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FITTING SURPLUS-PRODUCTION MODELS WITH MISSING CATCH DATA USING ASPIC: EVALUATION WITH SIMULATED DATA ON ATLANTIC BLUE MARLIN

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SUMMARY

Assessments of sailfish and marlins usually rely on application of surplus–production models, because size and age composition of catches are not known. However, even annual catches of these species are unreported in some Atlantic fisheries where they are taken primarily as bycatch. Past ICCAT billfish assessments have omitted the missing data, an ad hoc *approach that reduces credibility of an assessment. In theory, if recent catch and effort data are available for fisheries lacking historical catch data, it should be possible to fit a surplus–production model by estimating historical catches from corresponding data on fishing effort. Enhancements to ASPIC (the computer program used for non-equilibrium surplus-production modeling in previous ICCAT assessments) for this task were evaluated on simulated fisheries data generated by a computer program constructed around life history characteristics of Atlantic blue marlin* (Makaira nigricans). *The resulting simulated population included sex, size, and age structure on a monthly basis; growth was sexually dimorphic, with females attaining larger asymptotic mean sizes; and size at age was variable. Annual recruitment was determined from spawning biomass with a Beverton–Holt stock-recruitment function, as modified by density-independent stochastic survival. The simulation model was used to generate sample time series of simulated catches and population abundance histories using several alternative assumptions about natural and fishing mortalities, the slope of the stock-recruitment relationship, and measurement error. The resulting time series of simulated catches and abundances were fitted with and without missing catches using ASPIC. Estimates of maximum sustainable yield (MSY) and the ratios of final-year stock biomass to biomass at MSY ($B./B_{MSY}$) and fishing mortality to fishing mortality at MSY ($F./F_{MSY}$) were compared to known values from the simulations; results with and without missing catches were contrasted. Results characterize biases most likely arising from dissimilarity of the strongly age-structured simulation model and the age-aggregated surplus–production model. Nonetheless, fitted values for $B./B_{MSY}$ and $F./F_{MSY}$ averaged very near the true values. ASPIC results obtained with missing catches were very similar to those based on complete catch data, but not surprisingly were somewhat more variable.*

RÉSUMÉ

L'évaluation du voilier et des makaires dépend normalement de l'application de modèles de production excédentaire, du fait que l'on ignore quelle est la composition en tailles et la structure démographique des prises. Toutefois, certaines pêcheries atlantiques qui les capturent de façon accessoire ne déclarent même pas la prise annuelle de ces espèces. Les évaluations antérieures des istiophoridés ont omis les données manquantes, ce qui est un processus ad hoc *réduisant la crédibilité d'une évaluation. En théorie, si l'on dispose de données récentes de capture et d'effort pour des pêcheries pour lesquelles les données historiques de capture manquent, il devrait être possible d'ajuster un modèle de production excédentaire en estimant les prises historiques d'après les données correspondantes sur l'effort de pêche. Des améliorations de l'ASPIC (programme informatique utilisé pour la modélisation de la production excédentaire en conditions de non-équilibre dans les évaluations antérieures de l'ICCAT) destinées à cette tâche ont été évaluées sur des données simulées de pêche issues d'un programme informatique élaboré autour des caractéristiques du cycle vital du makaire bleu* (Makaira nigricans). *La population simulée qui en résultait comprenait le sexe, la taille et la structure démographique sur une base*

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mensuelle; la croissance montrait un dimorphisme sexuel, les femelles atteigant une taille asymptotique moyenne plus élevée; et la taille à l'âge était variable. Le recrutement annuel a été déterminé d'après la biomasse reproductrice au moyen d'une fonction stock-recrutement de Beverton-Holt, modifiée par un facteur de survie stochastique indépendant de la densité. Le modèle de simulation a été utilisé pour obtenir des modèles de séries temporelles de prises simulées et l'évolution de l'abondance de la population au moyen de plusieurs alternatives hypothétiques concernant la mortalité, naturelle et par pêche, la pente de la relation stock-recrutement et l'erreur de mensuration. Les séries temporelles de la capture et de l'abondance simulées qui en découlent ont été ajustées avec et sans les prises manquantes au moyen de l'ASPIC. Les estimations de la prise maximale soutenable (PME) et le ratio de la biomasse de la dernière année et de la biomasse au niveau de la PME (B/B_{PME}) *et celui de la mortalité par pêche et de la mortalité par pêche au niveau de la PME* (F/F_{PME}) *ont été comparées à des valeurs connues provenant des simulations; les résultats obtenus avec et sans les prises manquantes ont été comparés. Les résultats mettent en évidence des biais qui proviennent le plus probablement du manque de similarités entre le modèle de simulation fortement structuré et le modèle de production excédentaire agrégé par âge. Toutefois, les valeurs ajustées de* B/B_{PME} *et de* F/F_{PME} *étaient en moyenne très proches des valeurs réelles. Les résultats de l'ASPIC obtenus avec les prises manquantes était très semblables à ceux qui se fondaient sur les données complètes de capture, mais s'avéraient, ce qui n'est pas surprenant, quelque peu plus variables.*

RESUMEN

*Las evaluaciones de pez vela y marlines dependen generalmente de la aplicación de modelos de producción excedente ya que no se conoce la composición por tallas y edades de las capturas. Sin embargo, en algunas pesquerías del Atl?ntico donde estas especies son capturadas principalmente como captura fortuita, las capturas anuales no se comunican. Anteriores evaluaciones ICCAT de marlines han pasado por alto los datos omitidos, un enfoque ad hoc que reduce la credibilidad de una evaluación. En teoría, si los datos recientes de captura y esfuerzo de pesquerías sin datos históricos de captura est?n disponibles, debería ser posible ajustar un modelo de producción excedente estimando las capturas históricas a partir de los datos correspondientes al esfuerzo pesquero. Para esta tarea, fueron evaluadas las mejoras de ASPIC (el programa de ordenador utilizado para los modelos de producción excedente de no-equilibrio en anteriores evaluaciones de ICCAT) sobre datos simulados de pesquerías generados por un programa de ordenador diseñado en torno a las características del ciclo vital de la aguja azul del Atl?ntico (*Makaira nigricans*). La población simulada resultante incluía sexo, talla y estructura de edad de forma mensual; el crecimiento era sexualmente dimórfico, con hembras que alcanzan mayores tallas asintóticas medias; y la talla por edad era variable. El reclutamiento anual se determinó a partir de la biomasa reproductora utilizando una función de stock-reclutamiento Beverton-Holt, modificada por la supervivencia estoc?stica independiente de la densidad. El modelo de simulación se utilizó para generar series temporales de muestra de capturas simuladas e historiales de abundancia de la población utilizando diversos supuestos alternativos sobre mortalidad natural y mortalidad por pesca, la curva de la relación stock-reclutamiento y el error de medición. Las series temporales resultantes de capturas y abundancias simuladas fueron ajustadas con y sin las capturas omitidas utilizando ASPIC. Las estimaciones del Rendimiento M?ximo Sostenible (RMS) y la relación de la biomasa del stock del último año con la biomasa en RMS (B./BRMS) y la relación de la mortalidad por pesca con la mortalidad por pesca en RMS (F./FRMS) fueron comparadas con los valores conocidos a partir de las simulaciones; se contrastaron los resultados con y sin las capturas omitidas. Los resultados indican que los sesgos surgen probablemente de la diferencia del modelo de simulación estructurado por edad y el modelo de producción excedente agregado por edad. Sin embargo, los valores ajustados para B./BRMS y F./FRMS alcanzaron una media muy cercana a los valores verdaderos. Los resultados ASPIC obtenidos con las capturas omitidas fueron muy similares a los resultados basados en datos completos de captura, pero como se esperaba fueron algo m?s variables.*

KEYWORDS

Stock assessment, Simulation, Accuracy, Fish catch statistics, Tuna fisheries

INTRODUCTION

Like data on many other stocks, Atlantic catch data on blue and white marlins (*Makaira nigricans* and *Tetrapturus albidus*, respectively) cannot be classified by age or sex. Consequently, it is not possible to apply age-structured assessment methods to these stocks; recent ICCAT assessments have applied the dynamic logistic surplus-production model described by Prager (1994) as implemented in the computer program ASPIC (Prager 1995). An additional complication to assessment of these species is that annual catch data are not reported from some Atlantic fisheries in which they are caught primarily as bycatch. This incomplete historical record complicates and undermines confidence in stock assessments. The most recent ICCAT assessments of Atlantic blue and white marlin noted this problem, and the missing data were necessarily omitted from application of the surplus-production model, with unknown consequences to assessment results. Here, we evaluate the feasibility of fitting a surplus-production model to catch and effort data from an age-structured population when substantial portions of the catch time series are missing but can be estimated from corresponding records of fishing effort.

METHODS

Overview

We used simulation to examine the properties of a procedure to accommodate missing catch values in fitting a logistic surplus–production model. Catch, effort, and abundance data were simulated with a population simulation model incorporating biological characteristics of Atlantic blue marlin. The surplus–production model was then fit to the simulated data using an observation-error estimator (ASPIC) conditioned on fishing effort, and resulting estimates were compared to known true values used in the simulations. The preceding steps were undertaken both for full data sets and data sets in which portions of the catch records were missing. To judge reliability of estimation in general and specifically in the presence of missing values, we examined errors in estimates of four management benchmarks: maximum population size, K; maximum sustainable yield, MSY; ratio of final-year fishing mortality rate F to F at which MSY can be attained, $F./F_{MSY}$; and ratio of final-year population biomass B to B at which MSY can be attained, $B./B_{MSY}$.

Biological Characteristics of Simulated Population

The age-structured population model we used for generating simulated data is described in Goodyear (1989); its application in the context of MSY estimation is described in Goodyear (1996). The simulation model is implemented with monthly time steps, is sex-specific, and includes variability in size at age. To minimize any possible effects of truncating age structure, 100 explicit ages were modeled.

Growth – The range of growth rates reported in the literature illustrates that mean sizes at age and asymptotic maximum size ($L_?$) of blue marlin are poorly known (Wilson 1984, Cyr 1987, Boggs 1989, Wilson *et al.* 1991). The growth model (Figure 1) used for our simulations combines mean sizes at age for the first year of life from Prince *et al.* (1991) with sizes for fish at age 1 and beyond from Wilson (1984). Within-year growth after age 0 was modeled without seasonal variability. Atlantic blue marlin shows strong sexual dimorphism in size at age (e.g., Wilson *et al.* 1991); accordingly, we modeled growth of each sex separately. Variability in size at age of each sex was simulated as normally distributed with constant coefficient of variation of 0.12, a value based on experience with other species. Length–weight models were those of Prager *et al.* (1995).

Fecundity – Data on reproduction in Atlantic blue marlin were reported by Erdman (1968), Cyr (1985) and de Sylva and Breder (1997). De Sylva and Breder (1997) state that female blue marlin reach maturity at 120 kg (perhaps smaller) and are capable of spawning up to four times per reproductive year, which in the north Atlantic includes July and August. Erdman (1968) also concluded that the spawning season was July and August, but found a minimum spawning size for females of about 45 kg.

Fecundity in many fish species increases as a power function of fish length, often with exponent greater than that of the length–weight equation. Data available from the literature are too sparse to characterize the underlying relation between blue marlin length and fecundity, so fecundity was modeled as a constant multiple of body weight for females above 45 kg (Figure 2). It is likely that this assumption overestimates reproductive importance of newly maturing females. We assume that abundance of males never limits reproduction.

Recruitment **–** Annual recruitment was determined from simulated population fecundity at the beginning of each year using a Beverton–Holt stock–recruitment function $R=1/(c + d / S)$, where R is recruitment, S parent stock size, and c and d are parameters of the model, to set mean recruitment for a given adult stock size. The absolute magnitude of recruitment is unimportant to this study, and mean recruitment at MSY for all simulations was set to 1,000,000 individuals at 3 months of age.

The stock–recruitment curve controls the population response to fishing mortality, an attribute more important here than the absolute magnitude of recruitment. The slope at the origin of the unfished stock–recruitment curve (a slope referred to here as ?) sets the compensatory capacity of the population. (In terms of the Beverton–Holt model above, ? =1/d.) As for most other stocks, the true value of ? is unknown for blue marlin. Several other stocks have undergone important population declines or collapses when the spawning potential ratio (SPR) has fallen below about 20% (Clark 1991, Gabriel 1985, Gabriel *et al*. 1989, Goodyear 1993, Mace and Sissenwine 1993). The 20% value is the level of SPR below which a population tends towards extinction for ? =5 (the reciprocal of 20%); thus, evidence from those other species suggests a minimum ? of about 5. Mace and Sissenwine (1993) further noted that replacement SPR was negatively correlated with maximum average body weight and body weight at 50% maturity, an observation that suggests a higher than average value of ? for blue marlin, since the species is quite large. Given this, and because the true compensatory capacity of this species is unknown, groups of data sets were simulated with four different values of ? : 5, 10, 15, and 25.

Recruitment in fish stocks is known to exhibit stochastic annual variability due to environmental factors not related to adult stock size. We simulated this by adding a random component to mimic the variability in egg-to-recruit survival seen in nature: predicted recruitment from the stock–recruitment relationship was multiplied by $\exp(R*\mathrm{CV} - 0.5*\mathrm{CV}^2)$; where R is a random normal deviate with mean zero and variance 1.0, CV is the coefficient of variation of the log of the random multiplier, and the second term is a bias correction. We assumed CV=0.15 for all analyses.

Natural Mortality **–** Natural mortality M is notoriously difficult to estimate, and especially difficult to separate from total mortality Z. A few data sets are available to estimate Z from the oldest age in a sample by the method of Hoenig (1983), as corrected for sample size. The oldest Pacific blue marlin reported by Hill *et al*. (1989) from a sample of 48 females was 27 years old. Assuming age of full recruitment to the sampling protocol of 2 years, the resulting estimate is Z=0.18. In a separate study, Wilson *et al*. (1991) found the oldest Pacific blue marlin from a sample of 18 females to be 21 years old; the resulting estimate is Z=0.19. Some part of total mortality Z is from fishing, so corresponding estimates of M must be lower than estimates of Z. Fishing mortality rates in the range F=0.03 to F=0.04 imply M?0.15, a likely upper bound on M. Wilson *et al*. (1991) also sampled Atlantic blue marlin: the oldest of a sample of 104 females was 17 years old, giving the estimate Z=0.36. Surplus–production model estimates of F from the last ICCAT assessment of Atlantic blue marlin averaged 0.31 for the years preceding the 1981–1984 collections included in Wilson *et al*. (1991); this gives the estimate M=0.36-0.31=0.05. However, estimates of absolute F from surplus-production models are known to be highly imprecise (Prager 1994). Because of the great uncertainty in estimating natural mortality, we conducted analyses over a range in M. In our simulated population, natural mortality declined from 0.5 for the youngest recruits to 0.05, 0.10, 0.15, 0.20 or 0.30 for the oldest fish in the population. Illustrations of M as functions of age for adult M of 0.05, 0.15, and 0.30 are given in Figure 3.

Simulation of Population Trajectories

Initial conditions **–** The first year of each simulation was designated 1955, and had the population at its unfished stable age distribution. This age distribution is a function of the natural mortality rate M and the unfished recruitment defined by the assumed level of mean recruitment at MSY and the initial stock–recruitment slope ? . The population was then simulated with growth, recruitment, natural mortality, and fishing mortality through 1998, for a series of 44 simulation years.

Trajectories of fishing mortality **–** Annual fishing mortality rates F for each combination of ? and M were adjusted so that the resulting pattern of simulated relative biomass (B_t / B_{MSY}, where *t* is time) approximated the trend estimated during the last ICCAT assessment (Figure 4, ICCAT 1998). Fishing selectivities were held constant across all simulations. Fish recruited to the simulated fishery at age 1; all ages older than age 0 were equally susceptible to fishing. Total annual fishing mortality was partitioned into five fisheries, each with a different historical pattern. Simulated catch and effort data for each fishery were saved for use in stock–production modeling.

Missing catches **–** Effects of missing catch information in time series used for production modeling were evaluated by constructing parallel simulated data sets, with and without missing catches, fitting the production model to both data sets, and inspecting both sets of estimates. Analyses with missing values simulated the rather severe situation in which catch data were available for each of the five fisheries only for the last 9 years (1990–1998) of the 44-year history of the exploitation. Simulated effort information was available for each fishery for the entire time series, as was the simulated stock biomass index.

Abundance indices – Stock abundance indices used in fitting production models are usually assumed to be in biomass units, i.e. to be indices of stock biomass rather than stock size in numbers of fish, at least when removals are also given in weight. Although the last Atlantic marlin assessment violated this assumption (ICCAT 1998), we maintained consistency between model assumptions and the simulated biomass index in the present analysis. To this end, a single time series of abundance was constructed for each simulated data set by multiplying an arbitrary catchability coefficient ($q=10^{-6}$) by the simulated annual average biomass of ages 1 and older. This formed the biomass index in fitting the model. We evaluate the effects of substituting an index of numbers for an index of biomass elsewhere (Prager and Goodyear 2000, this volume).

Process and Measurement Error – Other than stochastic variability in recruitment and size at age, no process error was included in the simulations. Measurement error was added to the simulated data when input files for fitting were generated. The input files themselves contained six time series: one series of annual effort and catch data for each of the five simulated fisheries, and one series of a simulated abundance index. Simulated measurement error was normally distributed for catch and lognormally distributed for effort and abundance, with its range constrained to ±2 SD. Four levels of error were added, corresponding to CVs of 0.01, 0.05, 0.125, and 0.25. The same CV of error was applied to catch, effort and (logarithm of the) abundance index in each error treatment.

Model Fitting and Evaluation

Runs made – Having chosen five values of M and four values of ? (the stock–recruitment parameter), we generated 100 simulated population trajectories for each, resulting in 2,000 simulated trajectories. To each of these, four levels of measurement error were added, giving 8,000 simulated data sets. Parameters of the surplus–production model (and related management benchmarks) were estimated twice for each simulated data set: first, with all catch data present; and second, with most catch data missing. The resulting 16,000 sets of estimates were examined, both to compare fits with and without missing data and to compare estimated values to the underlying true values used in the simulations.

Fitting method — The production model used was a logistic stock–production model (Schaefer 1954, 1957) in a dynamic (nonequilibrium) form due to Prager (1994). This model was fit with a modified version of the ASPIC computer program (Prager 1995), which implements an observation-error estimator through a forward-projection algorithm similar to that of Pella and Tomlinson (1969), but assuming log-normal errors in CPUE (Prager 1994). Optimization uses the polytope method of Nelder and Mead (1965), which we have found superior to gradient-based methods for fitting fisheries data and models, which often generate non-smooth surfaces of the objective function. Fitting in ASPIC can be conditioned on either catch or fishing effort rate. Prager (1994) pointed out that, when conditioning on catch, missing values of effort rate (or equivalently, CPUE) could be accommodated naturally by such an estimator and that estimates of those missing values would be obtained in the fitting process. The modified version of ASPIC used in this study implements an exactly analogous procedure when conditioning on effort.

Evaluation of estimates — We analyzed percent error (PE) in estimates of four parameters and benchmarks: maximum population size (K), maximum sustainable yield (MSY), ratio of fishing mortality in the final year to fishing mortality at MSY ($F./F_{MSY}$), and ratio of biomass in the final year to biomass at MSY ($B./B_{MSY}$). Percent error is computed as PE=100*(estimate-true)/true; the expected value would thus be zero in the absence of bias. (An advantage of using PE is that it is scale invariant. The disadvantage is that when a true value is small, a small absolute error may seem exceedingly large in a relative measure, such as PE.) Results were analyzed graphically through box-and-whisker diagrams (Tukey 1977) using S-Plus software (Mathsoft 1999).

RESULTS

The primary focus of the study was to determine effects of missing catch data on production-model estimates, and whether the use of data sets with estimation of missing data might constitute an improvement over the previous procedure of ignoring missing values. However, given the structural incongruity of the highly age-structured population simulator and the age-aggregated surplus–production model used for estimation, accuracy and precision of the surplus–production model estimates themselves were also of significant interest.

Population properties of simulated data sets

Equilibrium production curves were evaluated for each combination of ? and M used in simulations. For all parameter combinations evaluated here, maximum equilibrium yield (equivalent to MSY) was obtained at less than half the fishing mortality rate that causes extinction and at an equilibrium biomass less than half the unfished biomass (i.e., less than K/2). Figures 5 through 8 illustrate the extremes, which were associated with the lowest and highest values of M and ? employed. In these plots, MSY occurs where the yield curve is at a maximum. For the age-structured model, MSY was estimated to a tolerance of 0.001%, as were values of F_{MSY} and $B_{MSY.}$

Other emergent properties of the simulations are also of interest. The magnitude of random fluctuations in recruitment introduced to reflect environmental variability in egg-to-juvenile survival is shown for two cases in Figures 9 and 10. Year to year variability employed in the simulations is substantial but not overwhelming. The vector of fishing mortality rates of the five fisheries for the parameter combination of ? =10 and natural mortality M=0.15 is given in Figure 11. One example of annual combined catch and stock biomass for a simulation with ? =5 and M=0.05 are given in Figures 12 and 13. This parameter combination results in the population least able to withstand fishing mortality of those examined in these analyses. An example for ? =25 and M=0.30, the population most able to withstand fishing mortality in these analyses, is given in Figures 14 and 15. Only catches indicated by the filled bars in Figures 12 and 14 were provided for the fits with missing catch data.

Production-model estimates with all data present

Four figures illustrate distributions of percent error (PE) in estimates from simulated data with all catches present. Distribution of PE in estimates of maximum stock size K (Figure 16) are given as a box-whisker unit for each combination of M, ? , and CV of measurement error. The same format is used for distribution of PE in other quantities, and is explained in detail here. In Figure 16, each panel gives results for single a combination of ? and CV (of simulated measurement error), combined with all levels of M, M being shown on the vertical axis of each panel. Within each panel, a separate box-whisker unit (Tukey 1977) corresponds to each value of M. In the figure as a whole, ? increases from 5 to 25 as one moves from the bottom row of panels to the topmost row. The measurement-error CV increases from 0.01 to 0.25 as one moves from the leftmost column of panels to the rightmost column. In each box-whisker unit, the filled circle is the median PE from 100 estimates; in Figure 16 these are estimates of K. The rectangle of each box-whisker unit encloses the interquartile range, the outer whiskers denote the range of most other observations and the open circles are “outside values” by the criteria of Tukey (1977, p.44). To provide more legible scaling, we have not always displayed the entire range of PE in estimates; in such cases, a few outside values have been repositioned near the smallest or largest value that can be displayed on the graph.

In general, there appears to be a negative bias in estimates of K, which seems to decrease with increasing natural mortality (Figure 16). The addition of sampling error within the range evaluated has little effect on median estimates of K, although it increases variability, an effect that may be most pronounced for the smallest and largest values of ? . It appears that data sets with the smallest values of ? provide the most precise estimates of K, at least when the CV of observation error is not at the highest value examined.

In contrast to estimates of K, estimates of MSY exhibit positive bias, by about 20% on average (Figure 17). This bias does not appear to have a pattern with respect to M or ? , but estimates tended to be more variable at ? =5 and also at lower levels of natural mortality.

Estimates of B./B_{MSY} do not show consistent bias, although there is a suggestion of positive correlation between the estimates (and thus the bias) and M, particularly for ? > 5 (Figure 18). Median estimates of B/B_{MSY} were mostly within about 10% of true values. For most combinations of ? and M, measurement error had surprisingly little effect on estimates of B/B_{MSY}. Exceptions are a noticeable decrease in estimation precision for CV=0.25 (its highest value), especially at lower values of M.

Estimates of F./F_{MSY} tended exhibit negative bias of about 10%, although the bias is less negative (and for ? =25, it is positive) at M=0.05. Bias in these estimates does not appear to change greatly with increasing measurement error, although there is a slight suggestion that, over the range examined, bias is slightly larger, in a negative sense, with increased observation error. The precision of estimation, not surprisingly, decreases with increased observation error.

Production-model estimates with missing data

In general, properties of estimates obtained with most catch data missing were almost identical to those obtained with all data present (Figures 20-23). This result is also illustrated more concisely: because the most realistic values for measurement error, stock–recruitment shape, and natural mortality rate are uncertain, we classified results only by whether all data were present or most catch data were missing (Figures 24-26). We omit estimates of K from this presentation as of little interest in most assessments, and present results for MSY, B./B_{MSY}, and F./F_{MSY}. Precision of estimates of each of these measures was slightly worse when most catch data were missing. Estimates of MSY were positively biased, with median PE about +20% when all data were used, slightly less when most catch data were missing. The small positive median bias in estimates of B./B_{MSY} and small negative median bias in estimates of F./F_{MSY} were nearly identical between treatments (Figures 25 and 26).

DISCUSSION

Distributions of estimates of MSY, $B./B_{MSY}$ and $F./F_{MSY}$ were very nearly the same for surplus–production model fits with all catch data present and most catch data missing. These results show that the model can be fitted, using the algorithm implemented in the modified version of ASPIC, to time series in which some –or even most– catch data are missing. In these simulations, corresponding effort data were available and observed catch, effort, and an index of biomass were known with reasonable accuracy. This study supports the hypothesis that assessment of the marlins by ICCAT can be improved without resorting to novel statistical procedures to estimate missing historical catches (e.g., Goodyear 2000).

Our results also bear on the issue of the utility of surplus–production models when applied to strongly age-structured populations. The structural dissimilarity between such populations and simple surplus–production models promotes uncertainty as to whether such models can be applied to such species with expectation of reasonable results. Our results support the findings of other investigations, which have shown that surplus production models can provide useful, and often accurate and precise, characterizations of stock status (Ludwig and Walters 1985, Punt 1992). Recently, Prager *et al*. (1996) used simulation methods to study the robustness of surplus–production model estimates on a strongly age-structured stock with changing gear selectivity through time. Their results suggested that for stocks similar to swordfish in the north Atlantic, the presence of strong age structure and moderate changes in selectivity should not proscribe the application of simple production models.

Goodyear (1999) noted difficulties with surplus production model fits for a natural mortality rate of M=0.05 at the lower levels of ? examined in that study, and concluded that some of the fits represented outliers. A similar pattern is evident in the current results for estimates of MSY, $B./B_{MSY}$ and $F./F_{MSY}$. Imprecision in estimates was highest at the lowest level of ? examined and also increased with decreasing natural mortality rates, particularly at the highest rate of measurement error we evaluated. Among the parameter combinations evaluated here, the capacity of the population to compensate for fishing deaths is lowest for ? =5 and low rates of natural mortality. This combination of characteristics may enhance the masking effect of observation error on the population response to fishing that the model-fitting process is trying to capture. If so, surplus–production model fits to some populations that are highly susceptible to fishing may be more prone to random error.

Current results are consistent with previous findings that estimates of MSY and terminal year estimates of B/B_{MSY} and F/F_{MSY} were highly correlated with true values but appeared somewhat biased (Goodyear 1999). However, Goodyear's (1999) study was of only 20 deterministic simulations and included no consideration of stochastic variation in recruitment nor of measurement error. In contrast, the current study considered those factors and should thus be a more robust treatment of the question. Our present results suggest that the surplus production model as implemented here tends to overestimate MSY when fit to an age-structured population similar to the blue marlin model used in this analysis and with a similar history of fishing. About half of the fitted MSY estimates were positively biased by between 10% and 25% of the true values. Estimates of $B./B_{MSY}$ were slightly positively biased however, the bias was small, with about half the fitted values of $B./B_{MSY}$ between -6% and +15% of the true value. Estimates of $F./F_{MSY}$ were biased slightly downward, with about 50% of the fitted values falling between -16% and -4% of the true value. Although our results covered a fairly wide range of natural mortality rates and population compensatory capacities, care should be exercised in extrapolating the results to fish stocks with very dissimilar life histories, particularly to those with much higher natural mortality rates, and/or that are suspected to have strongly dome-shaped stock-recruitment curves. The results may also be specific to the simulated exploitation pattern used, which was devised to mimic the previously estimated exploitation pattern of Atlantic blue marlin. Additional simulations with other life histories and exploitation patterns would be advisable before extrapolating results to other stocks.

REFERENCES

BOGGS, C.H. 1989. Vital rate statistics for billfish stock assessment. Pages 225-233 i*n* R. H. Stroud (ed) Planning the future of billfishes: research and management in the 90's and beyond. Marine Recreational Fisheries 13, Part 1 National Coalition For Marine Conservation, Savannah Georgia, USA.

CLARK, W.G. 1991. Groundfish exploitation rates based on life history parameters. Can. J. Fish. Aquat. Sci. 48:734-750.

CYR, E.C. 1987. Age growth and reproduction of blue marlin, Makaira nigricans, from South Carolina billfish tournament collections. MS Thesis University of South Carolina, USA.41 pp.

DE SYLVA, D.P. and P.R. Breder. 1997. Reproduction, gonad histology, and spawning cycles of north Atlantic billfishes (Istuiphoridae). Bull. Mar. Sci. 60 (3):668-697.

ERDMAN, D.S. 1968. Spawning cycle, sex ratio, and weights of blue marlin off Puerto Rico and the Virgin Islands. Trans. Am. Fish. Soc. 97: 131-137.

GABRIEL, W.L. 1985. Spawning stock biomass per recruit analysis for seven Northwest Atlantic demersal finfish species. NMFS, NEFC, Woods Hole Laboratory Ref. Doc. No. 85-04.

GABRIEL, W.L., M.P. Sissenwine and W.J. Overholtz. 1989. Analysis of spawning stock biomass per recruit: an example for Georges Bank haddock. N. Am. J. Fish. Manage. 9:381-382.

GOODYEAR, C. P. 1989. LSIM — a length-based fish population simulation model. NOAA Tech. Memo. NMFS-SEFC-219, iii plus 55 pages.

GOODYEAR, C.P. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use. Pages 67-81. *in* S.J. Smith, J.J. Hunt and D. Rivard [eds.] Risk evaluation and biological reference points for fisheries management. Can. Spec. Pub. Fish. Aquat. Sci. 120.

GOODYEAR, C.P. 1996. Variability of fishing mortality by age: Consequences for MSY. N. Am. J. Fish. Manage.16:8-13.

GOODYEAR, C.P. 1999. A simulation model for Atlantic blue marlin and its application to test the robustness of stock assessments using ASPIC. Col. Vol. Sci. Pap. ICCAT, 49(1):503-513.

GOODYEAR, C.P. 2000. Preliminary analyses of the possible magnitude of the blue marlin catch by the Spanish longline fleet. Col. Vol. Sci. Pap. ICCAT, 51: 961-967.

HILL, K. T., G. M. Cailliet, and K. T. Hill. 1989 A comparative analysis of growth zones in four calcified-structures of Pacific blue marlin, Makaira, nigricans. Fish. Bull. 87: 829-843.

HOENIG, J. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 82:898-902.

ICCAT. 1998. Report of the third ICCAT billfish workshop. Col. Vol. Sci. Pap. ICCAT, 47: 1-128.

LUDWIG, D., and C.J. Walters. 1985.Are age-structured models appropriate for catch-effort data? Can. J. Fish. Aquat. Sci. 42:1066-1072.

MACE, P.M., and M.P. Sissenwine. 1993. How much spawning per recruit is enough? Pages 101-118 *in* S.J. Smith, J.J. Hunt and D. Rivard [eds.] Risk evaluation and biological reference points for fisheries management. Can. Spec. Pub. Fish. Aquat. Sci. 120.

MATHSOFT. 1999. S-Plus 2000 programmer's guide. Data Analysis Products Division, Mathsoft, Inc., Seattle, Washington, USA. 868 p.

NELDER, J.A., and R. Mead. 1965. A simplex method for function minimization. Computer J. 7:308–313.

PELLA, J.J. and P.K. Tomlinson. 1969. A generalized stock production model. Bull. I-ATTC 13:419–496.

PRAGER, M.H. 1994. A suite of extensions to a non-equilibrium surplus production model. Fish. Bull. 92:374-389.

PRAGER, M.H. 1995. User's manual for ASPIC: a stock-production model incorporating covariates, program version 3.6x. NMFS, Southeast Fisheries Science Center, Miami Lab., Document MIA-92/93-55, 4th edition, Miami, Florida, USA.

PRAGER , M.H. and C.P Goodyear. 2000 (this volume). Fitting a surplus-production model with numbers- vs. weight-based indices of abundance together with removals data in weight: an evaluation on simulated fisheries similar to blue marlin in the Atlantic ocean. Document SCRS/00/53.

PRAGER, M.H., C.P. Goodyear, and G.P. Scott 1996. Application of a surplus production model to a swordfish-like simulated stock with time-changing gear selectivity. Trans. Am. Fish. Soc.125:729-740.

PRAGER, M.H., E.D. Prince,. and D.W. Lee. 1995. Empirical length and weight conversion equations for blue marlin, white marlin, and sailfish from the North Atlantic Ocean. Bull. Mar. Sci. 56 (1):201-210.

PRINCE, E.D., D.W. Lee., J.R. Zweifel, and E.B. Brothers. 1991. Estimating age and growth of young Atlantic blue marlin Makaira nigricans from otolith microstructure. Fish. Bull. 89(3): 441-459.

PUNT, A.E. 1992. Selecting management methodologies for marine resources, with an illustration for southern hake. S. Afr. J. Mar. Sci. 12:943-958.

SCHAEFER, M.B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bull. I-ATTC 1(2):27–56.

SCHAEFER, M.B. 1957. A study of the dynamics of the fishery for yellowfin tuna in the eastern tropical Pacific Ocean. Bull. I-ATTC 2:247–268.

TUKEY, J.W. 1977. Exploratory data analysis. Addison-Wesley Publishing Company, Reading, Massachusetts, USA. 688 p.

WILSON, C.A. 1984. Age and growth aspects of the life history of billfishes. Ph.D. Dissertation. University of South Carolina, USA..180 pages.

WILSON, C.A., J.M. Dean, E.D. Prince, and D.W. Lee. 1991. An examination of sexual dimorphism in Atlantic and Pacific blue marlin using body weight, sagittae weight, and age estimates. J. Exper. Mar. Biol. Ecol..151:209-225.

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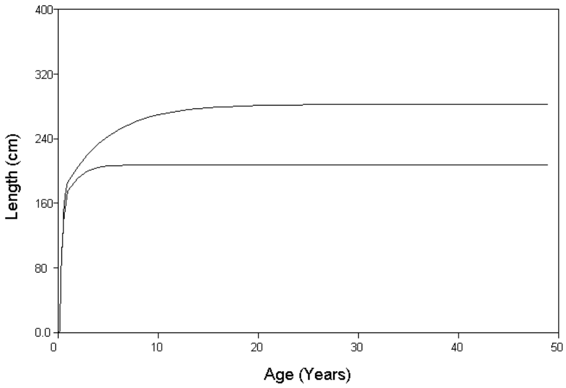

Figure 1. Growth of males (lower curve) and females (upper curve) used in this analysis to simulate blue marlin.

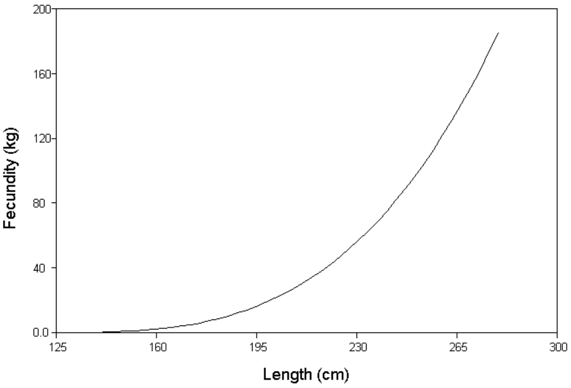

Figure 2. Relationship between female fecundity and length used in population simulations.

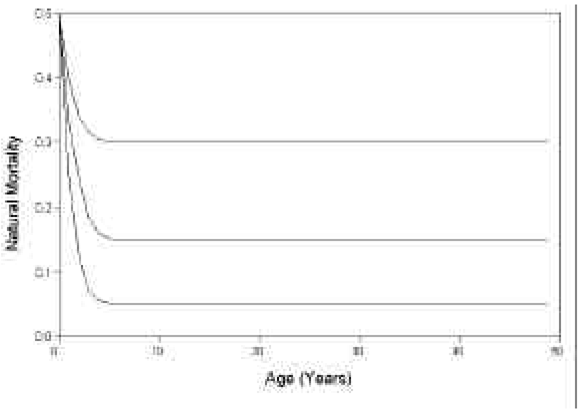

Figure 3. Pattern of natural mortality M by age for simulations with adult M=0.05, M=0.15, and M=0.30.

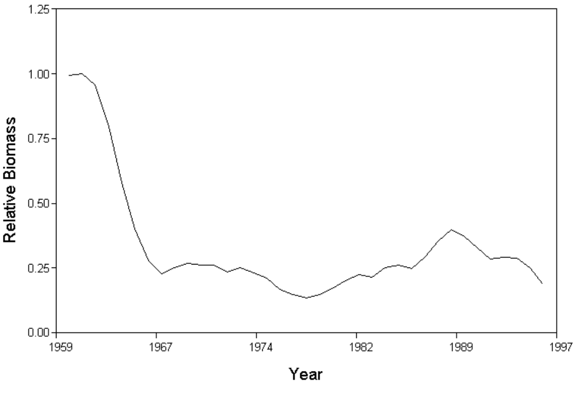

Figure 4. Estimated time trajectory of Atlantic blue marlin biomass relative to B_{MSY}, from 1996 ICCAT assessment.

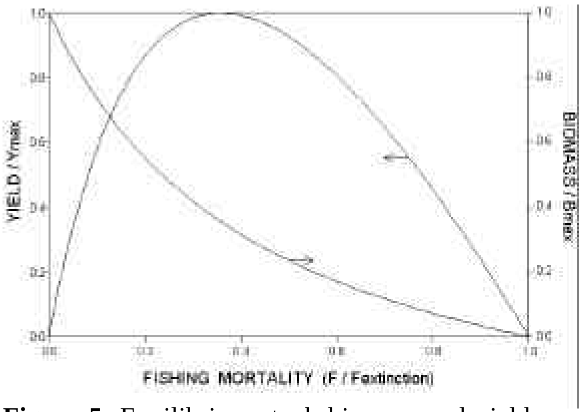

Figure 5. Equilibrium stock biomass and yield as functions of fishing mortality rate for simulated population with a ? =5 and M=0.05.

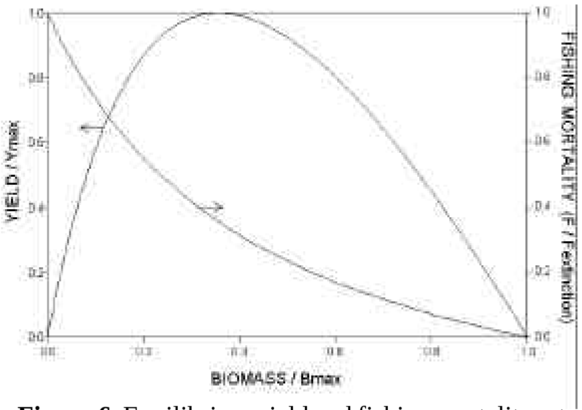

Figure 6. Equilibrium yield and fishing mortality rate as functions of stock biomass for simulated population with ? =5 and M=0.05.

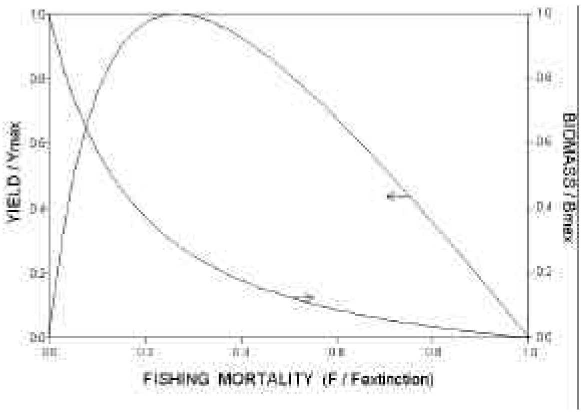

Figure 7. Equilibrium stock biomass and yield as functions of fishing mortality rate for simulated population with ? =25 and M=0.30.

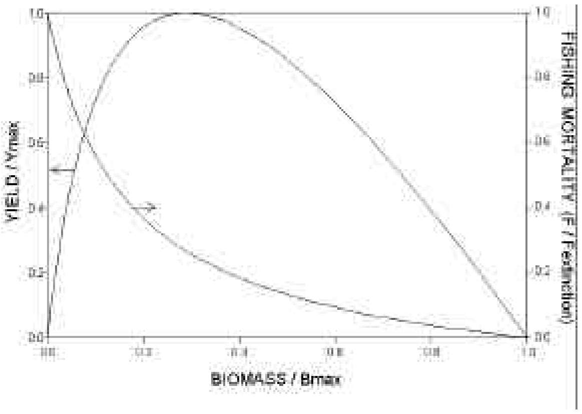

Figure 8. Equilibrium yield and fishing mortality rate as functions of stock biomass for simulated population with ? =25 and M=0.30.

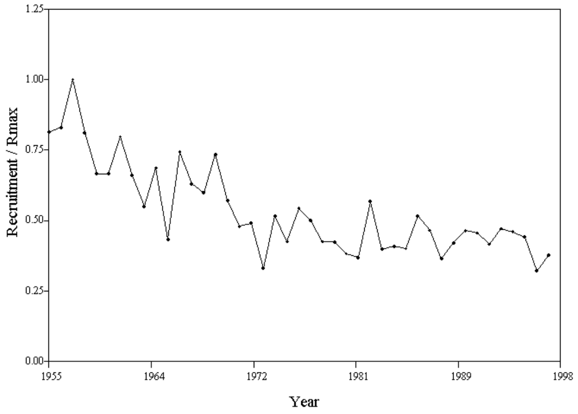

Figure 9. Typical trajectory of recruitment for simulated population with ? =5, M=0.05, and subject to time-varying fishing mortality that terminates below $F_{MSY.}$

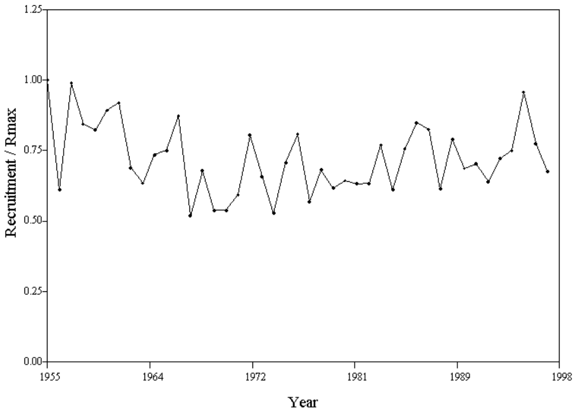

Figure 10. Typical trajectory of recruitment for simulated population with ? =25, M=0.3, and subject to time-varying fishing mortality that terminates below F_{MSY}.

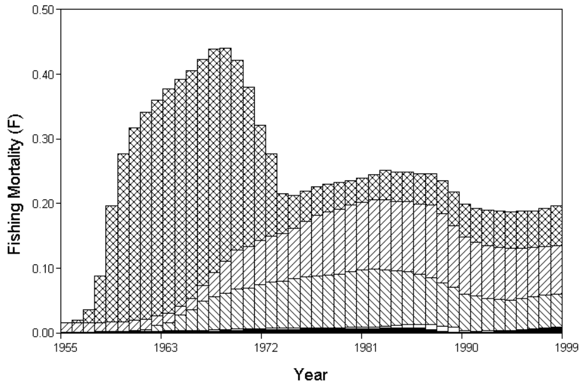

Figure 11. Typical fishing mortality rate F to which simulated population was exposed. Fill patterns show allocation of F among five simulated fisheries.

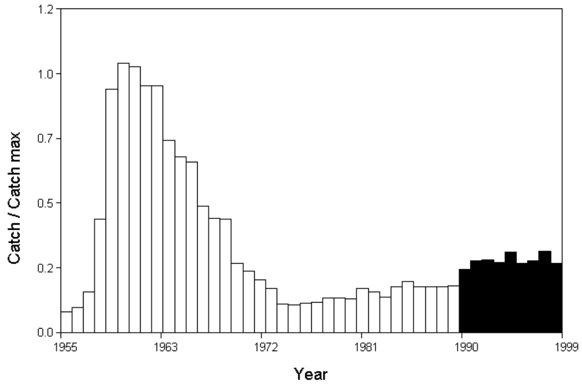

Figure 12. Typical annual total catches from simulated population with ? =5 and M=0.05. Only catches indicated by filled bars were provided to fitting routine (ASPIC) for model fits with missing catch data.

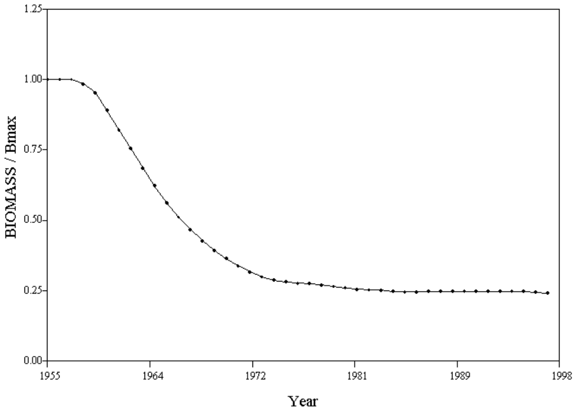

Figure 13. Simulated annual stock biomass corresponding to population simulation depicted in Figure 12.

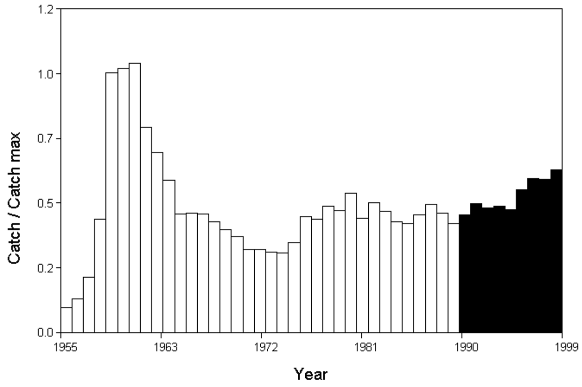

Figure 14. Typical annual total catches from simulated population with ? =25 and M=0.30. Only catches indicated by the filled bars were provided to fitting routine (ASPIC) for model fits with missing catch data.

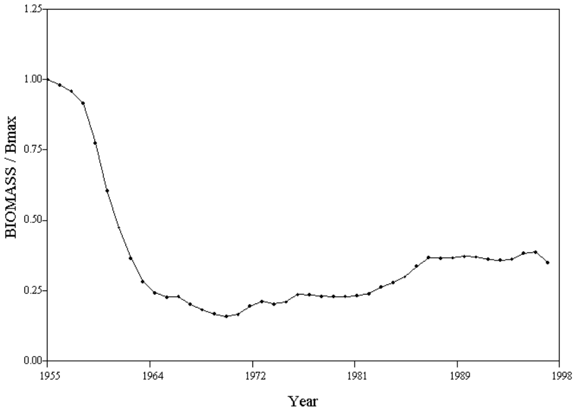

Figure 15. Simulated annual stock biomass corresponding to population simulation depicted in Figure 14.

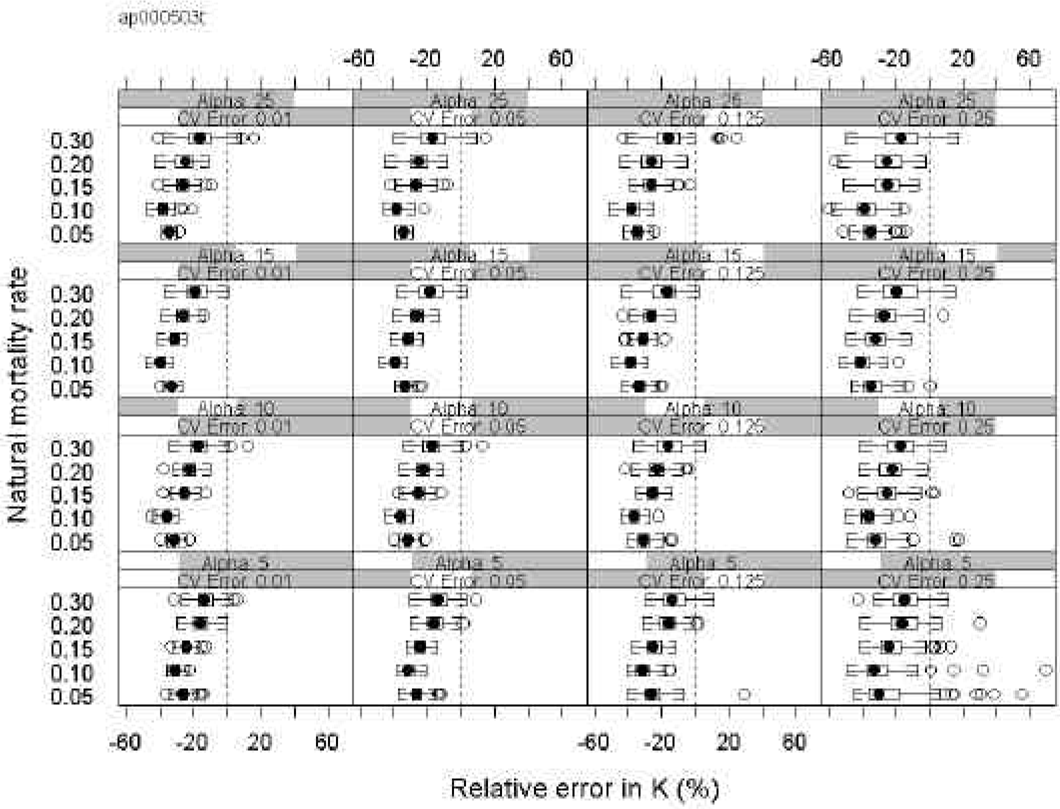

Figure 16. Relative error in estimates of maximum stock size (K) for simulated population similar to Atlantic blue marlin, fit with all catch data present. Error shown as a function of natural mortality, initial slope of the stock-recruitment curve (Alpha), and magnitude of random measurement error.

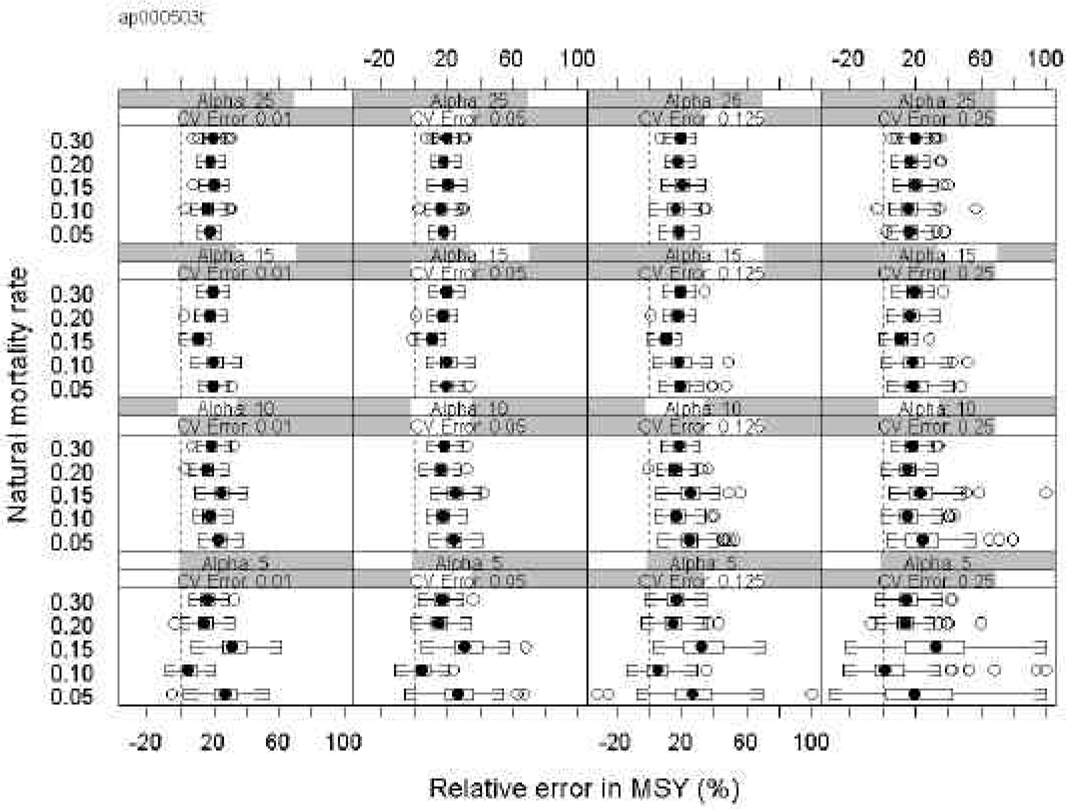

Figure 17. Relative error in estimates of maximum sustainable yield (MSY) for simulated population similar to Atlantic blue marlin, fit with all catch data present. Error shown as a function of natural mortality, initial slope of stock-recruitment curve (Alpha), and magnitude of random measurement error.

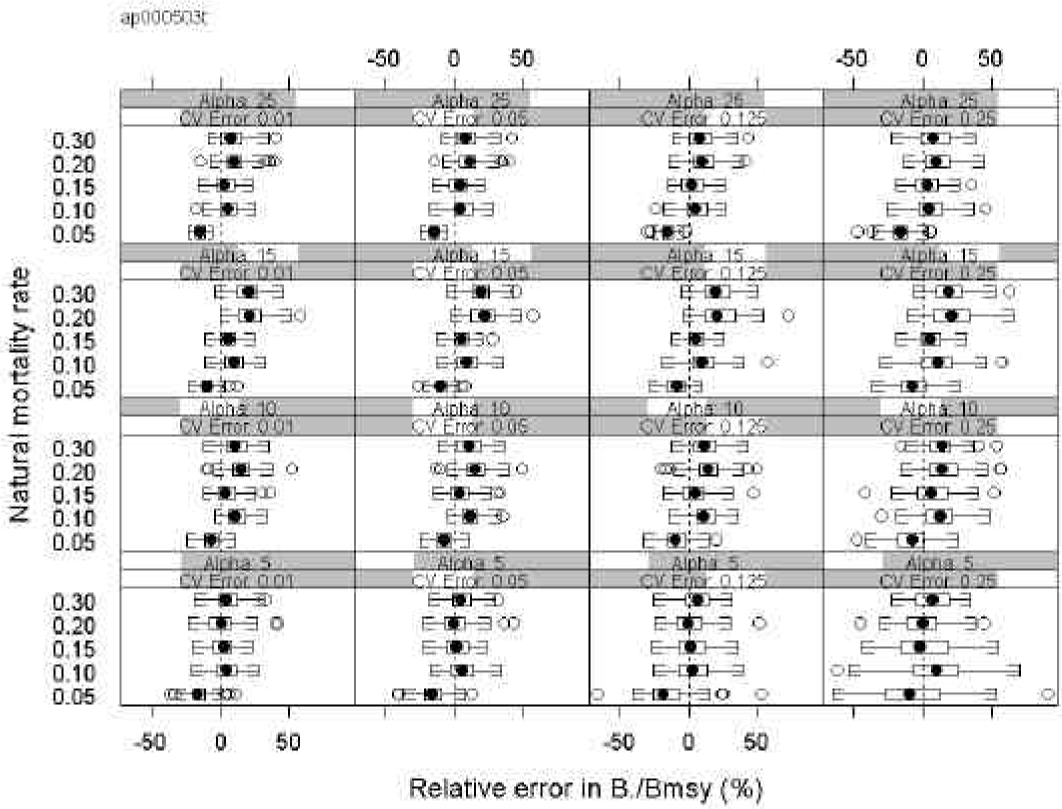

Figure 18. Relative error in estimates of ratio of final-year biomass to biomass at MSY (B./B_{MSY}) for simulated population similar to Atlantic blue marlin, fit with all catch data present. Error shown as a function of natural mortality, initial slope of stock-recruitment curve (Alpha), and magnitude of random measurement error.

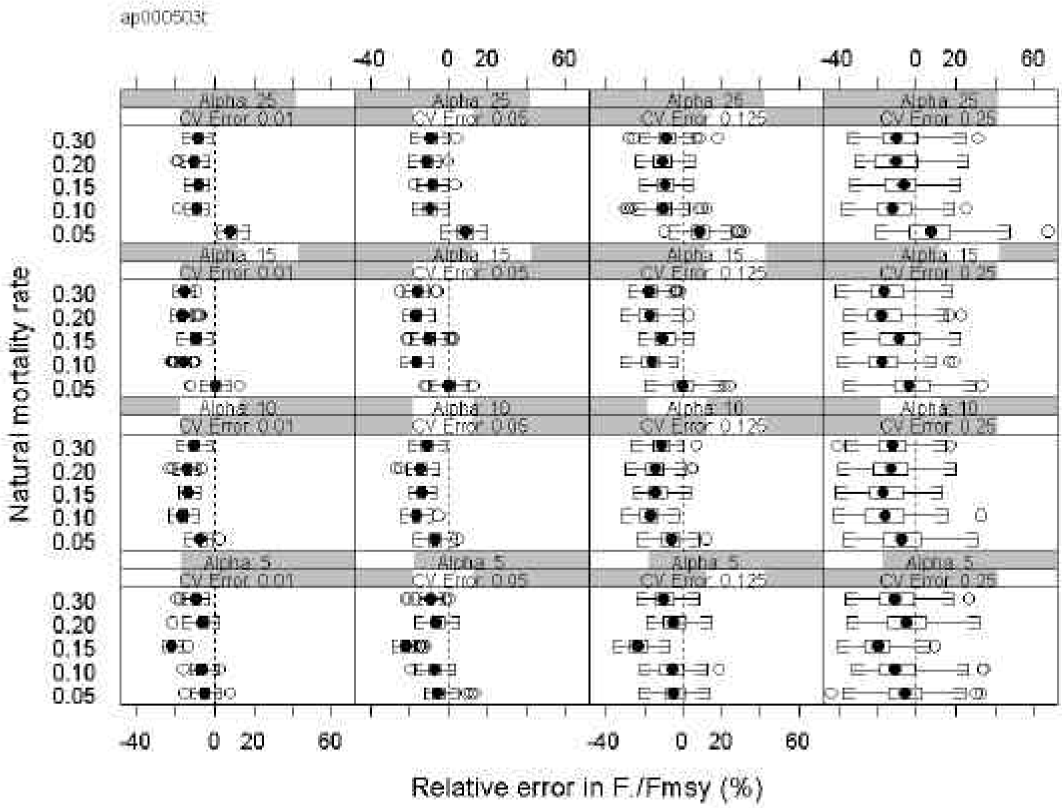

Figure 19. Relative error in estimates of ratio of final-year fishing mortality to fishing mortality at MSY (F./F_{MSY}) for simulated population similar to Atlantic blue marlin, fit with all catch data present. Error shown as a function of natural mortality, initial slope of stock-recruitment curve (Alpha), and magnitude of random measurement error.

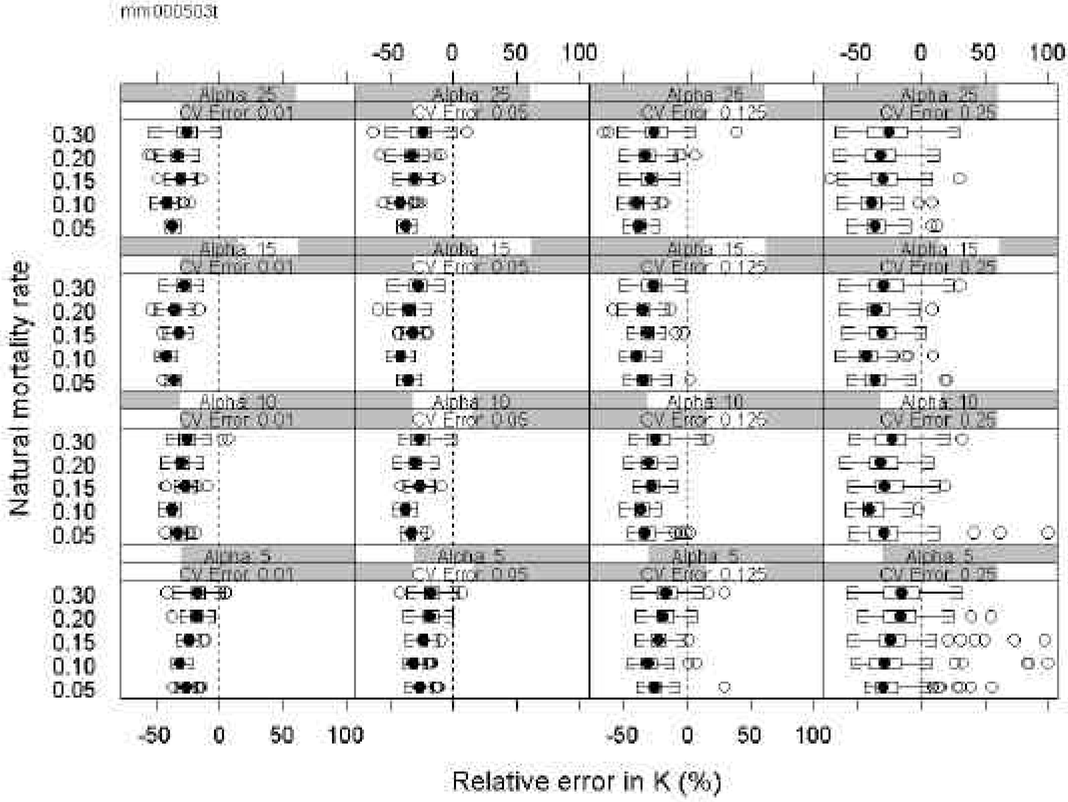

Figure 20. Relative error in estimates of maximum stock size (K) for simulated population similar to Atlantic blue marlin, fit to data with most catches missing. Error shown as a function of natural mortality, initial slope of stock recruitment curve (Alpha), and magnitude of random measurement error.

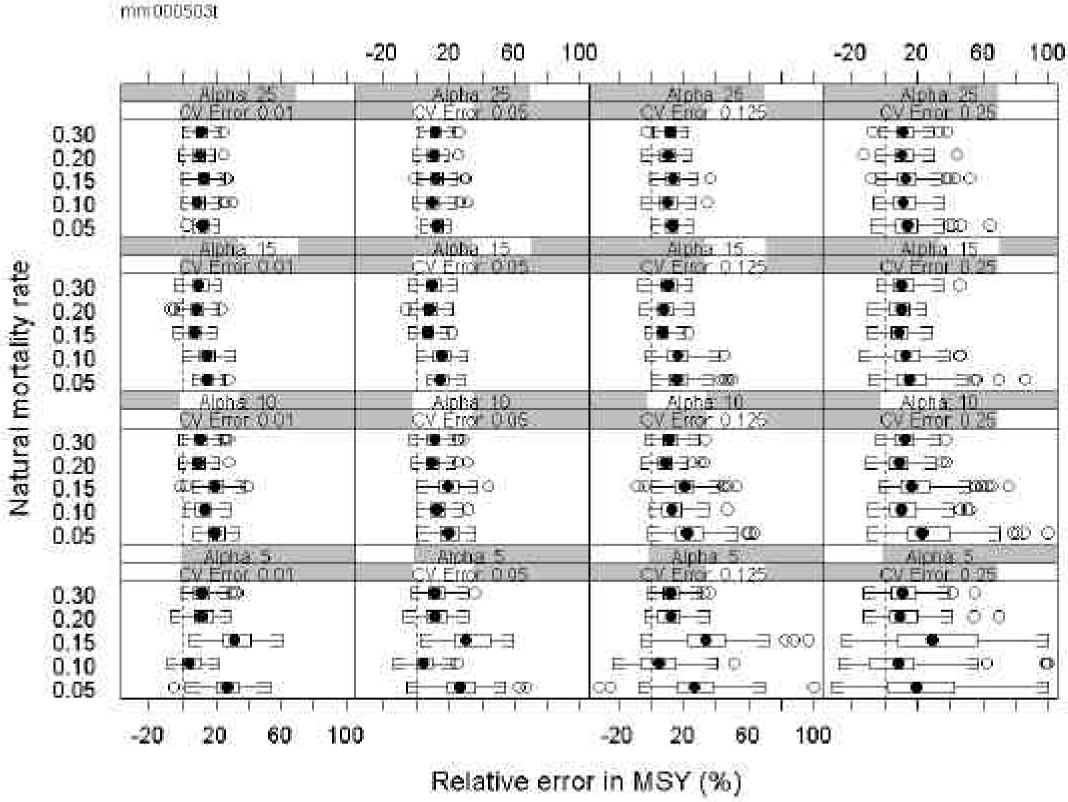

Figure 21. Relative error in estimates of maximum sustainable yield (MSY) for simulated population similar to Atlantic blue marlin, fit to data with most catches missing. Error shown as a function of natural mortality, initial slope of stock recruitment curve (Alpha), and magnitude of random measurement error.

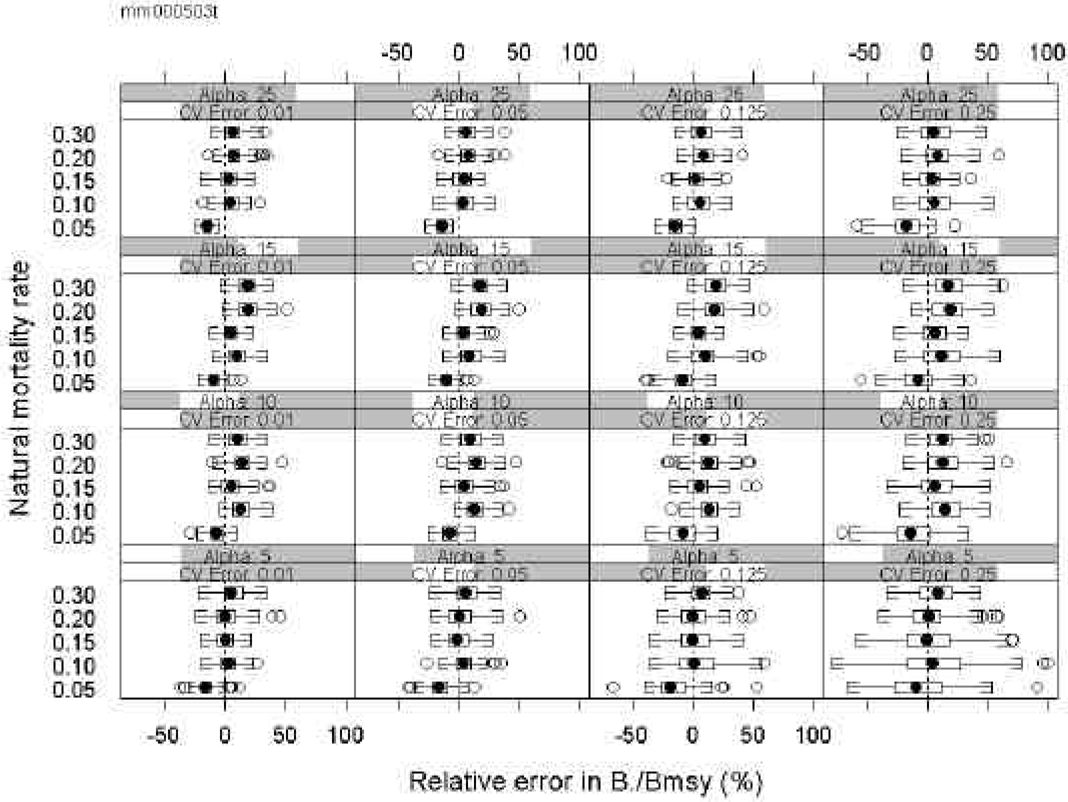

Figure 22. Relative error in estimates of ratio of final-year biomass to biomass at MSY (B./B_{MSY}) for simulated population similar to Atlantic blue marlin, fit to data with most catches missing. Error shown as a function of natural mortality, initial slope of stock recruitment curve (Alpha), and magnitude of random measurement error.

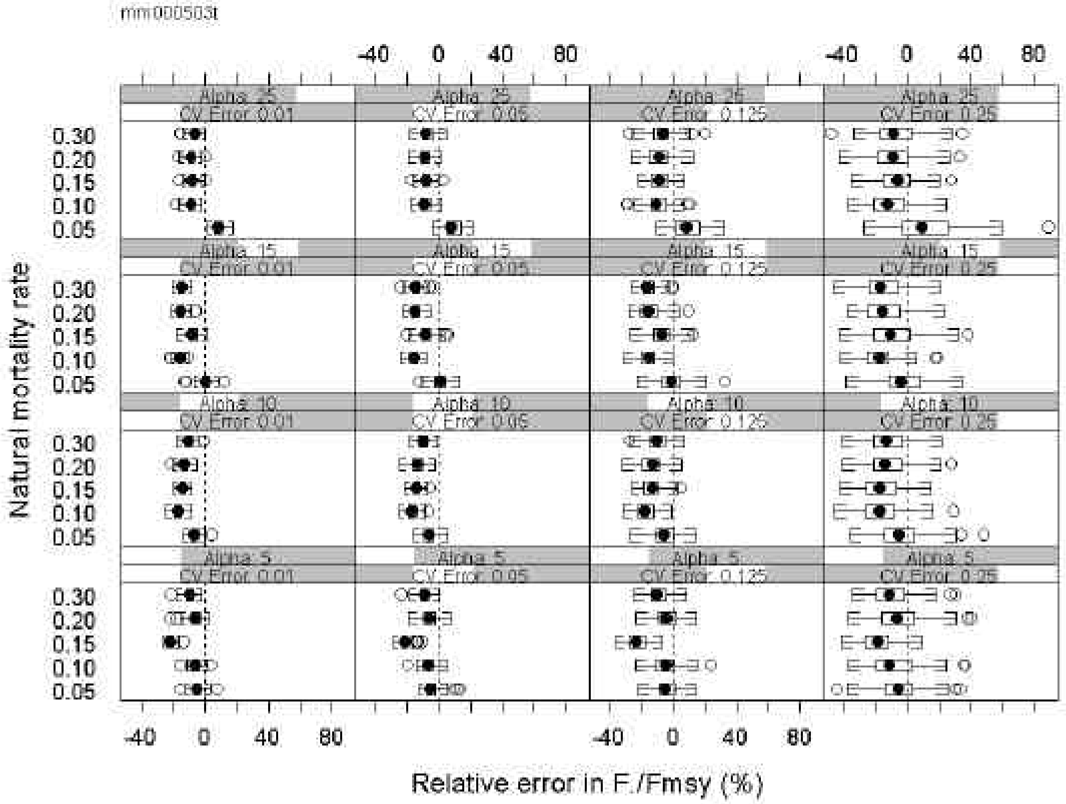

Figure 23. Relative error in estimates of ratio of final-year fishing mortality F to F at MSY (F./F_{MSY}) for simulated population similar to Atlantic blue marlin, fit to data with most catches missing. Error shown as a function of natural mortality, initial slope of stock recruitment curve (Alpha), and magnitude of random measurement error.

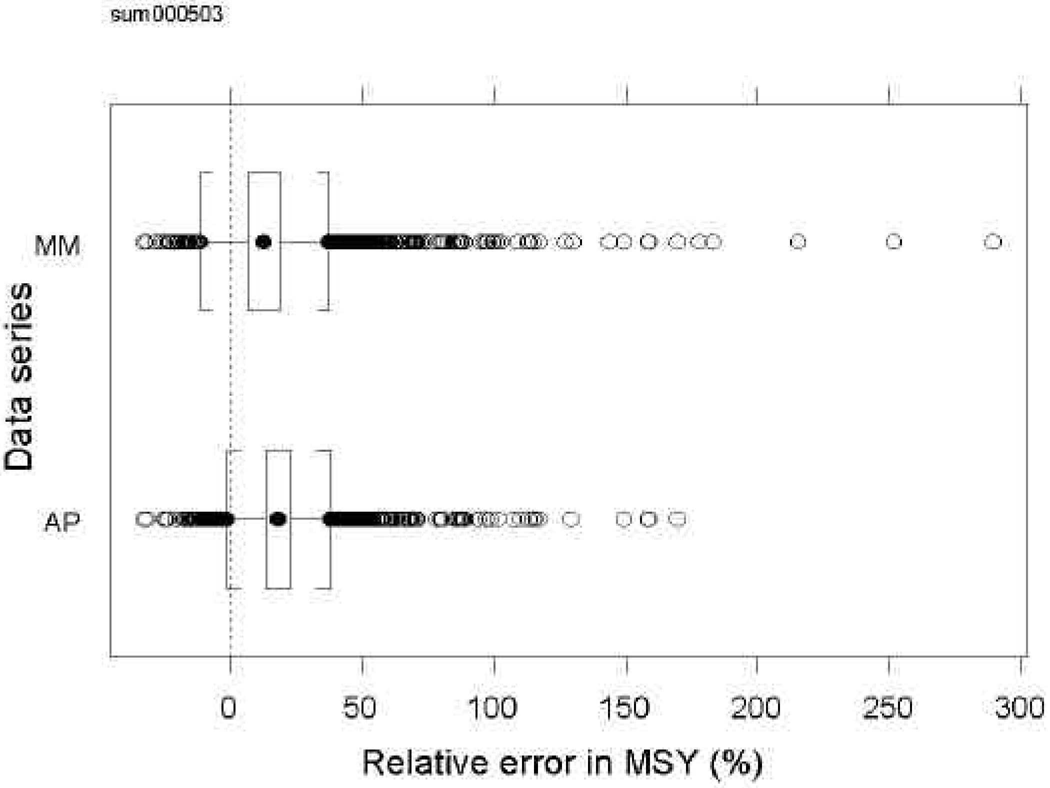

Figure 24. Relative error in estimates of MSY for simulated population. Comparison is between fits with all catch data present (AP) and those with most catch data missing (MM) and is pooled over all values of natural mortality rate, initial slope of the stock-recruitment curve (?), and magnitude of random measurement error.

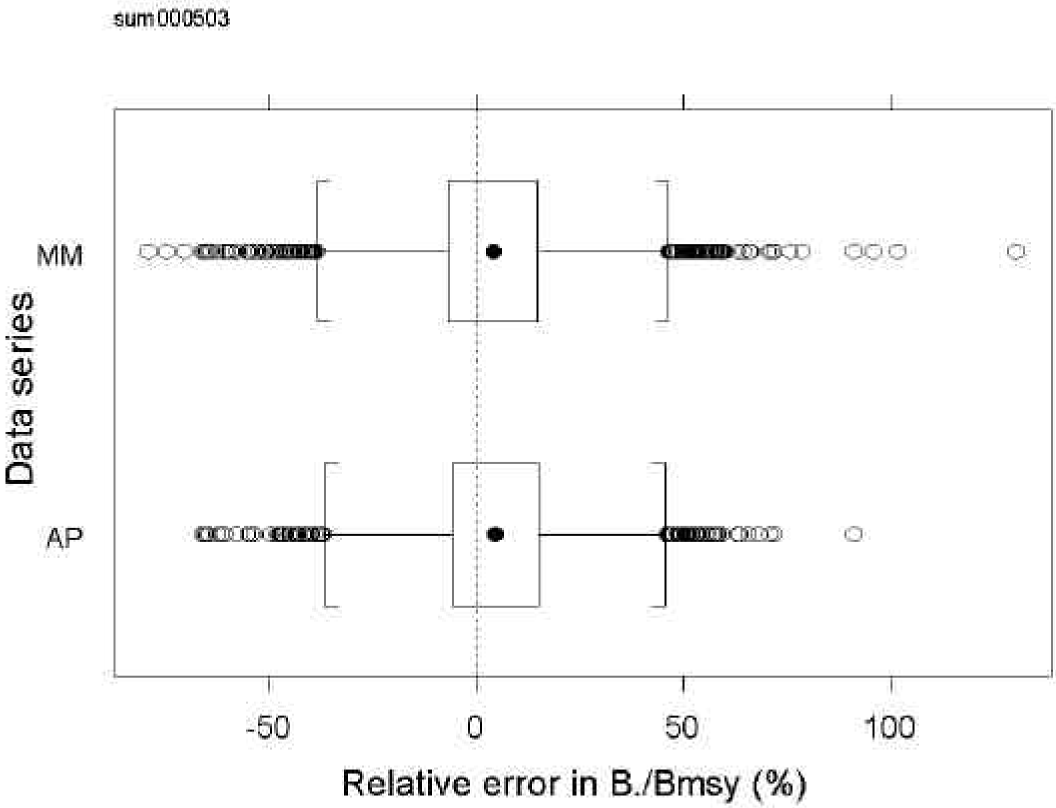

Figure 25. Relative error in estimates of ratio of final-year biomass to biomass at MSY (B./B_{MSY}) for simulated population. Comparison is between fits with all catch data present (AP) and those with most catch data missing (MM) and is pooled over all values of natural mortality rate, initial slope of the stock-recruitment curve (?), and magnitude of random measurement error.

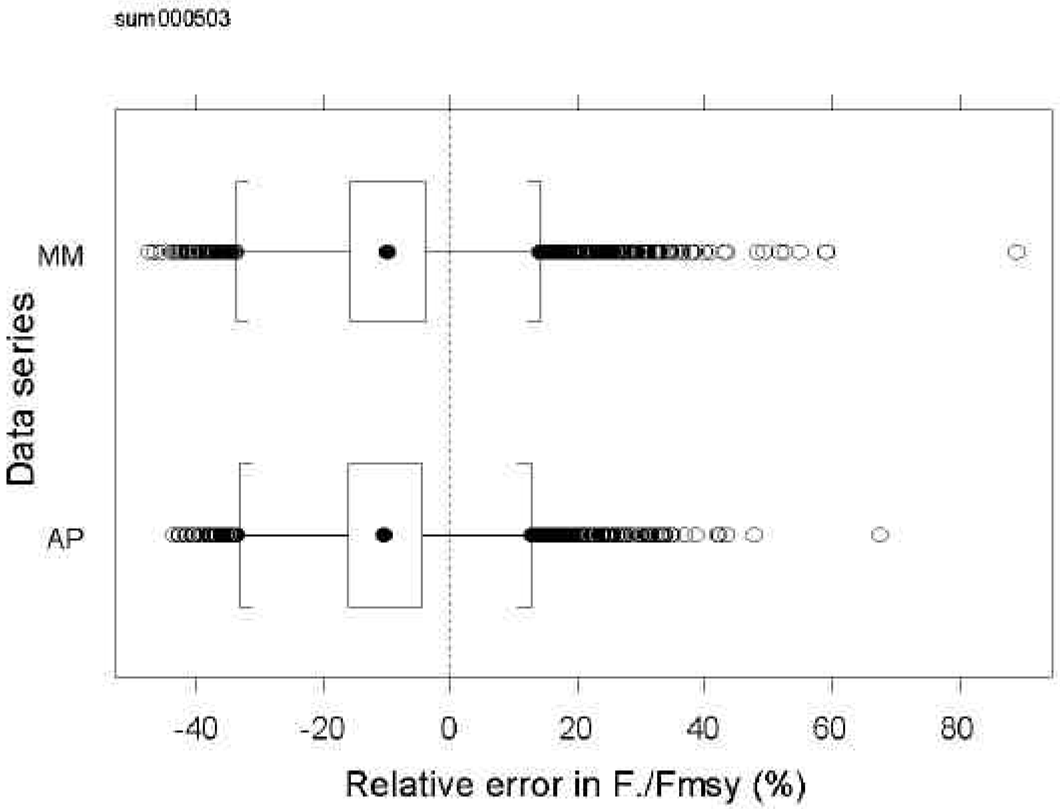

Figure 26. Relative error in estimates of ratio of final-year fishing mortality F to the F at MSY (F./F_{MSY}). Comparison is between fits with all catch data present (AP) and those with most catch data missing (MM) and is pooled over all values of natural mortality rate, initial slope of the stock-recruitment curve (?), and magnitude of random measurement error.