carrying capacities (~80,000 tonnes) that are consistent with the base case scenario. The intrinsic rate of increase was inflated in the low tag loss rate scenario. The consequence of these updates is that the low tag loss rate scenario predicts a larger more productive stock (maximum sustainable yield is 300 tonnes larger). The alternative prior specifications where however sufficient to produce different stock trajectories under a TAC strategy of 2,000 tonnes (how tag loss rate: Pr(*P[2016]*>*P[2006]*) = 0.67, high tag loss rate: Pr(*P[2016]*>*P[2006]*) = 0.28).

Table 5. The results of the high and low tag loss rate scenarios including projections

Low tag loss rate							**High tag loss rate**						
TAC	**Parameter / Variable**	**Mean**	**StDev**	**5%**	**Median**	**95%**	**TAC**	**Parameter / Variable**	**Mean**	**StDev**	**5%**	**Median**	**95%**
	r	0.120683	0.022669	0.092089	0.1203	0.1495		*r*	0.10926	0.025902	0.075209	0.1102	0.142
	K	82173.02	13918.75	66230	80420	99891		*K*	80982.81	17629.93	63720	77070	103000
	q	1.38E-05	2.50E-06	1.09E-05	1.36E-05	1.70E-05		*q*	1.59E-05	2.70E-06	1.26E-05	1.57E-05	1.95E-05
	H0	0.065222	0.013372	0.04785	0.065135	0.082333		*H0*	0.059283	0.01422	0.040879	0.059335	0.077711
	MSY (tonnes)	2432.716	392.5922	1954	2425	2925		*MSY (tonnes)*	2136.04	382.766	1652	2135	2614
	Tag loss rate	0.220905	0.008419	0.21039	0.2207	0.2319		*Tag loss rate*	0.352974	0.017404	0.3308	0.35255	0.37551
	Reporting rate	0.177177	0.012398	0.1617	0.17675	0.1933		*Reporting rate*	0.203512	0.013709	0.1861	0.2031	0.2214
	Deviance	959.8304	10.2107	947.1	959.4	973		*Deviance*	958.9072	11.15288	945	958.4	973.5
500t	*Pr(P[2016]>P[2006])*	0.988857					500t	*Pr(P[2016]>P[2006])*	0.966857				
1000t	*Pr(P[2016]>P[2006])*	0.965714					1000t	*Pr(P[2016]>P[2006])*	0.799				
2000t	*Pr(P[2016]>P[2006])*	0.671429					2000t	*Pr(P[2016]>P[2006])*	0.284143				
3000t	*Pr(P[2016]>P[2006])*	0.176571					3000t	*Pr(P[2016]>P[2006])*	0.031857				
	B [1983]	37336.52	5613.789	30689	36790	44641		*B [1983]*	36006.63	5461.981	29620	35290	43331
	B [1990]	32750.63	4723.235	26999	32480	38801		*B [1990]*	30358.23	4049.964	25400	30000	35741
	B [2000]	31709.5	4624.512	26110	31350	37900		*B [2000]*	25143.92	3837.8	20510	24840	30070
	B [2006]	30565.8	5923.202	23250	30130	38440		*B [2006]*	19857.48	5652.145	12980	19230	27382
	H [1983]	0.074321	0.028023	0.042939	0.070085	0.11051		*H [1983]*	0.074459	0.026484	0.04459	0.070895	0.1092
	H [1990]	0.119293	0.030886	0.082329	0.1164	0.1601		*H [1990]*	0.117071	0.029573	0.082059	0.1139	0.1559
	H [2000]	0.052116	0.010218	0.039698	0.05124	0.065473		*H [2000]*	0.070355	0.013194	0.05441	0.06925	0.08802
	H [2006]	0.039346	0.012633	0.02467	0.03765	0.056262		*H [2006]*	0.062759	0.020885	0.038509	0.05999	0.090866
	P [1983]	0.458833	0.054269	0.389	0.4602	0.5269		*P [1983]*	0.453727	0.064628	0.371	0.4561	0.5314
	P [1990]	0.40454	0.060938	0.32869	0.4037	0.4835		*P [1990]*	0.385047	0.065052	0.3021	0.38625	0.4654
	P [2000]	0.392591	0.065873	0.31119	0.3891	0.478		*P [2000]*	0.320679	0.067829	0.2363	0.3168	0.40702
	P [2006]	0.377714	0.075558	0.27989	0.37585	0.4788		*P [2006]*	0.254564	0.085252	0.151	0.2449	0.3693
500t	*B [2010]*	37078.79	7977.011	27410	36440	47522	500t	*B [2010]*	23796.2	8101.092	13880	22870	34731
	B [2016]	48127.67	10773.12	35009	47340	62031		*B [2016]*	31886.78	11692.03	17320	30960	47440
1000t	*B [2010]*	35556.39	8018.711	25790	34890	46030	1000t	*B [2010]*	22103.52	7955.318	12359	21170	32780
	B [2016]	43625.21	10966.06	30240	42990	57484		*B [2016]*	26582	11865.23	11860	25775	42251
2000t	*B [2010]*	32421.26	7847.923	22859	31800	42741	2000t	*B [2010]*	18953.62	7895.627	9302.2	18160	29621
	B [2016]	34172.32	10934.12	20810	33530	48104		*B [2016]*	15878.5	11791.01	972.2	14870	32230
3000t	*B [2010]*	29367.23	7719.944	20069	28650	39710	3000t	*B [2010]*	15448.74	7937.722	5905.7	14280	25990
	B [2016]	24038.79	11114.64	10428	23250	38751		*B [2016]*	7382.743	9029.105	683.99	1601	20761
500t	*H [2010]*	0.014132	0.00317	0.01052	0.01372	0.01824	500t	*H [2010]*	0.023675	0.008559	0.014399	0.02186	0.036021
	H [2016]	0.010947	0.002667	0.008061	0.01056	0.01428		*H [2016]*	0.018237	0.007896	0.01054	0.01615	0.02887
1000t	*H [2010]*	0.029595	0.006863	0.021729	0.02866	0.03877	1000t	*H [2010]*	0.051876	0.020549	0.03051	0.04723	0.080918
	H [2016]	0.024476	0.006654	0.017399	0.02326	0.033061		*H [2016]*	0.048862	0.034232	0.023669	0.0388	0.084284
2000t	*H [2010]*	0.065517	0.016794	0.046799	0.0629	0.087502	2000t	*H [2010]*	0.128502	0.064633	0.067508	0.11015	0.21502
	H [2016]	0.065936	0.026946	0.041576	0.059645	0.096112		*H [2016]*	0.509072	0.830051	0.06206	0.13445	2.0572
3000t	*H [2010]*	0.109594	0.030287	0.07555	0.1047	0.14951	3000t	*H [2010]*	0.286502	0.284735	0.1154	0.2101	0.50802
	H [2016]	0.196255	0.342901	0.077418	0.129	0.28774		*H [2016]*	2.03925	1.794276	0.14449	1.874	4.3861
500t	*P [2010]*	0.458759	0.103061	0.32849	0.4565	0.59272	500t	*P [2010]*	0.306537	0.119813	0.1607	0.29415	0.47151
	P [2016]	0.594945	0.134858	0.42059	0.59315	0.7693		*P [2016]*	0.412378	0.170636	0.19329	0.4003	0.6416
1000t	*P [2010]*	0.439548	0.101512	0.3128	0.4344	0.57261	1000t	*P [2010]*	0.284762	0.116278	0.1432	0.27195	0.4458
	P [2016]	0.538872	0.134234	0.366	0.5364	0.7138		*P [2016]*	0.344322	0.167879	0.1355	0.33055	0.57051
2000t	*P [2010]*	0.400737	0.098753	0.27429	0.3964	0.52821	2000t	*P [2010]*	0.244312	0.112419	0.106	0.2323	0.3991
	P [2016]	0.42189	0.133331	0.25149	0.4196	0.5949		*P [2016]*	0.207255	0.159525	0.01044	0.18575	0.43162
3000t	*P [2010]*	0.362153	0.093169	0.2442	0.3584	0.4855	3000t	*P [2010]*	0.199346	0.110065	0.070497	0.1889	0.34901
	P [2016]	0.29504	0.131566	0.1276	0.28975	0.46901		*P [2016]*	0.096299	0.119824	0.00958	0.017495	0.27401

Results of the long-term BSSSP-MR model

The posterior estimates of model parameters are very different on the advent of the additional tagging and catch data. Large observed catches of up to 18,500 tonnes during the mid 1960s require a greatly larger (K = 104,000 tonnes, 95% PI: 74,000-147,000 tonnes) and more productive stock (r = 0.149, 95% PI: 0.095 - 0.203) are estimated to explain the observed relative abundance indices and recapture data than is estimated under the short term models (Table 6). The long-term model offers by far the least precise predictions of biomass and biomass relative to carrying capacity, with most years exhibiting a coefficient of variation twice that of the base case scenario (**Error! Reference source not found.**). Consequently, posterior estimates of maximum sustainable yield were very large and uncertain (mean = 4,400 tonnes, 90% PI: 3,200-5,700 tonnes). The model estimated the current stock status to be 0.39 of carrying capacity at approximately 45,000 tonnes (see Table 6). Whilst these outputs are markedly higher they are sufficiently uncertain to overlap with those of the short-term models.

Tagging parameters were heavily updated

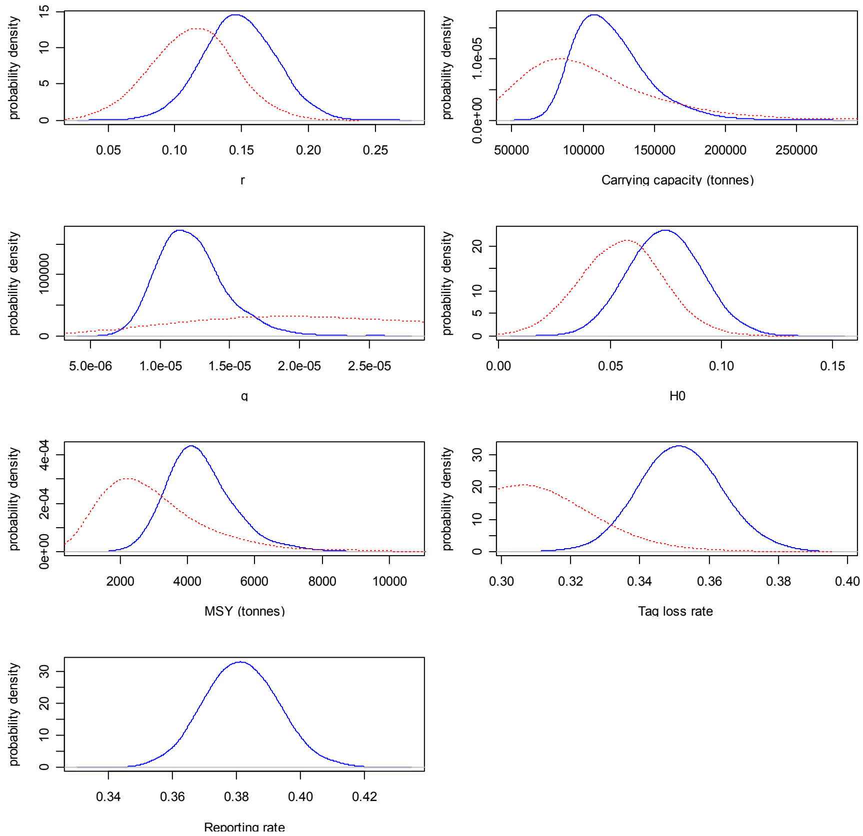

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Figure 13). The posterior for reporting rate, for example, hardly overlaps with the prior (mean = 0.38, 90% PI: 0.37 - 0.40). The tag loss rate parameter was positively updated to a greater extent than any other scenario. This might suggest that the large number of tags released during the mid 1970s and early 1980s could not be lost sufficiently quickly to explain the very small number of observed recaptures. Other explanations for the strong update in these parameters could include temporally variable tag reporting and shedding rates that are not well accounted for by the prior specification of single constant rates.

In general, the larger, more productive stock provided much lower estimates of exploitation rate (Figure 14) and optimistic stock projections given a 2,000 tonne TAC (**Error! Reference source not found.**). Estimates of harvest rate are very high from 1960 to 1980 and in the most extreme cases are estimated to be over 0.5.

Table 6. The results of the long term model including projections

Base case scenario

TAC	Parameter / Variable	Mean	StDev	5%	Median	95%
	r	0.111559	0.024356	0.08103	0.1104	0.14331
	K	81226.67	14844.24	64569	78780	101100
	q	1.51E-05	2.52E-06	1.21E-05	1.49E-05	1.84E-05
	H0	0.060395	0.014	0.04268	0.05982	0.078881
	MSY (tonnes)	2208.606	378.6319	1739.9	2198	2682
	Tag loss rate	0.308701	0.01408	0.291	0.3085	0.3268
	Reporting rate	0.19493	0.013084	0.1787	0.1945	0.2121
	Deviance	950.6694	9.698165	938.6	950.1	963.4
500t	*Pr(P[2016]> P[2006])*	0.985429				
1000t	*Pr(P[2016]> P[2006])*	0.906429				
2000t	*Pr(P[2016]> P[2006])*	0.346286				
3000t	*Pr(P[2016]> P[2006])*	0.052143				
	B [1983]	36609.72	5479.315	30140	36060	43802
	B [1990]	31198.77	4067.314	26270	30950	36491
	B [2000]	27101.16	3774.933	22659	26720	31980
	B [2006]	22821.47	5166.265	16920	22020	29730
	H [1983]	0.072986	0.025597	0.043748	0.06977	0.1065
	H [1990]	0.116391	0.029585	0.08211	0.1129	0.1551
	H [2000]	0.063897	0.011912	0.049099	0.06317	0.07996
	H [2006]	0.054423	0.017611	0.03421	0.05189	0.07816
	P [1983]	0.456973	0.060375	0.37749	0.458	0.53281
	P [1990]	0.391722	0.061169	0.3125	0.39105	0.4696
	P [2000]	0.341657	0.064382	0.262	0.3385	0.4223
	P [2006]	0.288379	0.078144	0.2008	0.2776	0.3914
500t	*B [2010]*	27405.75	7123.728	19080	26510	36881
	B [2016]	36456.86	10111.11	24268	35570	49872
1000t	*B [2010]*	25911.44	7303.077	17480	24850	35700
	B [2016]	31575.9	10557.63	19030	30600	45450
2000t	*B [2010]*	22603.71	7098.259	14450	21630	32060
	B [2016]	20789.35	10544.25	8174.7	19430	35041
3000t	*B [2010]*	19419.63	7176.383	11350	18310	29162
	B [2016]	10444.5	10235.89	754.19	7822	25030
500t	*H [2010]*	0.019481	0.005059	0.013559	0.01886	0.026201
	H [2016]	0.014858	0.004492	0.010029	0.014055	0.020602
1000t	*H [2010]*	0.041692	0.011882	0.02801	0.040245	0.057201
	H [2016]	0.035959	0.017492	0.022	0.03268	0.05256
2000t	*H [2010]*	0.097238	0.030181	0.06238	0.09248	0.13841
	H [2016]	0.142147	0.160927	0.057088	0.1029	0.2447
3000t	*H [2010]*	0.176196	0.065438	0.10289	0.16385	0.2643
	H [2016]	1.345713	1.584829	0.1199	0.3835	3.978
500t	*P [2010]*	0.347394	0.106857	0.22179	0.33375	0.49052
	P [2016]	0.462784	0.148279	0.2788	0.45075	0.66251
1000t	*P [2010]*	0.328151	0.10588	0.2077	0.3139	0.4738
	P [2016]	0.40063	0.147574	0.2228	0.3835	0.60381
2000t	*P [2010]*	0.286304	0.101729	0.1724	0.2697	0.42442
	P [2016]	0.264426	0.142945	0.09969	0.2415	0.46491
3000t	*P [2010]*	0.246105	0.100057	0.1364	0.2292	0.38291
	P [2016]	0.133615	0.133925	0.009827	0.09731	0.32633

Long-term model

TAC	Parameter / Variable	Mean	StDev	5%	Median	95%
	r	0.148282	0.026729	0.11473	0.1479	0.1824
	K	119873.9	25305.45	91881	115600	153570
	q	1.23E-05	2.46E-06	9.45E-06	1.20E-05	1.55E-05
	H0	0.074693	0.01621	0.053876	0.07452	0.09544
	MSY (tonnes)	4389.391	1008.631	3233.3	4267	5694.4
	Tag loss rate	0.351787	0.01184	0.3368	0.3517	0.36707
	Reporting rate	0.381457	0.011564	0.3668	0.3814	0.3962
	Deviance	3574.695	28.16303	3541	3572	3612
500t	*Pr(P[2016]> P[2006])*	0.836145				
1000t	*Pr(P[2016]> P[2006])*	0.794526				
2000t	*Pr(P[2016]> P[2006])*	0.68129				
3000t	*Pr(P[2016]> P[2006])*	0.572928				
	B [1983]	59679.47	16444.66	39823	58020	81020
	B [1990]	49417.75	10817.69	36430	48285	63594
	B [2000]	53842	12935.63	38726	52570	70827
	B [2006]	44816.61	12118.2	29886	44145	60561
	H [1983]	0.027256	0.006163	0.019863	0.026725	0.035487
	H [1990]	0.069072	0.017283	0.048433	0.06711	0.09211
	H [2000]	0.031193	0.005401	0.0245	0.03096	0.0383
	H [2006]	0.027477	0.009146	0.016763	0.02642	0.03974
	P [1983]	0.509521	0.143549	0.33833	0.49285	0.70447
	P [1990]	0.427484	0.119561	0.28456	0.4164	0.58391
	P [2000]	0.463199	0.128851	0.30806	0.45	0.63777
	P [2006]	0.387177	0.122864	0.23643	0.3744	0.55147
500t	*B [2010]*	55359.19	20832.33	30093	53700	82356
	B [2016]	69054.99	27005.02	35570	68145	101900
1000t	*B [2010]*	53556.45	20251.11	28726	51775	79865
	B [2016]	65424.97	27273.52	31873	63585	100400
2000t	*B [2010]*	50989.8	20898.14	25530	49000	77718
	B [2016]	58114.17	28273.26	22519	56660	93728
3000t	*B [2010]*	48857.55	21042.1	23393	46950	75571
	B [2016]	51331.33	28876.31	14288	49395	88957
500t	*H [2010]*	0.010628	0.005181	0.006072	0.009311	0.016617
	H [2016]	0.00904	0.007686	0.004907	0.007338	0.01406
1000t	*H [2010]*	0.022009	0.010558	0.012523	0.019315	0.034814
	H [2016]	0.019492	0.017014	0.009958	0.015725	0.031377
2000t	*H [2010]*	0.048449	0.031702	0.025733	0.04082	0.078347
	H [2016]	0.067271	0.192568	0.021336	0.0353	0.088803
3000t	*H [2010]*	0.076915	0.047629	0.039696	0.063895	0.12827
	H [2016]	0.147222	0.366031	0.033723	0.060735	0.21
500t	*P [2010]*	0.474766	0.179678	0.24426	0.46375	0.71864
	P [2016]	0.587831	0.214576	0.29593	0.5981	0.8684
1000t	*P [2010]*	0.459483	0.176658	0.23773	0.44895	0.70088
	P [2016]	0.556632	0.217091	0.2589	0.56015	0.85234
2000t	*P [2010]*	0.438785	0.183285	0.20543	0.4274	0.69074
	P [2016]	0.49632	0.231099	0.18426	0.49505	0.8095
3000t	*P [2010]*	0.420807	0.183345	0.18949	0.4056	0.67364
	P [2016]	0.439415	0.239255	0.11673	0.4289	0.76907

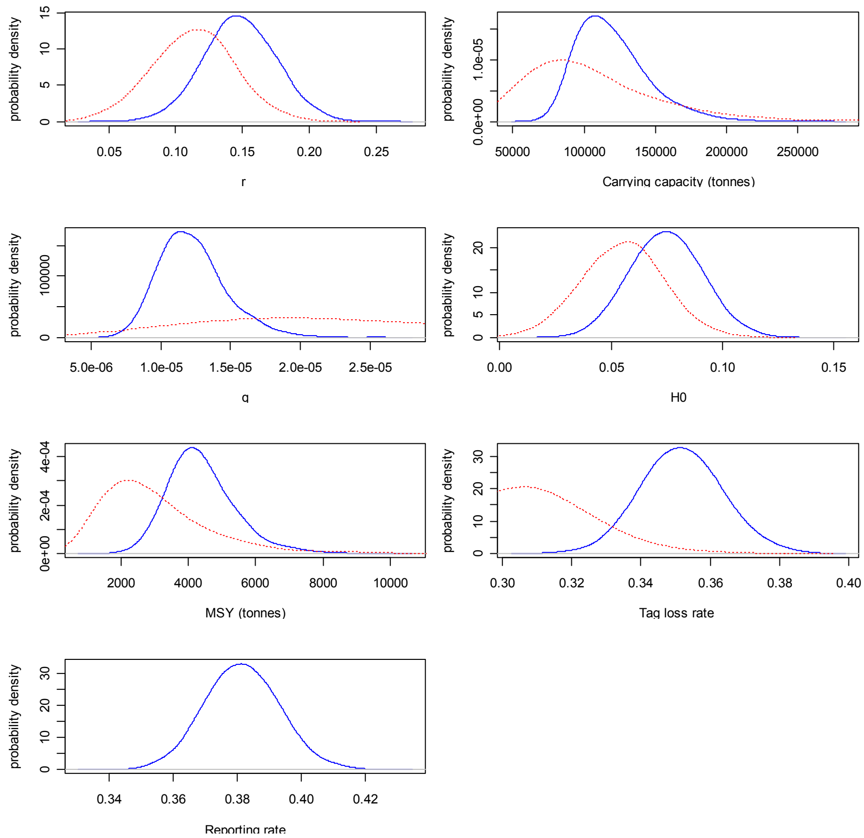

Figure 13. Posterior (solid blue line) versus prior (dotted red line) distributions of BSSSP-MR model parameters for the long term model.

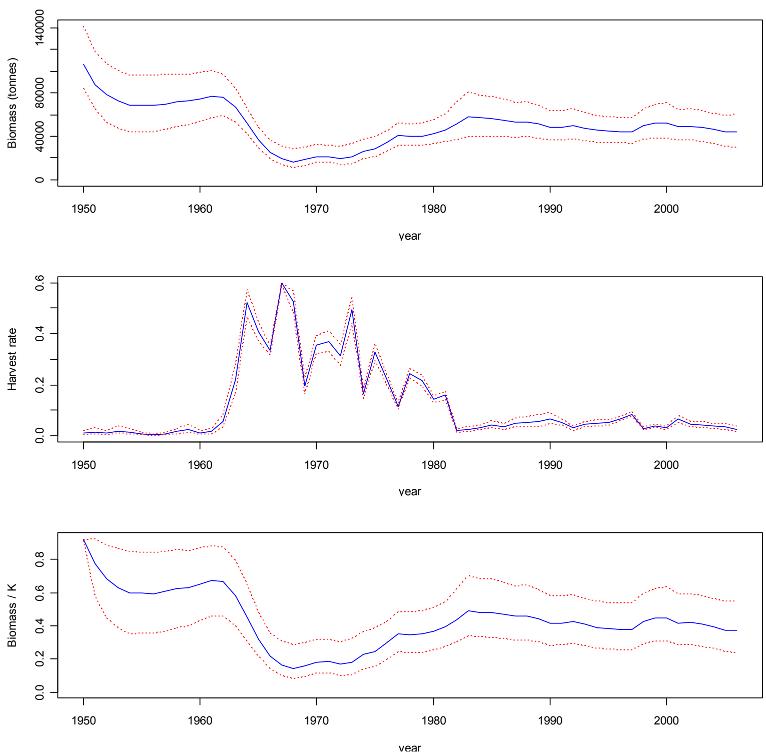

Figure 14. Posterior estimates of biomass, harvest rate and biomass relative to carrying capacity (*P*) under the long-term model. The blue represent the median posterior estimate and the red dotted lines, the 90 per cent probability interval.

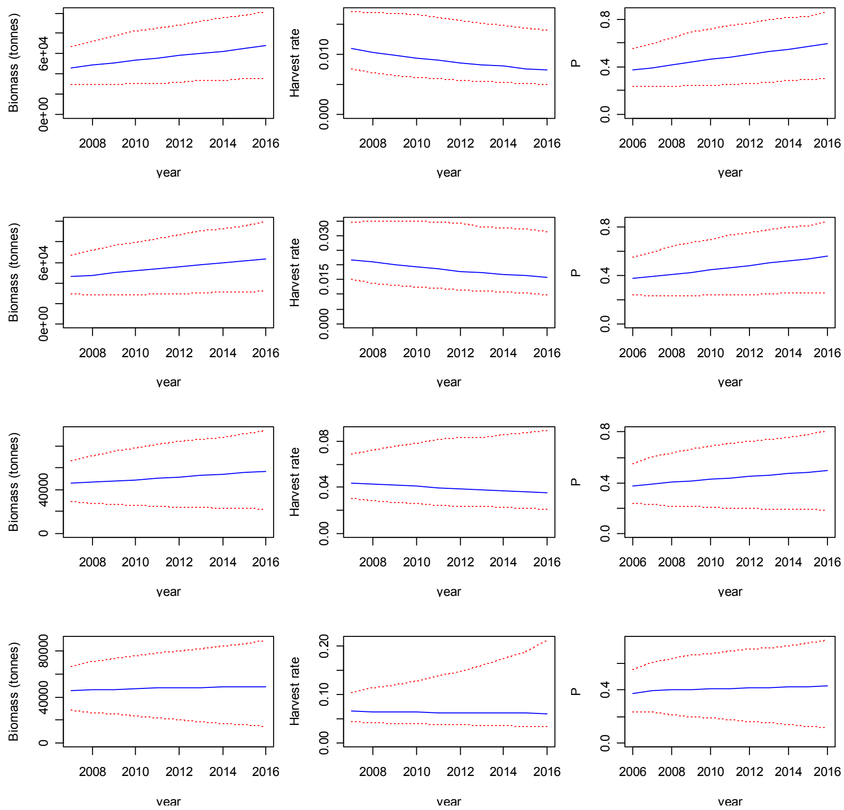

Figure 15. Biomass and harvest rate projections under different TAC strategies under the long-term model. Each row represents a different level of TAC. The blue line represents the median of the posterior estimates, the dotted red lines, the 90 per cent probability interval.

Discussion

By combining the mark-recapture and surplus production models, model parameters and variables of interest may be estimated that account for a more complete range of available data including the relative abundance indices, observed catch, and tag releases and recaptures. This is quite different from model averaging (*e.g.* King and Brooks, 2001; Raftery, 1996); exploitation rates are determined probabilistically, relative to the informational quality of the component models and data. Integrated stock assessment models have been advocated previously on the basis that they include a greater range of data (Pollock *et al*., 2002) and therefore do not rely as strongly on CPUE based indices that may not provide reliable information about relative stock sizes (Maunder *et al*., 2006). In trying to admit as much of the available data into the analysis as possible, the model was extended to include tagging and catch data since 1950. While a long time series model such as this may be seen as desirable, in the case of the BSSSP-MR model it results in optimistic estimates of stock status that are questionable. A probable explanation for this is the poor fit of a model with tagging parameters that are largely constant. The possible lack of model fidelity provides a reminder of both the significant assumption of temporally consistent tagging coefficients and the benefits of state-space model formulations (advocated by Millar and Meyer, 1999 and Michielsens *et al*., 2006). For example, it is likely that anchor design, size and materials have all changed to reduce shedding rate that is a component of tag loss rate in this analysis (Bayley and Prince, 1994). By adding an additional parameter, it may be possible to model a linear decrease in shedding rate that may be more considerate of the underlying tagging dynamics.

The short-term models all suggest that given current conditions, catches of 2000 tonnes are not likely to be sustainable, showing neutral (high reporting rate, low tag loss rate, constant tagging) or negative stock trajectories (low reporting rate, high shedding rate). The short-term models estimate a current stock status of between 0.2 and 0.4 of carrying capacity which appears to be somewhat optimistic given the available evidence supporting heavy over-fishing (Fromentin and Powers, 2005) such as an inability of the commercial fleet to meet its quotas over recent years. This result may offer support the low reporting rate scenario that also offered the most precise estimates of stock status and biggest agreement in terms of exploitation rates among mark-recapture and surplus production model components.

Under all prior specifications that were investigated, the short-term tagging model provided significantly lower estimates of carrying capacity and maximum sustainable yield than the BSSSP model in isolation (the mean estimate of the BSSSP-MR model is 2,200 tonnes compared with 3,400 tonnes of the BSSSP model). These posteriors were also significantly less precise (CVs were roughly double) providing further evidence that the mark-recapture model and data provide different information about exploitation rates (and thus support a more vague posterior distribution of BSSSP model parameters).

On reviewing recent updates in the conventional tagging data base, it is clear that the reported catches in recent years often increase after updates. Possible explanations for this include late reporting by fishermen or a lag due to processing of the tagging information. Regardless of the mechanism, using recent tagging data may lead to negative bias in the estimation of recent exploitation rates if some of the reported tags have yet to be included in the data set. There are two possible ways to deal with such a problem. The missing data mechanism can be modelled and the number of missing tags imputed, or the current data ignored. If the series of updated tagging datasets can be made available, constructing an imputation model (based on the assumption that past increases in recorded tag recaptures are relevant today) is preferable to ignoring the data since it is these recent exploitation rates that are of most interest.

It is clear that the priors for reporting rate (and to a lesser extent tag loss rate) can strongly affect the outcome of the combined model (that has been demonstrated widely elsewhere: Hearn *et al.*, 1998; Martell and Walters, 2002). The current reporting rate prior is derived from archival tagging data and is to an extent, corroborated by mark-recapture analyses of Atlantic swordfish that are under development. Further work into the estimation of priors for reporting rate would be desirable. For example, it is likely that reporting rate does not remain constant over time. More precise temporally variable reporting rate estimates could greatly increase the weight of the mark-recapture model in this analysis and effect model outputs markedly. More detailed methods that utilise the data of the pelagic observer programme program (US NMFS 1992-1997; POP, 2006) are under development to improve reporting rate estimation. Additionally, the analysis of the data from electronic tagging programs may offer better information on tag loss rates (Block *et al.*, 1998; 2002; Ludcavage *et al*., 1999; Goodyear, 1999). Further sensitivity analyses would be desirable in order to investigate the effect on model outputs of different relative abundance indices.

It is likely that the model could be improved by incorporating further covariate data. For example an area currently under investigation is how covariate data may be incorporated into the model to improve the prior specification of yearly harvest rates. Similarly, archival tagging data could support better estimation of movement rates and support spatially disaggregated population dynamics and mark-recapture components. In addition, an age structured population dynamics model may explain the data better in the case of Atlantic bluefin tuna (see MULTIFAN-CL, Hampton and Fournier, 2001).

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Appendix

Surplus production – mark-recapture model

```
# Bayesian state space surplus production - mark-recapture model.
# Tom Carruthers.
# The Fisheries Group.
# Imperial College.
# 07/2007.

Model{

# Loop through all model years
for(y in Ystart : Ycur+Yproj){

  #  Initial year(s)
  for(dummy1 in INITloop[y]:1){
        P[y]<-max(Binit,0.01)       # Initial biomass relative to K
        Binit<-1-hreqm/r
        #P[y] <- BrelK                 # Initial biomass relative to K (long term model only)
        B[y] <- P[y]*K                # Initial biomass
        H[y]~dunif(0.001,0.6)         # Harvest rate prior
        Cpred[y]<-log(B[y]*H[y])      # Model predicted catch
        C[y] ~dlnorm(Cpred[y],tauC)   # LHF. The probability of observed catch
  }

  # All years after initialisation including projections
  for(dummy1 in 2:INITloop[y]){


        # Not projected years (and those after initialisation)
        for(dummy2 in PROJloop[y]:1){
              C[y]~dlnorm(Cpred[y],tauC)     # LHF. The probability of observed catch
              H[y]~dunif(0.001,0.6)          # Harvest rate prior
              Cpred[y]<-log(B[y]*H[y])       # Model predicted catch
              Pmu[y]<-max(P[y-1] + r*P[y-1]*(1-P[y-1]) - (C[y-1]/K),0.01)   # Average biomass relative to K
              Pm[y]<-log(Pmu[y])
              P[y] ~ dlnorm(Pm[y],tauPEbsp)I(,1) # Biomass relative to K including process error
              B[y] <- P[y]*K                 # Biomass
              Ipred[y]<-log(q*K*P[y])        # Model predicted
        }

        # Just projected years
        for(dummy4 in 2:PROJloop[y]){
              for(TAC in 1:4){
                    Ct[TAC,y]<-TAC*1000
                    Ht[TAC,y]<-Ct[TAC,y]/Bt[TAC,y]
                    Pmut[TAC,y]<-max(Pt[TAC,y-1] + r*Pt[TAC,y-1]*(1-Pt[TAC,y-1]) - (Ct[TAC,y-1]/K),0.01)   # Average biomass
                                                                                                  relative to K
                    Pmt[TAC,y]<-log(Pmut[TAC,y])
                    Pt[TAC,y] ~ dlnorm(Pmt[TAC,y],tauPEbsp)I(,1)  # Biomass relative to K including process error
                    Bt[TAC,y] <- Pt[TAC,y]*K
              }

        }

        # Years with observed relative abundance index
        for(dummy3 in 1:iloop[y]){
```

```
            I[y] ~ dlnorm(Ipred[y],tauI)              # LHF. The probability of observed abundance indices
        }

    }

    # No mark-recapture calculations (initial period union projected years)
    for(dummy1 in PROJloop[y]:1){

        # First year at liberty
        caprob[y,1]<-log(H[y]*RR*RRind[y])           # Probability of catching, detecting and reporting a tag at liberty in the
                                                        first year at liberty
        invcaprob[y,1]<-log(1-H[y])            # Probability of not catching a tag at liberty in the first year at liberty
        mnp[y,1]<-exp(caprob[y,1])*exp(-L/2)*(1-F)        # Probability that a tag released in year y, is caught, detected and
                                                            reported in the first year at liberty

        # (Years at liberty > year at liberty 1) AND (Years at liberty < maximum ylib)
        for(ylib in 2:ylibs[y]-1){
            caprob[y,ylib]<-log(H[y+ylib-1]*RR*RRind[y])      # Probability of catching, detecting and reporting a tag at
                                                                liberty released in year y, in year at liberty ylib.
            invcaprob[y,ylib]<-log(1-H[y+ylib-1])    # Probability of not catching a tag at liberty released in year y, in year at
                                                        liberty ylib.
            mnp[y,ylib]<-exp(caprob[y,ylib]+sum(invcaprob[y,1:ylib-1]))*pow(exp(-L),ylib-1)*exp(-L/2)*(1-F)   # Probability
                                        that a tag released in year y, is caught detected and reported in year at liberty ylib.

        }
        # Last year at liberty
        mnp[y,ylibs[y]]<-1-sum(mnp[y,1:ylibs[y]-1])# Probability that a tag released in year y, is not caught before the
                                                    maximum ylib.
        Cap[y, 1:ylibs[y]]~dmulti(mnp[y,],rel[y])   # LHF. The probability of the observed tag recaptures for all years at
                                                      liberty from a cohort released in year y
    }
}

for(TAC in 1:4){
    PTAC35[TAC]<-step(Pt[TAC,Ycur+Yproj]-P[Ycur])
    Pt[TAC,Ycur]<-P[Ycur]
    Ct[TAC,Ycur]<-C[Ycur]
}
MSY <- (r*K)/4
MSY_prior<-(r_prior*K_prior)/4

# Priors
K<-exp(lnKq[1:1])  #first member is lnK
K_prior<-exp(lnKq_prior[1:1])  # first member of vector is lnlnlnK

q<-exp(lnKq[2:2])   #2nd member is lnq
q_prior<-exp(lnKq_prior[2:2])  # first member of vector is lnlnlnK
hreqm<-h0LnMr[1:1]  #first member of vector is h0
hreqm_prior<-h0LnMr_prior[1:1]
NatM<-exp(h0LnMr[2:2])  #second member of vector is ln(Mval)
r<-h0LnMr[3:3]   # third member of vector is r
r_prior<-h0LnMr_prior[3:3]   # third member of vector is r
lnK<-lnKq[1:1]
lnq<-lnKq[2:2]
lnM<-h0LnMr[2:2]
h0LnMr[1:3] ~ dmnorm(meanh[1:3],prech[1:3 ,1:3])       # vector of h0, ln(Mval), r is trivariate normal
h0LnMr_prior[1:3]~ dmnorm(meanh[1:3],prech[1:3 ,1:3])
lnKq[1:2] ~ dmnorm(meanKq[1:2],precKq[1:2 ,1:2])       # vector of lnK, lnq is bivariate normal
lnKq_prior[1:2]~ dmnorm(meanKq[1:2],precKq[1:2 ,1:2])
L ~dlnorm(-1.1836,277)
L_prior ~dlnorm(-1.1836,277)
SR ~ dlnorm(SRav,SRtau)I(0.1,)
RR_prior~dlnorm(RRm,RRtau)I(,1)
F<-0.1
Ft~dlnorm(Fav,Ftau)                  # Prior for tag failure rate, F
RR~dlnorm(RRm,RRtau)I(,1)            # Prior for the aggregated reporting rate, RR
RRm<-log(RRav)
tauPEbsp ~ dgamma(3.785518,0.008613854)   # Precision of the log-normal distribution of biomass relative to K
tauC<-1/(tauCSD*tauCSD)                   # Precision of the log-normal likelihood function of observed catch
tauCSD~dunif(0.1,1000)
tauI~ dgamma(1.708603,0.010223)   #1/(tauISD*tauISD) # Precision of the log-normal likelihood function of
                                                        observed abundance indices
}   # End of model
```